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A Proposed Framework for Simultaneous Optimization of Evacuation Traffic Distribution and Assignment

Fang Yuan
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Fang Yuan entitled "A Proposed Framework for Simultaneous Optimization of Evacuation Traffic Distribution and Assignment." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

Lee D. Han, Major Professor

We have read this dissertation and recommend its acceptance:

Arun Chatterjee, Frederick J. Wegmann, Yueh-er Kuo

Accepted for the Council:

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Acceptance for the Council:

Anne Mayhew
Vice Chancellor and
Dean of Graduate Studies

A PROPOSED FRAMEWORK FOR SIMULTANEOUS OPTIMIZATION OF EVACUATION TRAFFIC DISTRIBUTION AND ASSIGNMENT

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Fang Yuan
December 2005

DEDICATION

To my parents, Guolin Yuan and Shawei Huang,

for their love, support and education

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ABSTRACT

In the conventional evacuation planning process, evacuees are assigned to fixed destinations based mainly on the criterion of geographical proximity. However, such pre-specified destinations (OD table) almost always lead to sub-optimal evacuation efficiencies due to uncertain road conditions such as congestion, road blockage, and other hazards associated with the emergency. By relaxing the constraint of assigning evacuees to pre-specified destinations, a one-destination evacuation (ODE) concept has the potential of greatly improving the evacuation efficiency. A framework for simultaneous optimization of evacuation traffic distribution and assignment is therefore proposed in this study. Based on the concept of ODE, the optimal destination and route assignment can be determined by solving a one-destination (*1D*) traffic assignment problem on a modified network representation.

When tested on real-world networks for evacuation studies, the proposed *1D* model presents substantial improvement over the conventional multiple-destination (*nD*) model. For instance, for a hypothetical county-wide evacuation, a nearly 80% reduction in the overall evacuation time can be achieved when modeling of traffic routing with en route information in the *1D* framework, and the *1D* optimization results can also be used to improve the planning OD tables, resulting in an up to 60% reduction in the overall evacuation time. More importantly, this framework can be actually implemented, and its efficiency enhancement can be realized simply by instructing evacuees to head for more efficient destinations determined from the *1D* optimization performed beforehand.

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CHAPTER 1

INTRODUCTION

1.1 Background

Over the past 30 years, both natural and man-made disasters have been increasing. Hurricanes, earthquakes, floods, and accidents with nuclear power plants and chemical or hazardous materials have both threatened resident populations and compromised population growth and development in areas potentially exposed to danger. To cope with such potential public risks and to minimize the negative consequences associated with a disaster, the development of efficient emergency response plans and management strategies, including evacuation plans, is essential. As one of the most practical protective measures available during emergencies, evacuation planning is now a crucial component of emergency preparedness and response.

To be effective, evacuation planning and management must combine the skills and knowledge of emergency management agencies, law-enforcement agencies, and transportation professionals. In recent years, transportation professionals have turned increasingly to evacuation planning and modeling in response to heightened interest in emergency management and evacuation operations. Most studies in evacuation modeling have extended the applications of conventional transportation planning models, e.g., as a four-step process, to tackle the evacuation problem. These planning models were designed for day-to-day travel under normal situations in which origins and destinations (OD) are easy to determine and, for practical purposes, remain relatively stable over time. Emergency evacuation, on the other hand, is different from more conventional transportation planning problems. It calls for expeditiously mobilizing and transporting a sizable population out of harm's way and overcoming temporal and spatial constraints while facing, at times, uncertain road conditions due to congestion, road blockage, and other hazards associated with the emergency. Evacuation destinations may be difficult to determine and subject to change as a result of road closures or traffic jams. In addition, it is difficult to predict human behavior under emergency conditions. To estimate evacuation time, identify network bottlenecks, and develop effective planning and operational strategies under a wide range of unpredictable traffic, roadway, and weather conditions, it is essential to take into consideration and address the dynamic, transient nature of the evacuation process.

Although the transient and potentially chaotic nature of evacuation makes it far more challenging to manage than normal traffic operations, evacuation does have a unique advantage as far as planning goes. That is, while motorists have to head for and arrive at their specific destinations just as they must under normal conditions, they are more flexible under emergency evacuation conditions. In other words, as long as an evacuee safely exits the evacuation zone in a timely fashion, it is not that important which route he takes or at which location he leaves the zone. This flexibility in evacuees' destination selection and its associated benefit to the planning process is not well understood and is seldom exploited. In fact, the potential benefits of this flexibility are often wasted through the common practice of rigidly assigning evacuees to designated routes, shelters, and/or destinations based mainly on proximity.

Past experience suggests that a major problem in evacuation operations is that routes exiting an evacuation zone are often limited in number and insufficient in capacity to handle the unusual surge in resultant demand from a large-scale emergency evacuation (Alsnih and Stopher, 2004; Urbina and Wolshon, 2003). In most cases, constructing new routes and increasing roadway capacities are simply too cost-prohibitive to be considered practical for improving evacuation efficiency. Therefore, ways of improving the planning and operational aspects of the evacuation process in order to best utilize the existing transportation network have often been the focus of past studies. Some such efforts include the implementation of counter/contra-flow lanes, staggered departure times, traffic-signal control, multi-jurisdiction coordination, special routing consideration for heavy vehicles, and so on (Franzese and Han, 2001a,b; Chin et al., 2005). Yet no effort has to date recognized or explored the aforementioned flexibility in the destination selection process of evacuees.

In current evacuation planning, the distribution and assignment of evacuees to available routes and destinations has routinely been more of an art than a science, performed by municipalities with so-called local knowledge and past experience as their guides. This approach, while mostly sensible, does little to optimize the destination assignment (OD table) to ensure minimal personnel loss and evacuation time. The OD table, used in most evacuation models, thus represents a fixed and static assignment that almost never leads to optimal efficiency as traffic demand and roadway conditions continue to fluctuate throughout the evacuation period. Even with the implementation of dynamic traffic assignment (DTA), which is supposed to find the best routes for evacuees by taking into consideration changing traffic conditions, models based on fixed OD tables can be quite inefficient when a destination becomes hard (or even impossible) to access due to congestion or blockage. In such situations, the flexibility that affords evacuees the option to head for other exit routes/destinations should be explored.

1.2 Research Objectives

For effective evacuation planning and operations, it is essential to estimate as accurately as possible the number of evacuees and their distribution throughout the evacuation planning zone (EPZ) and to decide the most efficient routes outward from the EPZ for evacuees according to updated network and traffic conditions. To reduce evacuation time and exposure to danger, both the evacuation route selection and the destination choices can and should be optimized during evacuations. By offering flexible destination choices, it is possible to give evacuees more (and more efficient) route choices as well. As the traffic distribution to different destinations, is optimized, network flow patterns can also be changed and optimized, ultimately improving the whole network performance during evacuations. This study is motivated by a clear need for such an effective optimization method for evacuation destination assignment.

Destination assignment and route assignment for optimal evacuation operations are really interrelated and constitute almost a chicken-and-egg situation. The destination assignment first relies on the accessibility of the road network in an evacuation area, and then is determined by factors such as distance, travel time, and reliability of the routes toward a potential destination as well as the availability and capacity of shelter or emergency services at that destination. To optimize the routing problem, one has to know the destinations, but to optimize the destination assignment, one has to know the minimal travel time, and hence route assignment, to all destinations. To tackle the inherent complexity of the problem, this study proposes a framework for simultaneously optimizing evacuation traffic destination and route assignment. Based on the proposed framework, the optimal evacuation destination and route assignment can be determined through a one-step optimization procedure. This framework could be applied at different stages of evacuation planning and management, from evaluating and improving existing evacuation plans to real-time evacuation operations.

1.3 Research Scope

The framework for simultaneously optimizing evacuation traffic distribution and assignment is based on the concept of one-destination evacuation (ODE). By changing the network representation with one dummy point as the final destination of evacuation, a two-step decision-making process, including demand distribution and traffic assignment, is translated to a one-step optimization process. By solving a one-destination traffic assignment problem on a modified network representation, the optimal destination assignment can be determined along with the route assignment toward a globally optimal network flow pattern. The ODE concept, modeling strategy, mathematic formulation, potential applications, and some implementation issues are here presented and discussed.

To demonstrate the feasibility and superiority of the ODE model, simulation analyses were conducted for two study sites/cases, including a regional evacuation due to nuclear power plant mishaps and a county-wide special-event evacuation. For each case, the potential applications of the ODE model from evacuation planning to real-time operations were demonstrated and evaluated. Two widely used traffic simulation and assignment tools, VISSIM and DYNASMART_P, were selected to implement and test the ODE model in the different cases. Both static traffic assignment (STA) and dynamic traffic assignment (DTA) were employed to model and optimize various evacuation scenarios, representing various destination/route assignment strategies that are used in evacuation planning and operations.

To guide the optimization process and evaluate its benefits, various measures of effectiveness (MOEs) utilized in evacuation studies must also be examined. In evacuation research literatures, a wide range of MOEs has been identified and used, but none of them provides comprehensive assessment or a thorough understanding of different evacuation scenarios. For this reason, a four-tier MOE framework is proposed to take into consideration, in a comprehensive fashion, evacuation time, cumulative exposure, and risk factors. The ways in which these MOEs may be calculated, measured, and used for different evacuation scenarios are also presented.

1.4 Organization of Dissertation

The research will be presented in seven chapters, as follows:

Chapter 1 introduces the research background, objectives, and scope of this study.

Chapter 2 reviews the current practices of evacuation planning and modeling, evacuation models developed, and MOEs used in evacuation studies.

Chapter 3 proposes a four-tier MOE framework for evacuation studies. For each tier of MOE, the optimization formulation is presented.

Chapter 4 introduces the ODE concept and the method for simultaneous optimization of evacuation traffic distribution and assignment. The network representation, mathematical formulation, potential applications, and implementation of the ODE model are introduced.

Chapter 5 describes two case studies in which the ODE model is tested and evaluated. The network setup, modeling scenarios, and simulation results are presented.

Chapter 6 further tests the ODE model on a hypothetical grid network to compare its performance under various demand distribution and network constraints.

Chapter 7 presents conclusions and recommendations resulting from this study.

CHAPTER 2

LITERATURE REVIEW

As a result of heightened interest in emergency management, transportation professionals have been more involved in evacuation modeling, planning and operations in recent years. Many studies have extended the applications of conventional transportation planning tools to tackle the problem of evacuation, and many of the newest policies and practices related to evacuation have been developed incorporating the knowledge and experience of transportation professionals. Therefore, transportation analysis has become a critical component of overall evacuation planning. This chapter reviews, from a transportation perspective, current practices of evacuation planning and operations. Functional requirements of evacuation modeling and some practical needs for effective evacuation management are then highlighted. A review of various analytical and simulation models that have been developed and applied to evacuation modeling follows. Various performance measures that have been utilized in studies on emergency evacuation are also introduced.

2.1 Evacuation Modeling Practices

As an important measure of emergency preparedness and response, evacuation plans at all levels of government are required by federal law. Their purpose is to help guide people as they leave areas threatened by all types of hazards from natural ones such as hurricanes to manmade and technological ones such as nuclear power plant incidents. Depending on the characteristics of the hazard, evacuations are typically classified as one of three types: voluntary, recommended, or mandatory. The type of evacuation order, naturally, directly affects people's decisions on whether and when to evacuate. However, different people behave differently under stress: evacuees may make flawed decisions that can result in evacuation shadow or excessive evacuation, evacuation convergence, evacuation stress, panic, failure to use an officially allocated transport route, or even delay or failure to respond to an evacuation warning at all (Alsnih and Stopher, 2004). Understanding evacuee behavior is, therefore, essential for evacuation modeling and decision-making in evacuation planning and operations.

Based as they are on input from evacuee behavioral analyses and road-network evaluation, evacuation transportation analysis and modeling seek 1) to define the shape, size, and rate of growth of an evacuation area according to the emergency scenario; 2) to predict the size, makeup and spatial distribution of the evacuation population by time of day and type of activity; and 3) to facilitate optimal decision-making about when to evacuate, how to travel, where to go, and how to choose a route. Therefore, functionally, evacuation management requires transportation models that include demand estimation, destination choice, mode choice, departure time choice and route choice. These models can be developed and used to minimize the perceived costs for individual evacuee and/or the total costs of system management (Barrett et al., 2000). If the evacuation management is to be successful and effective, these models should be integrated and applied in a continuous modeling and decision-making process, in which current and/or real-time information can be used to continuously update the evacuation plan and operational strategies in order to improve the network performance during an evacuation. An accurate representation of the transportation network and traffic operations is also required in the evacuation modeling. The network performance needs to be properly measured and evaluated against various evacuation traffic management strategies.

Current evacuation planning and most evacuation models developed to date are based on the conventional four-step transportation planning process (Luo et al., 2002). The four-step process includes modeling of trip generation, trip distribution, mode split, and traffic assignment. These models are trip-based, meaning that person-trips to and from each transportation analysis zone (TAZ) are estimated based on various trip purposes, distributed by origin and destination, split to different travel modes, and assigned to various routes. The trip-based four-step process has been widely used in conventional transportation planning and analysis. However, the usefulness of the four-step process as a base for evacuation modeling is limited with respect to human behavior, by its sequential structure, and by the difficulties in modeling complex trip chains at evacuation, such as when household members seek each other and then evacuate together. Most importantly, emergency evacuation has different characteristics from conventional transportation planning and operation problems. It entails rapidly moving a sizable population over considerable distances under uncertain road conditions when the road network is or is likely to become highly congested. By nature, emergency evacuation is not an orderly process, and therefore it is essential to model and address the dynamic and transient nature of such evacuations.

Many research activities are under way to develop new evacuation models and tools in order to better facilitate the decision-making process for evacuation planning and operations. This is required by the practical and operational needs of the current evacuation practices. From past experience, it has been noted that evacuation routes out of an affected area are often either limited in number or insufficient in efficiency to cope with the expected increase in demand resulting from a mass emergency (Urbina and Wolshon, 2002; Alsnih and Stopher, 2004). These circumstances warrant a change in traffic management to accommodate the needs of the emergency evacuation. In other words, there is a practical need to increase the capacity of the evacuation routes and/or to maximize the efficiency of the existing road network by effective traffic management.

Potential traffic management strategies for better evacuation operations include the use of counter/contra-flow or lane reversing on limited access evacuation routes, the coordination of traffic control on arterial streets, and the utilization of real-time travel information for dynamic routing and destination reassignment. Most of these new practices are still at the stage of experiment, due to the existence of only limited experience with the actual implementation of these strategies and very limited studies of these practices in terms of design, operation, safety, cost, and effectiveness. Intelligent transportation system (ITS) applications such as dynamic traffic assignment are only conceptually planned for evacuation practices, due to the cost, availability and operational issues of the ITS system. Over the long term, all these traffic management strategies need to be carefully modeled, evaluated, and incorporated in evacuation plans.

Overall, the unique characteristics of emergency evacuations present great challenges to the participants, planners, decision-makers and researchers in the fields of evacuation modeling, planning, and operations. Difficulties exist in the needs to realistically predict evacuee behavior, to accurately estimate evacuation demand, to precisely describe evacuation conditions (including traffic, roadways, and weather), and to properly evaluate the evacuation strategies. To accommodate the unusual and increased travel demand during a mass evacuation event, it is necessary to continuously optimize the existing evacuation plans and implement more effective evacuation operational strategies. Distinct from the conventional four-step process, effective evacuation planning and operations need to be responsive to the dynamics of the evacuation process. New transportation models and research initiatives are, therefore, required to address these various needs that currently exist and to assist evacuation planning and operations.

2.2 Evacuation Modeling Software

Various analytical and simulation models have been developed and/or applied for modeling evacuation activities, estimating evacuation time, and supporting a decision-making process for evacuation planning and operations. These models provide a base for this study and therefore deserve mention here.

Since the 1970s, analytical models have been developed and used mainly to estimate evacuation time, a term that, in a more general context, includes evacuation decision time (hazard detection and verification), evacuation notification time (evacuation warning), individual preparation time (response to the evacuation order and preparation for leaving), and network clearance time (time needed to travel to safety). Evacuation time estimation involves the estimation of the evacuation demand, assessment of the available road capacity, estimation of the time required to move the evacuation population outside the evacuation area, and the analysis of the possible impacts from surrounding areas, uncontrollable events, and traffic management strategies (Urbanik, 2000; Alsnih and Stopher, 2004). Evacuation time estimates are important data that help guide planners to develop effective traffic management strategies that will enable the safe evacuation of residents of threatened areas.

Two analytical methods used to describe travel patterns and estimate clearance times during an emergency evacuation are the dissipation rate model and manual capacity analysis. The dissipation rate model (Houston, 1975) used a simple aggregate formula to correlate evacuation area size and population density with evacuation clearance time. It assumed a negative exponential functional form of area-wide delay and a constant flow rate per egress route. This model is simple and easy to use, but it is grossly aggregate and weak in representing network-related factors such as spatial distribution of the population, network topology, and intersection capacity and control. In the approach of the manual capacity analysis, the capacity of each road in the area was first calculated. Several possible evacuation routes for each sector were then identified and the population of each sector was allocated to these routes. Clearance times were obtained by dividing the total number of vehicles assumed to participate in the evacuation process by the capacity of the evacuation routes. This analytical method is also weak in capturing network effectors, and it would not be able to describe the effect of intersection delay and congestion in the network. For this same reason, evacuation times obtained from the dissipation rate model and the manual capacity analysis are not reliable.

In order to improve this situation, there have been several attempts to use existing microscopic simulation models for evacuation studies. Network Flow Simulation for Urban Traffic Control System (NETSIM) was such an example (HMM, 1980). NETSIM was initially developed to analyze traffic control strategies for small urban street networks. It requires very detailed representation of roadways, intersections, and controls. A turning movement at every intersection needs to be specified instead of allowing dynamic route selection. The model has been validated in a few studies under normal operation conditions, which, however, are different from an emergency evacuation situation. The main drawback of NETSIM is its limited capacity, which makes it impractical for use with a large-scale network. These limitations in early practices led to the development of macroscopic traffic simulation models specifically designed for evacuations in the 1980s.

The Network Emergency Evacuation Simulation Model (NETVAC) is a fixed-time macroscopic simulation model for simulating traffic patterns during an emergency evacuation. The development of NETVAC was motivated by the need to estimate network clearance time for areas surrounding nuclear power plant sites (Sheffi et al., 1982). The great advantage of the model is its capability to handle large networks, and it is also sensitive to network topology, intersection design and control, weather changes, and a wide array of evacuation management strategies. NETVAC uses a graph representation of the transportation network, and instead of tracking individual vehicles, it uses mathematical relationships between flows, speeds, densities, queue lengths, and other relevant traffic variables to simulate the evacuation process. Given a description of the transportation network and the location and rates of originating traffic, NETVAC provides a detailed account of the traffic conditions on the entire network including queue formation and dynamic route selection. Route selection in NETVAC is based on a static equilibrium assignment. It assumes that a driver's choice of route is based on prior knowledge of the network and a myopic view of the traffic conditions directly ahead. Drivers approaching an intersection make a choice of outbound link based on how fast this outbound link can get them to safety, which is a function of the direction of the outbound links (away from the nuclear plant or other source of disturbance) and the traffic conditions on those links. Although the assignment method is based on the stochastic traffic assignment, NETVAC is a deterministic model.

Mass Evacuation Computer Program (MASSVAC) is another macroscopic simulation model designed for nuclear power plant evacuation (Hobeika and Jamei, 1985). It incorporates three modules: a community and disaster characteristics module, a population distribution and characteristics module, and a network evacuation module. For a defined evacuation area and specified scenarios, MASSVAC uses socioeconomic data to produce vehicle trips by zone and employs a logic-based loading curve to represent the cumulative loading of evacuees onto the network. The model proceeds iteratively by dividing the assumed evacuation time into simulation intervals. In each interval, evacuation trips are sequentially loaded onto the network, distributed to the selected set of closest exit points, and assigned to highway links. The assignment method is also based on stochastic traffic assignment. Through the simulation, the network clearance time is obtained, the congested highway links are identified, and the network performance is evaluated under various evacuation scenarios and traffic management strategies. In its early version, MASSVAC 3.0 utilized the traffic assignment of all-or-nothing and Dial’s algorithm to simulate traffic movement. The later version, MASSVAC 4.0, incorporates the user equilibrium (UE) assignment algorithm. The UE algorithm generally outperforms Dial’s algorithm, but the performances of models are largely correlated with the network topology and the traffic demand (Hobeika and Kim, 1998). MASSVAC has now been incorporated into Transportation Evacuation Decision Support Systems (TEDSS), a microcomputer software package for the analysis, evaluation, and development of evacuation plans around nuclear power plants (Hobeika et al., 1994). It contains a graphic decision-aid interface, a knowledge-based system that stores the evacuation expert rules and disaster-related information, and an inference engine that is based on the MASSVAC simulation model.

Dynamic Network Evacuation Computer Model (DYNEV) is also a macroscopic deterministic traffic simulation model for evacuation planning (KLD, 1984). It was developed to assist the development of evacuation plans for nuclear power plants and was further enhanced to give it the capability of modeling regional hurricane planning processes. Besides network topology and evacuation demand, DYNEV can include human behavior and weather information as model inputs. Intersection capacity and the impacts of various traffic controls are also considered. In DYNEV, the trip distribution is based on the gravity model, and the traffic assignment is based on the static equilibrium model. DYNEV also considers a public transportation mode for evacuees without access to private vehicles. The model can generate comprehensive operational applications for each link besides the network clearance time. I-DYNEV, a derivative of DYNEV, has been used by the Federal Emergency Management Agency (FEMA) as a major component in the Integrated Emergency Management System (IEMIS). The I-DYNEV model differs from DYNEV in the way it computes the number of vehicles leaving a roadway segment. The improved computational efficiency serves to greatly decrease the computing resources required in a simulation.

The Nuclear Regulatory Commission also developed its own model, Calculated Logical Evacuation and Response Model (CLEAR), for evaluating evacuation time estimates (Moeller et al., 1982). CLEAR is a microscopic simulation-based model. In this model, the traffic assignment is based on the conditions of traffic flow. On the other hand, PRC Voorhees (1982) developed an Evacuation Planning Package (EVAC PLAN PACK), a dynamic and probabilistic model, for nuclear power plant emergencies. In this model, human behavior is taken into account to determine the loading and response rate of evacuees. The model is able to identify the traffic condition on each link and allows the diversion of traffic from more congested links to less congested links.

In the 1990s, more sophisticated models were developed for modeling evacuation activities in all type of disasters and for supporting decision-making in varying circumstances. The Oak Ridge Evacuation Modeling System (OREMS) developed by Oak Ridge National Laboratory (ORNL) is such a simulation model (Franzese and Han, 2002). OREMS is a macroscopic model and can be used to estimate evacuation time and to develop evacuation plans for different events or scenarios (e.g., good vs. bad weather conditions, day vs. night evacuations) for user-defined spatial boundaries of threatened areas. The model allows experimentation with alternate routes, destinations, traffic-control and management strategies (e.g., contra-flow), and evacuee response rates. For every scenario, it is possible to identify evacuation or clearance times incorporating such variables as population at risk, traffic operational characteristics such as average evacuation speed, best route choice, and network bottlenecks.

In OREMS, demographic information is used to estimate the evacuation demand for each evacuation planning zone (EPZ), and a user-defined demand loading curve can be utilized to describe varying distributions of evacuee response by time of day, location, and disaster type. Traffic simulation can be conducted for three types of demand inputs: 1) specified traffic flow for each origin-destination (OD) pair, 2) specified traffic flow from origins and turning movements at each intersection, or 3) specified traffic flow from origins and a list of candidate destination nodes for each origin. In OREMS, the internal destination selection is based on the nearest proximity to the origin, and the traffic assignment is a static process. OREMS has been applied to evacuation modeling for nuclear plants and has also been proposed for the modeling of hurricane evacuation.

Pidd et al. (1996) developed a prototype spatial decision support system (SDSS) for use by emergency planners in developing contingency plans for evacuation from disaster areas. This prototype is known as Configurable Emergency Management and Planning System (CEMPS). It links together a geographical information system (GIS: ARC/INFO) with a specially written object-oriented microscopic simulator via a Windows computer operating system. The GIS is used to define the terrain and population to be evacuated, and the simulation model is used to determine suitable evacuation plans for the movement of the population at risk to a designated safe area. The system enables a vehicle to find its way to the destination via available roads by taking account of immediate congestion. However, this system does not account for interactions between individual vehicles or for the effects of the collective behaviors of all evacuating vehicles.

Barrett et al. (2000) proposed a framework of a dynamic traffic management model for hurricane evacuation. By its nature, hurricane evacuation is different from other types of emergency evacuation such as nuclear disaster. It usually involves a larger regional evacuation area, requires a longer evacuation time, and has a higher potential for damage to the road infrastructure. Typically having advanced warning and knowledge of the approaching hurricane, storm evacuees respond differently to the evacuation order in terms of the participation rate and the response time, resulting in a different form of the evacuation loading curve. These characteristics heighten the need for more efficient methods of hurricane evacuation planning. Ran et al. describes the development of a dynamic hurricane evacuation modeling framework, including the determination of functional requirements, objectives, system architecture, and solution methodology. In the proposed framework, demand estimation, destination choice, mode split, and dynamic traffic assignment are implemented in a sequential process, but they are continuously fed back and revised. Both the minimum evacuation time and the expected actual evacuation time are estimated based on a dynamic system-optimal assignment and a dynamic user-optimal assignment respectively. This information, together with current road network and hurricane forecast data, allows evacuation planners and/or traffic managers to develop effective management strategies that will have the effect of moving the dispersed user optimal evacuation patterns towards the system optimal evacuation patterns.

Sattayhatewa and Ran (2000) also proposed analytical dynamic traffic assignment (DTA) for nuclear power plant evacuation management. Since the DTA model has the capability to predict the dynamic nature of traffic flow, such as time-dependent link flows and link travel time, this offers a great potential for the model to be utilized for real-time traffic management application. Because an evacuation process is dynamic by nature, the DTA models could become a viable alternative for developing dynamic evacuation plans. Two models were proposed and formulated as a system-optimal problem, which assumes that evacuee behaviors can be completely controlled and that the communication of information is possible. The model that is based on the arrival time penalty slightly outperforms the model that uses the departure time penalty.

There is also a web-based evacuation travel demand model, the Post, Buckley, Schuh, and Jernigan (PBS&J) model, developed by PBS&J Inc. (2000). It was constructed to anticipate and monitor major traffic congestion areas and traffic flows for a hurricane-type event. The model was developed to input county evacuation data, and to output forecast traffic volumes on a southeast regional roadway network. Within its special designed county-based input data structure, in contrast to the zone-based structure of the other models, it requires the input of destination distribution percentages of evacuees for each county (obtained from historical data). The PBS&J model employs a simple static traffic assignment process to forecast the traffic volume.

Current research and some studies have extended the applications of existing sophisticated simulation models to evacuation modeling and management for all types of emergency events. Sisiopiku et al. (2004) utilized Corridor Simulation Software (CORSIM) to create a regional transportation model comprising the major traffic corridors in the Birmingham, Alabama, area. The regional model was then used to test and evaluate various emergency management strategies in response to hypothetical incidents in the Birmingham area including an evacuation scenario. Jha et al. (2004) applied the Microscopic Traffic Simulation Laboratory (MITSIMLab) for simulating and evaluating emergency evacuations plans for Los Alamos National Laboratory. Yuan and Han (2005) used the Microscopic Simulation Model of PTV Vision Suite (VISSIM) for modeling the evacuation activities of a nuclear power plant. Use of the dynamic traffic assignment to route evacuees and consideration of the most desirable destinations for all evacuees at destination selection were demonstrated for effective evacuation operations. Chin et al. (2005) applied the Dynamic Network Assignment Simulation Model for Advanced Road Telematics for Planning Applications (DYNASMART_P), for the assessment of heavy vehicle impacts on emergency evacuation operations. A series of case studies was carried out for Knox County, Tennessee, to evaluate truck preferential treatment during partial capacity reduction on a highway facility during emergency evacuation operations.

2.3. Evacuation Performance Measures

A wide range of measures of effectiveness (MOE) have been proposed and used in evacuation studies and literatures. These MOEs commonly include evacuation times and various measures of the traffic operational characteristics of the study area.

Among these MOEs, network clearance time, also known as evacuation time, was used by many researchers and required for evacuation plans. While network clearance time is a simple measure to obtain in modeling, a complete clearance of all evacuees from the network is not always attainable or verifiable in reality. Furthermore, evacuation operations with very different efficiency levels may have similar network clearance times. Therefore, the times at which 50%, 75% and 95% of the population has cleared the EPZ, were used as MOEs by some studies (Franzese and Han, 2002). In fact, the time needed for 95% of evacuees to clear an EPZ is a more practical and meaningful MOE in terms of the time cost for representing the entire evacuation process and evaluating an evacuation plan. Considering the myriad uncertainties associated with evacuation demand (e.g., in the case of different vehicle trips per household) and the impacts of adverse weather and road conditions, Urbanik (2000) suggested that an estimate of a statistical range or a standard deviation of the network clearance time would provide more insight than the clearance time alone.

In addition to simply comparing points, albeit statistical points, in time, the evacuation curve, which represents the cumulative percentage of evacuees cleared from an EPZ (or arrived at evacuation destinations) as a function of time, can be used for direct comparison of different evacuation plans and traffic management strategies (Franzese and Han 2002; Jha et al. 2004; Tuydes and Ziliaskopoulos 2004). However, in these studies, the evacuation curve was considered and compared mainly for the time element alone without considering some other dimensions such as risks associated with cumulative time (e.g., exposure to airborne toxins or radiation) and space (e.g., proximity to the hazard). When the time cost is weighed by the risk factors, an evacuation curve may be interpreted differently; and quite different and, perhaps, more effective strategies may result to improve the evacuation plan based on such a more comprehensive MOE.

Besides evacuation times, various measures of traffic conditions on the entire network have been considered for evaluating evacuation operations. These include number of congested links, number of maximally utilized links (i.e., links have been utilized to capacity), origin-destination (OD) travel time, average speed, density, and total delay during the evacuation (Hobeika and Kim 1998; Sattayhatewa and Ran 2000; Sisiopiku et al. 2004). Some studies have also evaluated the loading time or the loading delay after an evacuation process has commenced, the clearance time from origin (i.e., elapsed time from the beginning of the evacuation process to when an origin is cleared of vehicles), and delay to the population before the onset of the evacuation process (Sattayhatewa and Ran 2000; Gants 1985). Each of these MOEs serves a certain, if not always obvious, purpose. However, none of them provides comprehensive flexibility for and universal applicability to all evacuation scenarios.

2.4. Summary

The literature review shows that most simulation-based evacuation models are macroscopic or mesoscopic. However, traffic simulation at a microscopic level is more desirable for evacuation studies. The microscopic simulation models have the advantages of modeling complex network conditions and manifold management strategies that may improve the efficiency of evacuation operations, including intersection control, contra-flow operations, and certain aspects of ITS. This makes microscopic simulation modeling a better tool to accurately estimate evacuation times and identify network bottlenecks (e.g., intersections and contra-flow endpoints). The review also shows that static traffic assignment (STA) is used in most evacuation models. STA assumes a steady state of traffic conditions over the evaluation period. However, the evacuation process usually involves long travel distances and travel times, and by nature, it is a transient and dynamic process. Therefore, neither the traffic nor the network conditions can be assumed to be constant. On the other side, dynamic traffic assignment (DTA), which can predict time-dependent link flows and travel times, could become a preferred alternative for developing dynamic evacuation plans and a viable tool for real-time evacuation operations. Compared with STA, DTA is able to capture traffic dynamics including queue buildup and dispersal, and therefore is more reliable for traffic-flow predictions.

As found in evacuation research literatures, only a few studies used microscopic traffic simulation and DTA for evacuation modeling. One constraint is that most microscopic simulation models require demand inputs by OD pair, and some even require more detailed travel information, e.g., specified routes or turning percentages at intersections. To perform DTA, a time-dependent OD demand is required, though one has to assume a priori knowledge for the entire planning horizon at the planning stage. In evacuation modeling, the OD table is usually furnished from the demand distribution process, based on the gravity models or simply on the criterion of geographical proximity. Certainly, in none of these approaches has it been attempted to find the best OD table for maximizing the network performance. However, it is more important and applicable to optimize the OD table in emergency evacuations. The destination pre-assessed to the evacuees is probably not the optimal choice from the onset of the evacuation travel. Not only does the initial OD (destination assignment at departure time) need to be optimized, but also the destination assignment should be updated and optimized with the route assignment during the evacuation. Therefore, a method for optimizing evacuation destination assignment is clearly needed in order to enable and enhance the use of the existing microscopic simulation models and DTA without modification for evacuation modeling and planning. This study is motivated by just such a need for a suitable optimization method.

CHAPTER 3

MEASURES OF EFFECTIVENESS

Transportation evacuation plans have been traditionally developed based on the knowledge and experience of local emergency management, law enforcement, and transportation professionals. Such plans, while mostly sensible, usually do little to ensure minimal personnel loss and evacuation time. As a result of the heightened interest in emergency management and evacuation operations and the availability of comprehensive traffic simulation software on high-speed computers, many research activities are under way to develop tools and models for better facilitating decision-making processes for evacuation planning and operations. Such tools often exploit operational strategies such as contra-flow lanes, priority traffic signal control, real-time information, and dynamic routing to “optimize” the evacuation operations. But what does “optimize” mean for evacuation? In other words, what is an effective evacuation operation?

Unfortunately, a set of well-defined and commonly accepted measures of effectiveness (MOEs) does not exist. Although a wide range of MOEs has been utilized in studies on emergency evacuation, and although each of these MOEs serves a certain purpose, none of them provides comprehensive assessment or a thorough understanding of different evacuation scenarios. For instance, the measures of total delay and evacuation exposure (e.g. to airborne toxins and radiation) are important but not used.

Optimizing an operation based on one MOE may lead to decisions and strategies quite different from those based on another MOE. For these reasons, properly selected and defined MOEs are essential in order to improve and optimize evacuation plans through modeling. In this chapter, a four-tier framework of MOEs is proposed, taking into consideration, in a comprehensive fashion, evacuation time, cumulative exposure, and risk factors. For each tier of MOE, the optimization formulation is also presented to illustrate how future efforts to improve and optimize evacuation plans may be constructed.

3.1 Evacuation Time

In the planning stage, the most commonly used MOE is the evacuation time, which can be defined as the duration, T_n, from the commencement of evacuation order up to a specified percentage, say n%, of all evacuees have cleared the EPZ. As already used by past studies, evacuation time can be both an indicator of the evacuation's progress and a measure of the evacuation's efficiency. Because a complete 100% evacuation rate is not always achieved, the time until 95% of the population has been evacuated, or T_{95}, is often a more statistically and practically meaningful MOE than T_{100}, the network clearance time, for representing the evacuation process.

For this MOE, the goal of optimizing evacuation operations is to achieve area clearance in minimal time. Therefore, the objective function of the optimization problem can be stated as:

$$Min\ T_n \tag{3.1}$$

subject to network capacity and flow constraints; where n is typically 95 or other suitable numbers.

Such a formulation is quite useful when a certain percentage of residents does not evacuate, by choice or for other reasons, or when an accurate estimate of evacuation time is needed to decide when the evacuation order has to be issued. An example of this may be the case of the imminent landfall of an approaching hurricane, when authorities have to weigh the probability of a direct assault of the hurricane against the need to issue the evacuation order while still allowing ample time for the actual evacuation to take place.

The optimization problem can be formulated from a different perspective with a time-constrained situation, in which a triggering incident would prompt each evacuee located in the EPZ to travel a certain distance to gain safety within a predetermined time period, t^*. An example of this might be an accidental release of chemical stockpile where the exposure to the toxic gas beyond a period of t^* would be lethal. Obviously, it would be desirable to accomplish $T_{100} \leq t^*$. However, due to the nature of such serious and often unexpected incidents, the objective function may be more realistically formulated as:

$$Max\ N_{t^*} \tag{3.2}$$

where N_{t*} is the number of evacuees that depart EPZ within a critical duration of $t*$, which, in turn, is a function of the nature of the emergency, the wind direction, and other factors.

Overall, evacuation time is intuitively straightforward and easy to obtain with all evacuation models. However, evacuation time does not necessarily give a representative picture of average travel time or delay experienced by the evacuees. The three evacuation curves shown in Figure 3.1 have similar evacuation times, with scenario C being slightly shorter than the others, yet scenario C will have the longest average travel time if all other conditions are the same. In addition, evacuation time alone as an MOE does not account for and, hence, cannot help minimize the exposure to the risks.

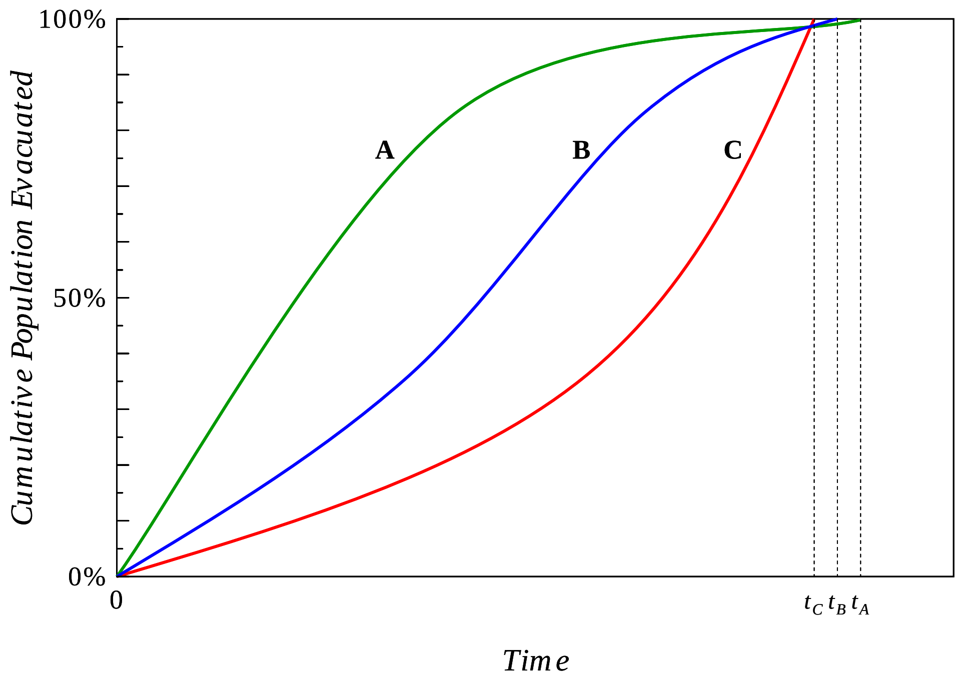


Figure 3.1 Different Evacuation Scenarios with Similar Clearance Time

3.2 Individual Travel Time and Evacuation Curve

The evacuation process starts at time 0, which may be the onset of a disastrous incident or the issuance of an evacuation order. As the "evacuation clock" starts to tick, the cumulative percentage of evacuees leaving their origins is represented by a loading curve, $L(t)$ (see Figure 3.2), while their arrivals at the evacuation destinations, or departures from EPZ, are described by an evacuation curve, $E(t)$. The horizontal distance, in time, between $L(t)$ and $E(t)$ represents the travel time experienced by various evacuees, and the vertical distance between these two curves represents the percentage of evacuees that are en route.

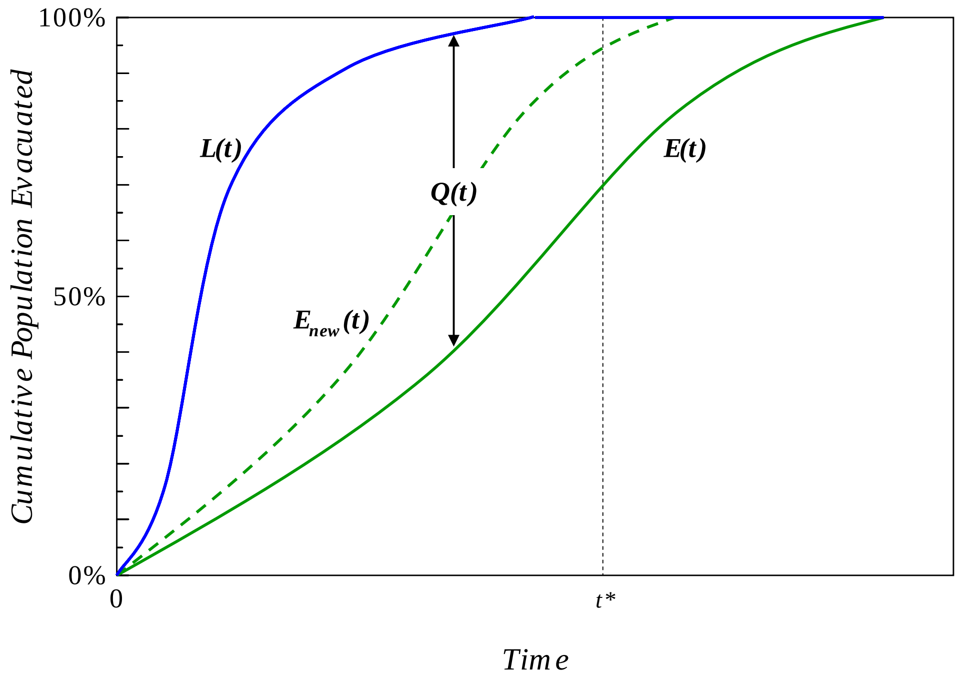


Figure 3.2 Loading Curve, Evacuation Curve, and Vehicles en Route

For an evacuation plan, the loading curve is affected by the nature of the emergency, the time of day, the efficiency of information dissemination mechanisms, the ownership of transportation means, and the preparedness of the evacuees in general. The evacuation curve is ultimately what active traffic management and plan optimization strive to improve. As such, the evacuation curve is an important measure for evaluating evacuation effectiveness. Intuitively, an evacuation plan is considered improved if the overall evacuation duration decreases or if the cumulative percentage of population evacuated within a time period increases. Such improvement can be visualized if the evacuation curve is "pushed left" or gets closer to the new evacuation curve, $E_{new}(t)$, as represented in Figure 3.2. Therefore, a quantitative MOE based on the evacuation curve could be the area encompassed by the evacuation curve and the time axis within an evaluation period. Accordingly, the objective function of the optimization problem can be formulated as:

$$Max \int_0^{t^*} E(t)dt \tag{3.3}$$

where

$E(t)$ = cumulative number of vehicles evacuated EPZ at time t

t^* = an selected time for efficiency assessment.

At first glance, Equation 3.3 is quite attractive and simple because one can evaluate the evacuation plans by comparing the area defined by different evacuation curves. However, the numerical solution to Equation 3.3 requires significant effort.

From an application perspective, other forms of formulations deserve further investigation. Equation 3.3 can be extended as:

$$\int_0^{t^*} E(t)dt = \int_0^{t^*} \left[L(t) - Q(t)\right] dt = \int_0^{t^*} L(t)dt - \int_0^{t^*} Q(t)dt \qquad (3.4)$$

where

$L(t)$ = cumulative number of vehicles leaving the origins by time t

$Q(t)$ = number of vehicles en route within EPZ at time t.

From the perspective of evacuation modeling and planning, it is essential to determine optimal evacuation routes and usage in order to attain system-wide objectives. When formulated and solved as a traffic assignment problem, it is usual to assume completely known or predicted evacuation demand, including OD information for the entire planning horizon of interest. Therefore, the loading curve can be assumed as fixed for the optimization problem, and the integral part of the loading curve, $\int_0^{T^*} L(t)dt$, can be approximated by a constant. Accordingly, the maximization problem defined in Equation 3.3 can be transformed to a minimization problem formulated as:

$$Min \int_0^{t^*} Q(t)dt \qquad (3.5)$$

The new objective function is straightforward. Graphically, it shows that evacuation optimization minimizes the area encompassed by the loading curve and the evacuation curve, i.e. pushing the evacuation curve closer to the loading curve. From another perspective, the ultimate goal of optimizing the flow patterns in the evacuation network, through modeling and planning, is to reduce the total travel (exposure) time experienced by all evacuees. This can be interpreted from the queuing theories: the loading curve and the evacuation curve in Figure 3.2 can be viewed as the arriving curve and the departing curve in the queuing diagram, respectively. Accordingly, the evacuation operations can be examined as a queuing problem with multiple services and varying service rate, in which each evacuation route is considered as a service and its travel time is the service time. The area between the arriving (loading) curve and the departing (evacuation) curve is the total delay for the queuing system, which, here, is the total travel time experienced by all evacuees. Therefore, the objective function defined in Equation 3.5 serves, in fact, to minimize the total evacuation travel time. The transformed objective function is stated as:

$$Min\ (Total\ Travel\ Time) \tag{3.6}$$

To this end, the optimization formulation becomes to minimize the total travel time. This is the same as the system optimal (SO) formulation of the traffic assignment problem. The objective of the SO traffic assignment for evacuation is to determine the flow patterns such that all travelers collectively minimize the total evacuation time of the system. To accomplish this goal, some travelers may need to take longer paths than in a user-optimal setting. Though the SO formulation is rarely applied for the conventional transportation planning problems, it is quite appropriate and more useful in the context of evacuation. From the perspective of evacuation management, the benefits for the entire system should be considered rather than only the individual's benefit. The numerical solution to the SO assignment problem can be obtained from analytical methods or simulation models with capability for traffic assignment. Obviously, according to the queuing theories, the optimization formulation in Equation 3.6 suggests that, to improve evacuation efficiency, one should increase the number of evacuation routes and/or reduce the delay on individual route. Therefore, instead of implementing contra-flow lanes and priority traffic signal control on limited evacuation routes, new strategies including dynamic traffic routing and destination assignment, which provides flexibility in route choices and fosters efficiency, is worthy of further investigation.

3.3 Time-Based Risk and Evacuation Exposure

To this end, time measure, either at the system or individual level, is the only factor considered in selecting and defining MOEs. For evacuation operations, time is important because the cost (or risk) for evacuees not being evacuated at an emergency always depends on time. Figure 3.3 shows examples of risk functions of time associated with different emergency situations. If the exposure risk is not constant over time, two different evacuation scenarios would have very different characteristics, even if they have similar clearance time and average travel time, as depicted in Figure 3.4.

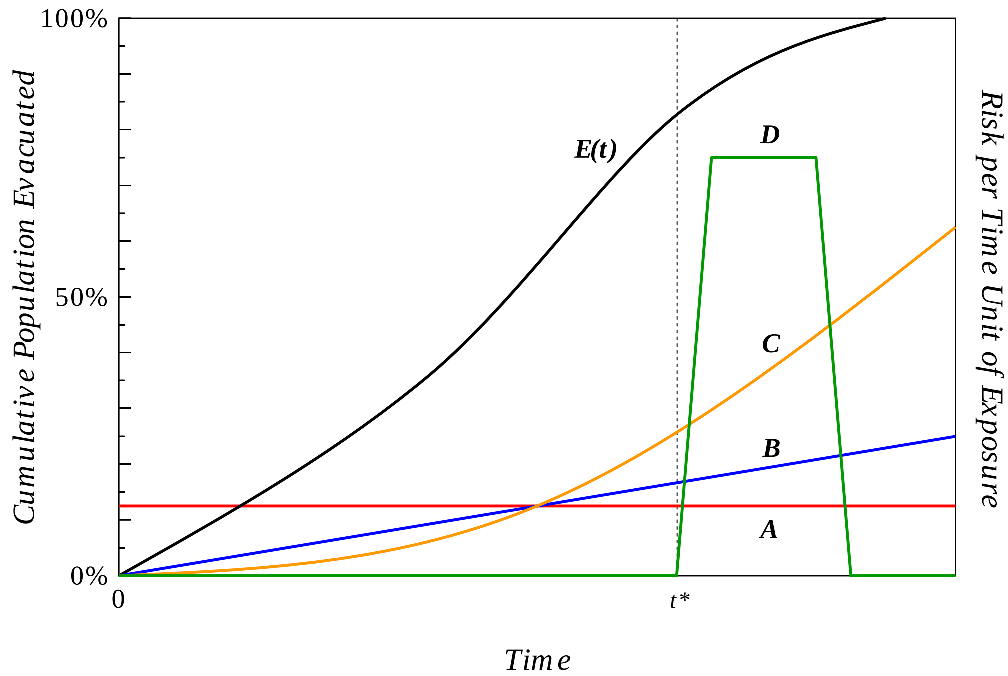


Figure 3.3 Example of Risk Functions of Time

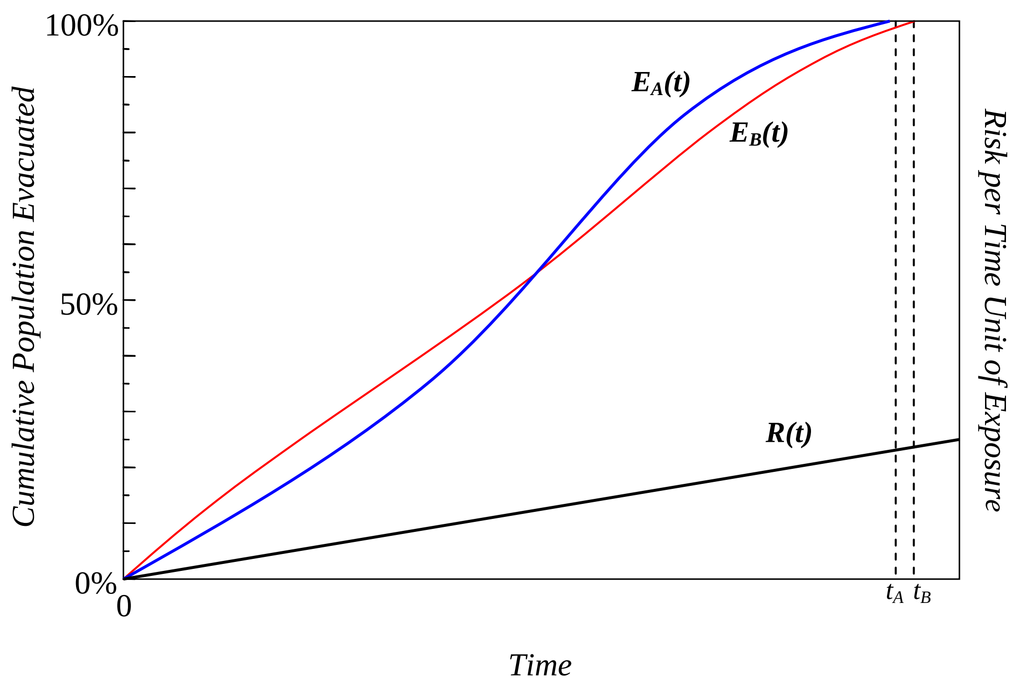


Figure 3.4 Different Evacuation Scenarios with Similar Clearance Time and Travel Time

Assuming a simple linear form of the exposure risk as a function of time, $R(t)$, for a hypothetical emergency situation, two evacuation curves, $E_A(t)$ and $E_B(t)$, shown in Figure 3.4 have similar evacuation times, with scenario A being slightly shorter than scenario B. Two scenarios also have a similar average travel time if all other conditions are the same, according to the MOE definition based on the evacuation curve (the area encompassed by the evacuation curve and the time axle). Yet after closer examination, one could conclude scenario A is more superior than scenario B, because it leaves fewer evacuees remaining in the risk area at the later stage of the evacuation when the exposure risk is much higher than that at the early stage. As such, either a system-wide evacuation time or individual travel time as a MOE does not account for this difference and cannot help minimize the exposure to the risks. Therefore, other than time, the time-dependent cost of evacuees being exposed to the danger needs to be considered and measured for an emergency evacuation.

Considering an evacuation curve, $E(t)$, and a risk curve, $R(t)$, shown in Figure 3.3, the MOE definition can be still based on the evacuation curve but weighted by a time-based risk factor, and therefore can be formulated as a measure of the cumulative time-based evacuation exposure. Quantitatively, it is the integral of the product of $E(t)$ and $R(t)$ over the entire evaluation period. Extended from Equation 3.5, the objective function is formulated as:

$$Min \int_0^{t^*} Q(t) \cdot R(t)\, dt \qquad (3.7)$$

where

$Q(t)$ = number of vehicles en route within EPZ at time t

$R(t)$ = risk index for evacuees remaining within EPZ at time t

t^* = any selected time for efficiency assessment

Despite the quantitative measure of the risk index and the cumulative time-based exposure, such an MOE definition can easily be applied to compare two evacuation curves, as shown in Figure 3.4. Scenario A is clearly superior to scenario B as it has a lower cumulative time-based exposure during an emergency evacuation.

3.4 Time-Space-Based Risk and Evacuation Exposure

More often, the cost (or risk) for evacuees not being evacuated during an emergency is not only time-dependent but also depends on the spatial location of the evacuees within EPZ. For instance, the exposure risk for evacuees to airborne toxins and radiation is directly related to the distance from where they are to the hazard source during the emergency. Considering a time-space-based risk function, $R(t, s)$, the MOE could be the cumulative time-space based evacuation exposure. Extended from Equation 3.7, the objective function is formulated as:

$$Min \int_{o}^{t^*} \int_{o}^{S} Q(t,s) \cdot R(t,s)\, dt\, ds \qquad (3.8)$$

where

$Q(t, s)$ = number of vehicles en route within EPZ at time t and location s

$R(t, s)$ = risk index for evacuees remaining within EPZ at time t and location s

t^* = an selected time for efficiency assessment

S = all locations within EPZ.

Equation 3.8 is a generalized form of the overall time-space based evacuation exposure, but it is difficult to measure and applied in evacuation optimization. To make it simpler for application, the time-space based risk, $R(t, s)$, could be decomposed into two parts: a time-dependent risk, $R(t)$, and a fixed space-dependent risk associated with an individual link within the EPZ, R_a. Accordingly, the cumulative time-space based evacuation exposure can be measured by the number of vehicles remaining on a different link within the EPZ at a different time and the risk associated with that particular time and link. Therefore, Equation 3.8 could be simplified as the following.

$$Min \int_0^{t^*} \left[\sum_a (x_a(t) \cdot R_a) \right] \cdot R(t)\, dt \qquad (3.9)$$

where

$x_a(t)$ = number of vehicles within EPZ on link a at time t

R_a = risk index for evacuees remaining on link a

$R(t)$ = risk index for evacuees remaining within EPZ at time t

t^* = any selected time for efficiency assessment

This simplified MOE formulation is easy to understand and could be directly measured for an emergency evacuation. The objective function in Equation 3.9 indicates that for the strategic planning of evacuation operations it is important to give special attention or preferential treatment to these evacuees trapped in any area with a higher exposure risk, in order to reduce the overall time-space based evacuation exposure. Moreover, it shows that some links with the highest risk, such as these closest to a hazard, should be restricted from being used as a part of the designated evacuation. These findings may be addressed in the traffic assignment procedure by incorporating the exposure risk associated with an individual link as an additional cost (or weight) to the general cost of the link. The evacuation routes and traffic assignment thus obtained would be more sensitive to the space-based risk and potentially could reduce the overall evacuation exposure.

CHAPTER 4

METHODOLOGY

From the perspective of evacuation planning and management, it is important to determine the most effective evacuation destinations and routes based on current roadway and traffic conditions in the evacuation area. In most evacuation plans, evacuation destinations are often predetermined according to the shortest distance or travel time in normal traffic conditions, and then great effort is made to optimize the selection and use of evacuation routes by using different formulations of the traffic assignment problem. However, these pre-specified destinations are not guaranteed to be optimal choices, and as the roadway and traffic conditions change, the predetermined destination choices may adversely impact the evacuation process by limiting route choice and creating or intensifying congestion in the evacuation network. Hence, evacuation destination choice and traffic distribution need to be optimized in order to change and optimize the network flow patterns so that evacuation time and exposure to hazards can be reduced.

In evacuation modeling, the processes of decision-making about the destination assignment and route assignment are really interrelated and interactive. It is difficult to maximize a network's usage to its full capacity by focusing on optimizing only the destination assignment or only the route assignment. Therefore, a framework for the simultaneous optimization of evacuation traffic distribution and assignment is presented in this chapter. The modeling strategy, mathematical formulation, potential applications, and implementations are discussed in order to address diverse purposes, from evacuation planning to real-time operations.

4.1 The Concept of One-Destination Evacuation

Given the spatial and temporal distributions of evacuation demand in the study area, or evacuation planning zone (EPZ), evacuation traffic distribution and assignment can be optimized simultaneously based on the concept of one-destination evacuation (ODE), where the optimal destination assignment is determined along with the traffic assignment process on a modified network representation. For a road network within the EPZ with m origins and n destinations, as shown in Figure 4.1, it can be modified and represented as the one in Figure 4.2, where the original network is augmented with "dummy links" leading from each real-world destination point to one common "dummy destination point," denoted as D^*. All these dummy links are assumed to have infinite capacity and zero cost (i.e. nil travel time) in order not to influence the route choice in the traffic assignment process. With this modification, a two-step decision-making process for the original evacuation network, including a demand distribution problem and a traffic assignment problem with m origins and n destinations (m-to-n assignment), is translated into a one-step decision-making process for the modified network, which is a traffic assignment problem with m origins and one destination (m-to-1 assignment).

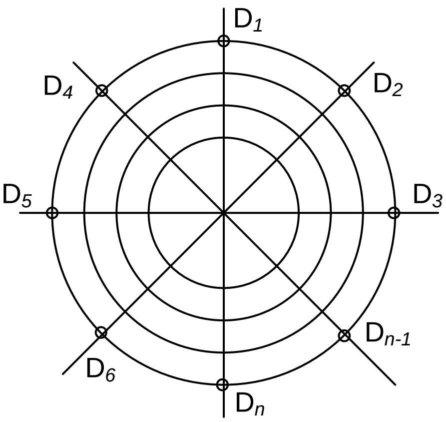


Figure 4.1 Original Multiple-Destination (*nD*) Network

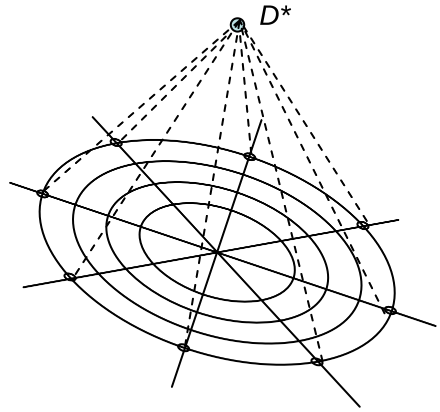


Figure 4.2 Modified One-Destination (*1D*) Network

The resultant *m*-to-1 traffic assignment problem can be solved by existing analytic algorithms or simulation methods towards user optimal (UO) or system optimal (SO) network flow patterns. Based on the traffic assignment results, the actual evacuation destination can be determined by tracing the real-world destination actually used by the evacuation traffic flowing from an origin to the dummy destination in the modified network. When the route selection and traffic assignment are optimized, the destination selection and demand distribution are also optimized at the same time.

This modeling strategy provides a theoretical way to find the optimal evacuation destination and route assignment for an emergency evacuation. Without the need of a separate model to find the best OD table (usually, an *m*-by-*n* matrix), the network flow patterns can be optimized directly by solving a one-destination traffic assignment problem based on a simple form of the OD table (an *m*-by-1 matrix). Based on the ODE concept, both static traffic assignment and dynamic traffic assignment can be used as optimization tools to provide a solution basis for evacuation planning and operations.

4.2 Mathematical Formulation

By modeling as ODE, it is possible to reduce the number of flow conservation constraints in the traffic assignment problem to facilitate the search for a globally optimal solution of the network flow patterns that satisfies the objectives of evacuation operations. The feasibility and superiority of this method are apparent through an examination of the mathematical formulations of the traffic assignment problem. Take as an example the classical formulation of the static UO traffic assignment problem as a mathematical programming problem (Sheffi, 1985), represented by Equations 4.1-4.4. The objective function is the sum of the integrals of the link performance functions (Equation 4.1). The decision variables in this optimization problem are the flow levels on each link; the objective is to decide these flows so that the objective function is minimized. The link flow levels that minimize the objective function must meet the following constraints: First, the total flow on a link must equal the summed flow for all paths that use that link (Equation 4.2). Second, the flow on all paths between an O-D pair must equal the aggregate travel demand for that pair (Equation 4.3), i.e. flow conservation. Finally, all the path flows must be non-negative (Equation 4.4).

$$Min \sum_{a} \int_{0}^{f_a} c_a(\omega) d\omega \tag{4.1}$$

subject to:

$$f_a = \sum_{r \in R} \delta_{ar} h_r \quad \forall\, a \in A \tag{4.2}$$

$$\sum_{r \in Rij} h_r = D_{ij} \quad \forall\, i \in I,\, j \in J \tag{4.3}$$

$$h_r \geq 0 \qquad \forall\, r \in R \tag{4.4}$$

where:

f_a = flow on link a

$c_a(f_a)$ = travel cost on link a

h_r = flow on path r

D_{ij} = total trips from origin i to destination j

δ_{ar} = link-path incidence variable; equal to one if link a is a part of path r or zero otherwise

A = set of links

I = set of origins

J = set of destinations

R = set of all paths between all zone pairs

R_{ij} = set of all paths from origin i to destination j

For the problem of one-destination traffic assignment, the objective function and most constraints remain the same, except that the set of flow conservation constraints represented in Equation 4.3 is now reduced and represented by Equation 4.5.

$$\sum_{r \in Ri} h_r = D_i \quad \forall\, i \in I \tag{4.5}$$

Obviously, the solution of the link flows, $\{f_a\}$, to the traffic assignment problem on a network with multiple destinations satisfying all the constraints (Equations 4.2, 4.3 and 4.4) and minimizing the objective function is also a feasible solution to the traffic assignment problem with the same objective function but relaxed constraints (Equations 4.2, 4.4, and 4.5) on a modified network representation with one destination. However, the solution to the multiple-destination, or *nD*, traffic assignment problem is varied by the form of the demand distribution (the *m*-by-*n* OD table used), but the solution to the one-destination, or *1D*, traffic assignment problem is unique and independent from the demand distribution (using an *m*-by-1 OD table). The minimum value of the objective function for the *nD* traffic assignment problem can only be equal to or larger than the minimum value of the objective function for the *1D* traffic assignment problem.

Theoretically, solving the *nD* traffic assignment problem based on a pre-specified OD table will allow one to find only a local minimum of the *1D* traffic assignment problem. Therefore, in any circumstances of evacuation planning and management that allow flexibility in destination selection and demand distribution, the proposed ODE modeling is better for finding the most or more optimal network flow patterns. The *1D* transformation only reduces the number of the flow conservation constraints, but will not change the mathematical properties such as the existence, uniqueness and stability of the solution to the original formulation of the traffic assignment problem. The strict convexity of the objective function is proved, and the convexity of the feasible region is assured for a set of linear equality constraints and nonnegative constraints (Sheffi, 1985). Therefore, the one-destination UE equivalent minimization problem has only one minimum, as its objective function is strictly convex in the vicinity of the optimal solution (and convex elsewhere) and the feasible region is convex.

The above observations could apply equally well to other types of traffic assignment formulation. For the SO formulation, the objective function is to minimize the total travel cost for all travelers in the network, such as:

$$Min \ z = \sum_a f_a c_a(f_a) \tag{4.6}$$

The constraints remain unchanged as Equations 4.2-4.4. The UO formulation postulates that travelers consider the average cost of the paths they select: travelers choose the path that has the minimum average cost. In contrast, the SO formulation implies that travelers only consider the marginal cost for paths, that is, the added cost of their entry into a path. Therefore, travelers will only choose routes that minimize the impact on the total travel cost. The proposed *1D* transformation can also be applied to the SO equivalent minimization problem by replacing Equation 4.3 with Equation 4.5. The objective function and other constraints remain unchanged.

For a dynamic traffic assignment problem, take, for example, the departure-based dynamic user-optimal equilibrium (DUO) formulation proposed by Janson (1991). The formulation is stated as follows:

$$Min \sum_{a \in A} \sum_{t \in T} \int_0^{f_a^t} c_a(\omega) d\omega \tag{4.7}$$

subject to:

(static constraints)

$$f_a^t = \sum_{r \in R} \sum_{d \in T} h_r^d \delta_{ra}^{dt} \ \ \forall a \in A, t \in T \tag{4.8}$$

$$D_{ij}^d = \sum_{r \in Rij} h_r^d \ \ \forall i \in I, j \in J, d \in T \tag{4.9}$$

$$h_r^d \geq 0 \ \ \forall r \in R, d \in T \tag{4.10}$$

(dynamic constraints)

$$\sum_{t \in T} \delta_{ra}^{dt} = 1 \;\; \forall r \in R, a \in A_r, d \in T, t \in T \tag{4.11}$$

$$b_{rn}^{t} = \sum_{t \in T} \sum_{a \in Arn} s_a(f_a^t)\delta_{ra}^{dt} \;\; \forall r \in R, n \in N, d \in T, t \in T \tag{4.12}$$

$$\left[b_{rn}^{t} - t\Delta t\right]\delta_{ra}^{dt} \leq 0 \;\forall r \in R, n \in N, d \in T, t \in T, a \in A_n \tag{4.13}$$

$$\left[b_{rn}^{t} - (t-1)\Delta t\right]\delta_{ra}^{dt} \geq 0 \;\forall r \in R, n \in N, d \in T, t \in T, a \in A_n \tag{4.14}$$

where:

$c_a(f_a^t)$ = travel cost on link *a* in time interval *t* (variable)

f_a^t = flow on link *a* in time interval *t*

Δt = length of each time interval

T = set of all time intervals in the full analysis period

h_r^d = flow on path *r* that departed during time interval *d* (variable)

D_{ij}^d = total flow from *i* to *j* departing in time interval *d*

δ_{ra}^{dt} = temporal link-path incidence variable; equal to one if trips departing during time interval *d* and assigned to path *r* used link *a* during time interval *t,* zero otherwise

b_{rn}^d = travel time of path *r* from its origin to node *n* for travelers departing in time interval *d*

A_n = set of all links incident from node *n*

A_r = set of all links on path *r*

A_{rn} = set of all links on path *r* prior to node *n*

A = set of all links

R_{ij} = set of all paths from origin i to destination j

R = set of all paths between all zone pairs

I = set of origins

J = set of destinations

N = set of all nodes

The objective function (Equation 4.7) and the static constraints (Equations 4.8-4.10) are the same as in the static UO problem, except for the addition of the discrete-time temporal dimension. This essentially extends the UO problem across multiple discrete time periods. The dynamic constraints (Equation 4.11-4.14) ensure temporal flow consistency. Among all constraints, Equation 4.9 constrains path flows in such a way as to sum to the proper trip departure totals in each time interval between each OD pair. The *1D* transformation can equally be applied to this formulation by modifying the network representation and by replacing Equation 4.9 with Equation 4.15, as follows:

$$D_i^d = \sum_{r \in Ri} h_r^d \ \forall \ i \in I, d \in T \tag{4.15}$$

The objective function and other constraints remain unchanged. By transforming the *nD* traffic assignment problem to the *1D* traffic assignment problem, the solution can be further improved towards a global minimum.

In general, regardless of the formulation of the traffic assignment problem (static or dynamic, UO or SO), flow conservation constraints must be satisfied. Therefore, the *1D* transformation discussed above can be equally applied. In fact, one destination is easier to formulate for the dynamic traffic assignment problem. The physical behavior of traffic on a roadway link exhibits the so-called "first-in, first-out" (FIFO) property: traffic that enters a road at a particular time exits from the facility, on average, before traffic which enters at a later time. The FIFO requirement creates an inherent difficulty in all mathematical programming approaches to time-dependent assignment problems. The multiple-destination assignment problem requires additional constraints to explicitly satisfy the FIFO requirement, but these constraints will make the feasible region non-convex, destroying many of the computational and mathematical advantages of the formulation. However, the FIFO requirement is easily satisfied in the one-destination formulation (Ziliaskopoulos and Peeta, 2002).

4.3 Potential Applications

The proposed *1D* framework for simultaneously optimizing evacuation traffic destination distribution and route assignment is a theoretical model directly deployable to solve real-world problems. Not only the resultant *1D* assignment problem has an exact solution through analytical methods (Lam and Huang, 1995; Ziliaskopoulos, 2000), but the concept of ODE can be applied to evacuation planning through the use of simulation models that are capable of performing static or dynamic traffic assignment. Simulation-based traffic assignment models, especially at microscopic level, have the advantages in modeling more complex network conditions and myriad management strategies that may improve the efficiency of evacuation operations but are generally too cumbersome to formulate by analytical methods. Based on the concept of ODE, the existing microscopic simulation models can be used without modification for evacuation modeling and optimization, and, in fact, various operational strategies can still be considered in the *1D* framework. The potential applications of the ODE model vary from evacuation planning to real-time operational purposes.

At the planning level, the ODE model provides a tool for assessing and greatly enhancing existing evacuation plans. In current evacuation planning, the evacuation area is partitioned into planning zones (or sectors), and for evacuees in the same zone, a specified evacuation destination and corresponding route are designated. This method is considered easier in terms of public perception and understanding of the evacuation instructions when the evacuation plan is being implemented. However, the effectiveness of the partition of the planning zones is not justified or guaranteed; nor is that of the evacuation destination and route assigned. The ODE model will solve for the optimal destination and route for each planning zone, against which the existing evacuation plans can be evaluated. The *1D* results can also be used to justify and potentially modify the partition of the planning zone according to the destination and route assigned to most evacuees from the same zone in the *1D* network. To maximize the network performance, some zones may be further subdivided, and some adjacent zones may be merged together, making the evacuation operations more effective and manageable.

The ODE method also promises to serve as a foundation for advancing current practice in its potential applications for planning real-time operations. When the ODE model is formulated and solved based on dynamic traffic assignment, it can be used to estimate the minimum network clearance time (or best system improvement) that could be achieved by intelligent transportation system (ITS) deployment. Real-time traffic operations based on ITS technologies appear as an emerging tool for transportation emergency and evacuation operations. Therefore, ultimately, the ODE model can be implemented for real-time evacuation operations taking advantages of the ITS infrastructure in the EPZ. The *1D* optimization results can be used to determine the best time-dependent destination and route assignment for evacuees, to redirect and/or reroute traffic on the route, and to develop effective real-time traffic control strategies under varying traffic, roadway, and weather conditions. The real-time implementation of the ODE model is directly based on the same framework as the dynamic traffic assignment for congestion management, assuming that real-time information can be collected and that evacuation traffic can be controlled by instructions delivered from the traffic management center.

4.4 Implementation Issues

The proposed ODE model needs to solve a *1D* traffic assignment problem. Compared with the *nD* traffic assignment problem, solving the *1D* traffic assignment problem may require more computational effort, especially for a large network with many potential destinations (real-world exits from the evacuation area). Potentially, the

1D assignment requires searching for the best paths from an origin to all potential destinations in the transportation network, in order to establish traffic flow on different links. In contrast, in the *nD* assignment, it is only necessary to search for the best path from an origin to a specified destination. Therefore, it might take a considerably longer time to solve the *1D* traffic assignment problem, which potentially could be an important concern for real-time operations. Moreover, when the model is implemented with existing simulation models, especially for conducting dynamic traffic assignment, it presents more challenges in terms of computation time and solution convergence. Simulation-based dynamic traffic assignment models are usually implemented via an iterative simulation and assignment approach. A longer searching time for the best path will increase the overall computation time for reaching the convergence of the solution, and a question raised is whether the solution would be able to converge within reasonable iterations or within an acceptable time frame.

To improve the computational efficiency, first, more efficient best-path searching methods (e.g. reducing the best-path search area or increasing the best-path searching interval) and dynamic traffic assignment algorithms are required for real-time operational purposes. Second, a hybrid method of destination modeling, using both real-world destinations and dummy destinations for the evacuation network, might be used in some circumstances. Figure 4.3 shows an example of the evacuation network with both real-world destinations and dummy destinations defined.

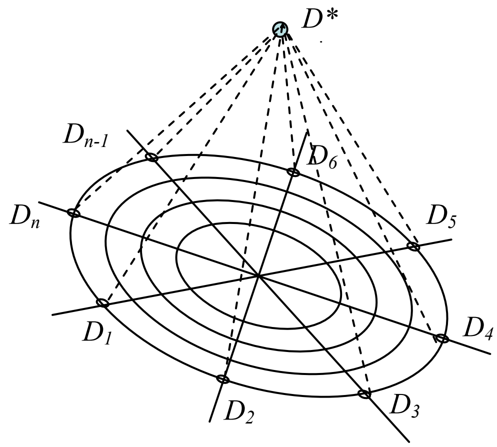


Figure 4.3 Hybrid Destinations for Evacuation Network

In this hybrid network representation, real-world destinations might be directly assigned to evacuees from areas where destinations are easy to decide, such as origin zones close to the network boundary, and one dummy destination would also be created and assigned to other evacuees from areas where optimal destinations are difficult to determine, such as origin zones in the center area. In the same vein, instead of using one super dummy destination for all origin zones, a few dummy destinations might be created and used, each serving as a common destination for a group of adjacent origin zones, either sharing the same characteristics (e.g. following a common travel direction) or separated from other zones by natural barriers in the evacuation area, as illustrated in Figure 4.4. Both of these methods of destination modeling and evacuation network representation could potentially reduce the computation burden of the *1D* formulation, especially in real-time evacuation operations, though the superiority of the solution might be sacrificed.

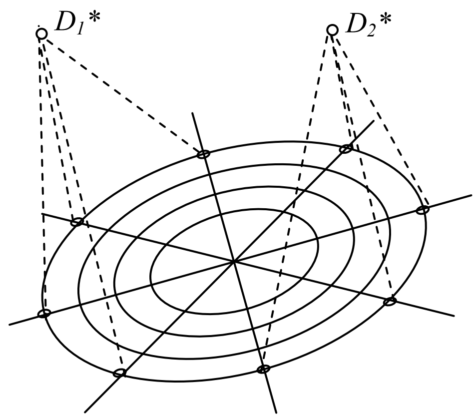


Figure 4.4 Multiple Dummy Destinations for Evacuation Network

In a real-world evacuation, evacuation route selection is not only dependent on travel time and road capacity but is also determined by factors such as roadway conditions and exposure risks. For example, some links might be restricted from being accessed by evacuees due to safety concerns. Destination selection is also affected by the availability of shelter and emergency services at the end of each destination (road exit from EPZ). Therefore, preferences arise. The proposed model, as it only considers travel time in best-path searching, as does the conventional traffic assignment problem, will be insufficient to model such preferences in destination and route selections.

A potential solution is that the preferences in destination and route selections might be represented as an additional component in the link cost function so that best-path searching and eventually traffic assignment results would be affected or biased. The route preference due to safety concerns is basically intended to steer evacuees farther away from an emergency source such as a nuclear plant; therefore, all evacuees should travel outwards but should not travel on links with hazards or toward the direction of plume dispersion. To model such preferences, an additional cost in inverse proportion to the distance from a link to the emergency source could be added to the general cost of a link in order to discourage backtracking of evacuation traffic, and a very high cost could be imposed to those links at higher risk (e.g. close to the emergency source) in order to restrict the cross-travel of evacuees. In the same way, the destination preference might be modeled by assigning a negative cost that was proportional to the attraction at each real-world destination (if it could be measured quantitatively) to the dummy link connecting the real-world destination and the dummy destination in the *1D* network. Therefore, the overall cost on the routes to the preferred destinations would be reduced so that potentially these destinations might attract more evacuation trips. Both of these methods could be sensitive to the weight for the component representing the preferences in the link cost function. These methods require further experiments to test and verify their feasibility and effectiveness in real-world implementation.

CHAPTER 5

CASE STUDIES

For this purpose of verification, a modeling and solution method for the simultaneous optimization of evacuation traffic distribution and assignment is advanced in this study. Based on the concept of ODE, the optimal destination and route assignment can be obtained by solving a one-destination traffic assignment problem on a modified network representation. To demonstrate the feasibility and benefits of the proposed ODE model for improving evacuation efficiency, simulation analyses were conducted for two case studies of real-world evacuation operations, including a regional evacuation following a nuclear power plant mishap and a county-wide special-event evacuation. The potential applications of the ODE model in evacuation planning and real-time operations are explored and evaluated through these case studies. This chapter details the study site/network, the evacuation demand, and the ODE implementation for each case study. Simulation results were collected and compared for various modeling and destination/route assignment strategies, according to the MOEs defined in Chapter 3.

5.1 Simulation Tools

Two simulation software packages, VISSIM and DYNASMART_P, were selected for the implementation and testing of the ODE model. Both models are versatile and well suited for network analysis and are capable of conducting static or dynamic traffic assignment and of modeling complex network conditions and myriad operational strategies at a microscopic level. Both models have also been widely used for transportation system simulations and analyses, including evacuation studies (Yuan and Han, 2005; Chiu et al., 2005; Chin et al., 2005; Kwon and Pitt, 2005; Murray-Tuite and Mahmassani, 2004). However, the ODE model is not limited in its applications to either of these two simulation models, VISSIM and DYNASMART_P; indeed, a wide range of simulation models with traffic assignment capabilities can be used. The broad applicability of the ODE mode will also be illustrated, by the selection and use of two different simulation tools for case studies. Either VISSIM or DYNASMART_P, using either static or dynamic traffic assignment, is a viable optimization method and can be used in different situations to satisfy different needs for modeling and optimization.

VISSIM (PTV, 2003) is a microscopic, time-step and behavior-based simulation model developed to analyze the full range of functionally classified roadways and public transportation operations. The model can analyze traffic and transit operations under a variety of constraints such as lane configuration, traffic composition, intersection controls, and preferential treatments, therefore making it a useful evaluation tool. Using a link-connector topology, VISSIM allows a very flexible geometric representation and high versatility in modeling vehicle movements at a detailed resolution level (including traffic within intersections). With a built-in dynamic assignment model, VISSIM can answer route choice-dependent questions regarding, for example, the potential for traffic diversion in the network. VISSIM has been used to simulate and analyze networks of all sizes, ranging from individual intersections to entire metropolitan areas (Gomes et al., 2004; Tian et al., 2002). It has been validated against field data collected from freeways (Fellendorf and Vortisch, 2001) and has been shown to be able to accurately replicate local traffic conditions and model intersection delays (Moen et al., 2000).

In VISSIM, dynamic traffic assignment is implemented through iterative simulations and assignments. In each repetition of the simulation, the best route for each OD pair is searched based on the general cost of the edges (i.e. a weighted sum of travel time, distance, and cost) that travelers have experienced during the preceding simulations. Since the traffic condition and travel times change from iteration to iteration, different best routes are found in successive iterations, and collectively a growing archive of best routes is built. Not only the current best route but this set of available best routes is considered for travelers to choose from. The route choice and traffic distribution among *k* best routes is modeled as a discrete choice problem by a Logit function. The iteration of the simulation runs is continued until a stable situation is reached in which the volumes and travel times on the edges of the network do not change significantly from one iteration to the next. Such a traffic assignment procedure can be used to determine the user equilibrium route choice.

DYNASMART_P (Mahmassani et al., 2004) is a state-of-the-art dynamic traffic operational planning tool developed under the Federal Highway Administration's (FHWA) Dynamic Traffic Assignment (DTA) research project. It integrates traffic flow models, path processing methodologies, behavioral rules, and information supply strategies into a single simulation-assignment framework. The model is designed to assign time-varying traffic demands and to model the corresponding traffic patterns to evaluate the overall network performance of Intelligent Transportation Systems (ITS). DYNASMART-P provides the capability to model the evolution of traffic flows in a network that have resulted from the decisions of individual travelers seeking the best paths to travel over a given planning horizon. It overcomes many known limitations in static assignment tools used in current practice. These limitations pertain to the types of alternative measures that may be represented and evaluated as well as the policy questions that planning agencies are increasingly asked to address. A detailed representation of transportation network and complete network elements including signalization and other operational controls can be modeled. The traffic model of the simulation component in DYNASMART_P has been calibrated for both arterial and freeway conditions and has been validated against field data (Mahmassani et al., 2003).

In DYNASMART_P, a simulation-based algorithm is used to solve the dynamic traffic assignment problem. An efficient hybrid traffic simulation approach, which moves individual particles according to robust macroscopic traffic flow relations, is used to represent the traffic interactions in the network and to evaluate the system performance under a given assignment, ensuring consistency with realistic traffic behaviors. A heuristic iterative procedure is applied for computing mutually consistent flow patterns and user decisions, such as time-varying user equilibrium (UE) where applicable. The solution to the time-dependent UE problem is obtained by assigning vehicles to the shortest average travel time paths. For the system optimal (SO) problem, it can be solved by assigning vehicles to the least marginal paths instead. Rather than solving only a single objective assignment problem, DYNASMART_P is capable of simultaneously modeling different classes of users with different choice and assignment rules (e.g. UE or SO) and under different information levels (e.g. in-vehicle equipment or variable message sign). This is an important feature for modeling real-time evacuation operations based on ITS traffic management and information strategies wherever applicable.

5.2 Sequoyah Network

The proposed ODE model was first tested on a real-world network for modeling evacuation activities and improving traffic operations in the event of a major nuclear power plant accident. The study site is located in the vicinity of the Sequoyah Nuclear Power Plant in Hamilton County, Tennessee, approximately 11 miles northeast of the Chickamauga Dam on the Tennessee River. A 10-mile evacuation planning zone (EPZ) encompasses a portion of Hamilton County and includes the entire City of Soddy Daisy, a part of the city of Chattanooga, and a portion of Bradley County, as shown in Figure 5.1. As this is a demonstration study, it was determined that the focus of the study would be directed toward modeling of the evacuation activities on the west bank of the Tennessee River, the more populated side, where the power plant is situated. With the Tennessee River flowing north-south at that point, evacuation activities would have to avoid eastward movement, which would require crossing the river at very limited locations, in order to sustain mobility. The study area is served by several major roads in the general north-south direction parallel to the river.

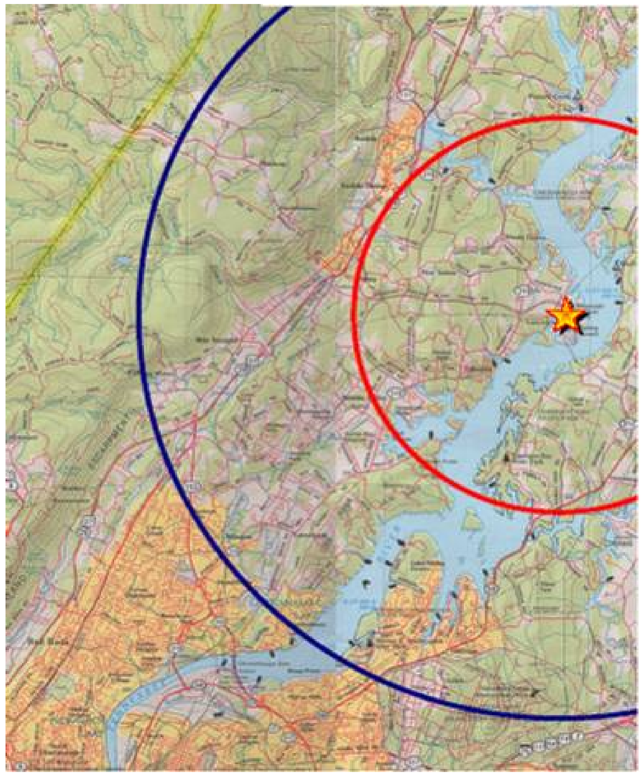


Figure 5.1 Study Area for Sequoyah Power Plant

5.2.1 Network Setup

An evacuation highway network within a 10-mile radius of the power plant was evaluated for evacuation operations and was modeled accordingly in VISSIM. The network includes major thoroughfares in the study area as well as roads that serve as feeders to mobilize the population onto the evacuation routes. GIS maps were used for the initial selection of links and nodes of modeling that collectively form the evacuation network. High-resolution satellite photos were used for the actual network coding in VISSIM, as shown in Figure 5.2.

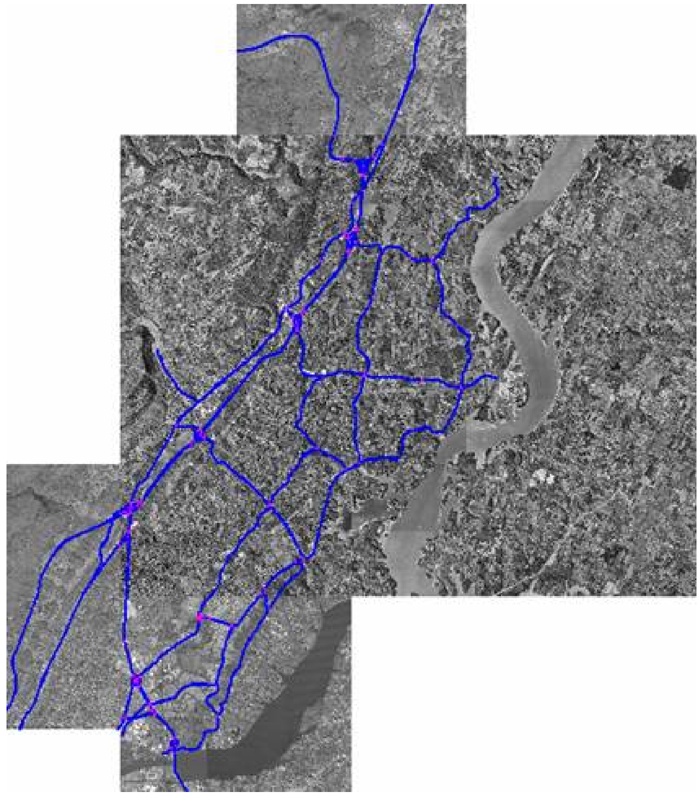


Figure 5.2 Evacuation Network and Satellite Photos for Sequoyah Area

These satellite photos not only complemented the GIS maps but also provided detailed information on the evacuation network, including the precise curvature of the links, the number of lanes, the basic types and locations of the traffic control devices, and the channelizations at the intersections. Information on traffic operational characteristics of the study area, such as the posted speed, the functional classification of the links, and the traffic control information, was primarily collected through Tennessee Department of Transportation's (TDOT) Tennessee Roadway Information Management System (TRIMS) as well as through field data collection. All this information was coded into VISSIM for the study at hand. The final evacuation network includes 283 links and 35 intersections, of which eight are signalized.

For effective evacuation modeling and planning, it is important to know the number of potential evacuees and their geographical distribution in the study area for any particular moment in time. The U.S. Census is a major source of information for night-time evacuation, and it provides a basis for evacuation demand estimation correlated with demographic information. In this study, 2000 census data are used to estimate evacuation demand. Because the census tracts in the study area are relatively large and irregularly shaped, it was difficult to estimate trip assignment by routes. Therefore, census data down to the block level were used to estimate travel demand and to assign trips to the network, as shown in Figure 5.3. For each census block, trip generation estimates were based on the number of households and the total population in the block, a procedure that provided a close estimation of the nighttime demand. In all, 19,762 vehicle trips were estimated and assumed for evacuation in a nuclear power plant emergency.

In VISSIM, traffic demand is modeled using origin-destination (OD) matrices. The study area needs to be divided into zones, and vehicles would be loaded into each zone from specified links. To provide such information, GIS tools were used to analyze the spatial relationship between the census blocks and the highway network in the study area. Trips were assigned to the nearest accessible link (arterials and feeders) in the network, and the travel demand was collectively counted on each link. As marked in Figure 5.4, a total of 29 origin zones (each associated with an accessible link) was defined for the study area, and during the simulation, vehicles were loaded into the network from the corresponding link.

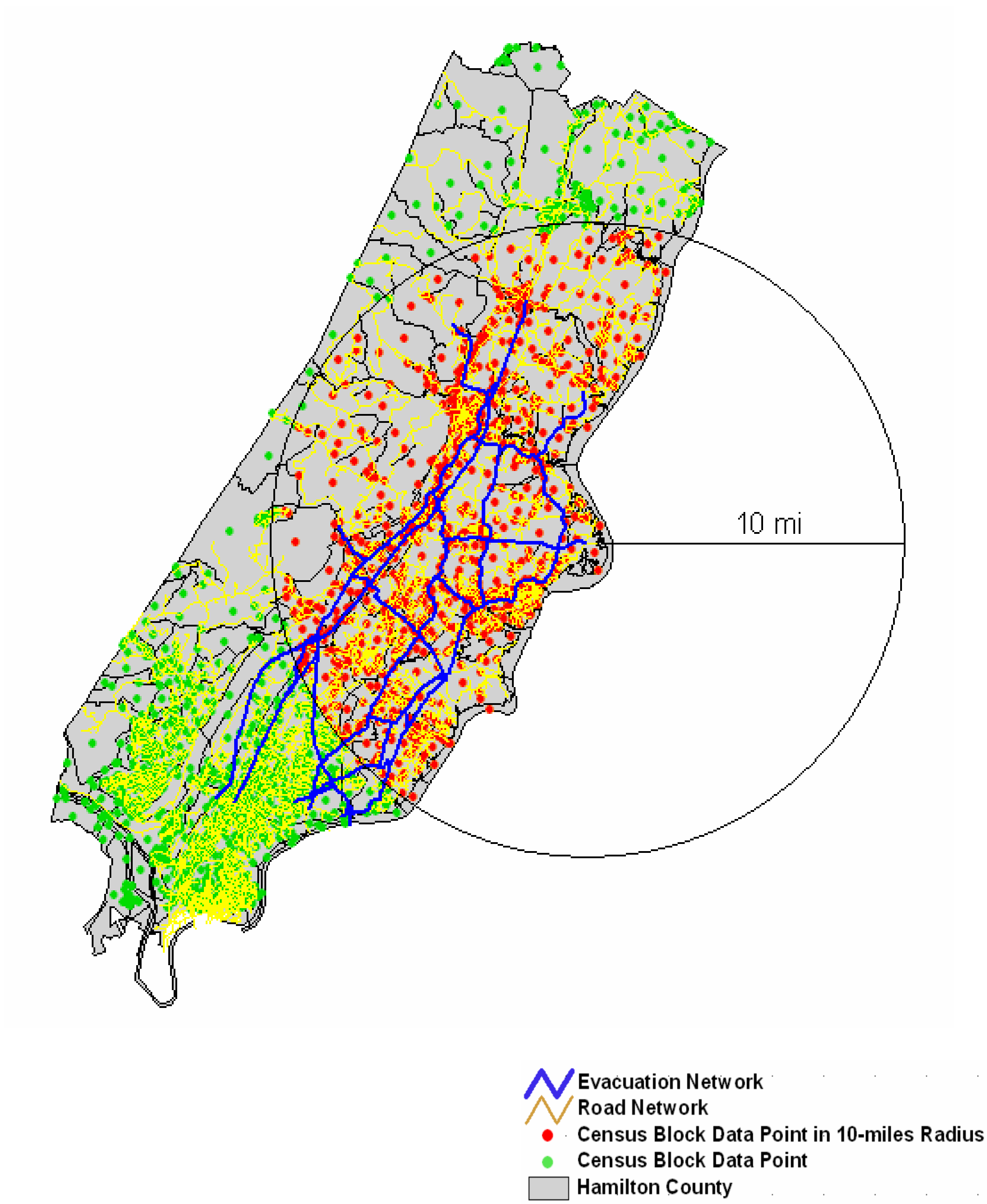
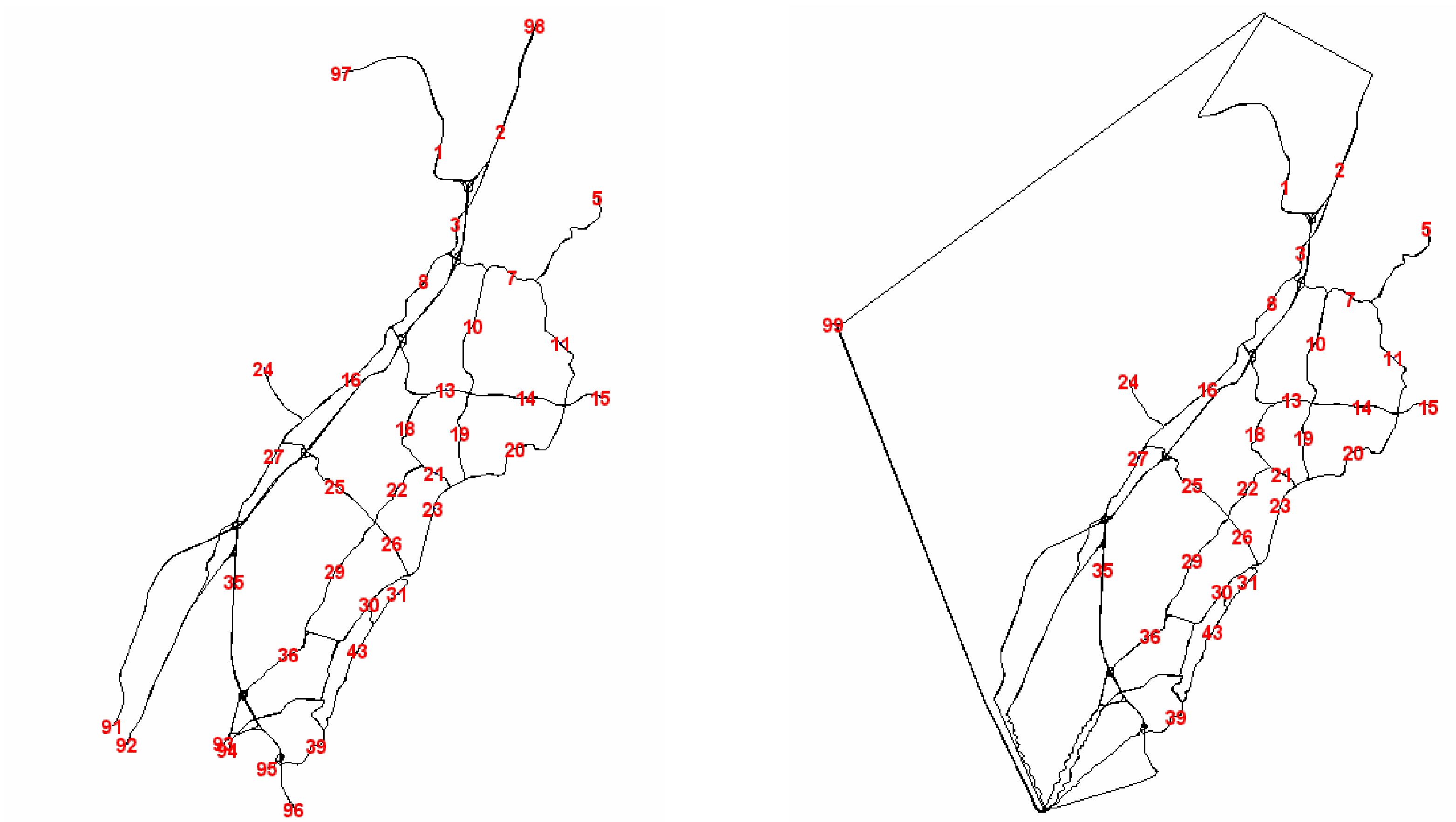


Figure 5.3 Census Blocks and Demand Distribution in Sequoyah Area



(a) Eight Destination Zones

(b) One Destination Zone

Figure 5.4 Sequoyah Network Setup in VISSIM

In this study area, eight links go out of the evacuation network (two at the north end and six at the south end), and all of them are potential destinations. Conventionally, individual destination zones are defined at each road exit point, and then such as a gravity model can be used to decide the traffic distribution from the origins to the destinations. This process results a multiple-destination (*nD*) network, as shown in Figure 5.4(a), where eight destination zones (No.91-98) were defined in the study area. Based on the ODE concept, additional links can be added to connect eight exit points in the real-world to one "dummy point," forming a one-destination (*1D*) network. In an emergency, all evacuation traffic would be assigned to the same destination zone (No. 99), as shown in Figure 5.4(b). The new links were designed with the same length and a high speed.

Besides assessing the population distribution in the study area, it is also important to estimate the response time of individuals from the moment that the evacuation order is issued to the moment that the evacuees start to leave the designated danger zone. An up-to-date emergency response plan (ERP) from the Tennessee Valley Authority (TVA) provides an estimated distribution time for the population within a 10-mile radius of the power plant (TVA, 2005). An estimated maximum preparation of 105 minutes allows time for people in southeast Hamilton County to get home and have roughly 30 minutes to prepare to leave. A Logit-based loading curve, which prescribes the percentage of evacuees being loaded onto the network as a function of time, was employed with a total loading period of 105 minutes, as shown in Figure 5.5. In simulation, seven OD tables of 15 minutes each were used to replicate this loading curve.

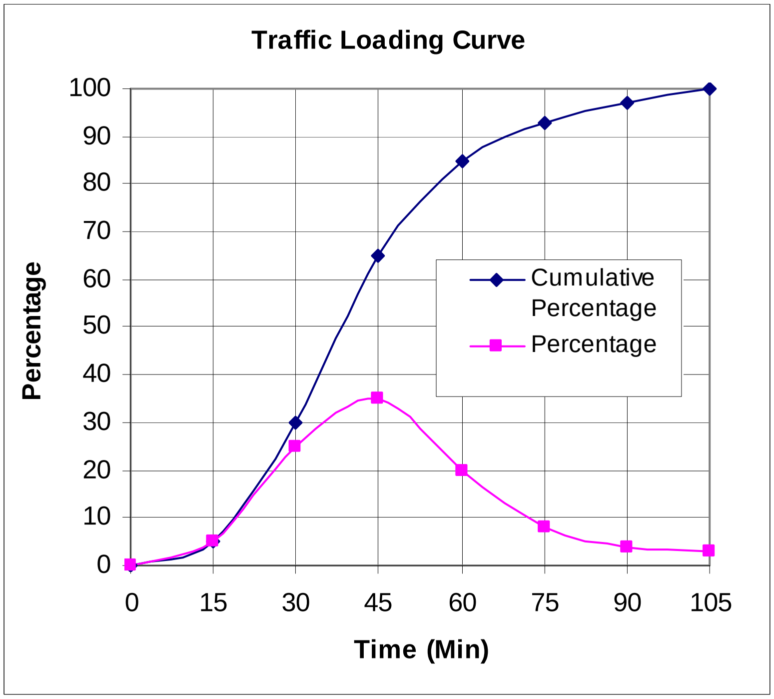


Figure 5.5 Traffic Loading Curve for Sequoyah Network

5.2.2 Scenarios and Simulation Results

Various scenarios, representing various destination/route assignment strategies, were modeled and simulated using VISSIM, to evaluate the performance of the proposed *1D* model against the conventional *nD* model for evacuation planning and operations. For the *1D* model, the destination assignment is straightforward that all evacuees are assigned to the dummy destination via whatever routes (note that the OD table is simply a 36-by-1 matrix). By relaxing the constraint of assigning evacuees to pre-specified destinations, the *1D* model has the potential for greatly improving an evacuation operation based on, and beyond, dynamic traffic assignment/routing. The *1D* model can also be used to enhance existing evacuation plans by employing static or dynamic traffic assignment as an optimization tool to optimize the destination assignment (OD table) at the planning level. All these potential applications of the *1D* model were investigated in different simulation scenarios. For the *nD* network, evacuees from the same origin zone can be explicitly distributed to various destination zones based on the gravity model (or the likes), or assigned to a specific destination based on geographical proximity. Generally, it would be better to base the network flow patterns on the gravity-based demand distribution, as it distributes traffic to a wider area of the network and thus potentially reduces network congestion. Therefore, the gravity-based demand distribution (the OD table is a 32-by-8 matrix) was selected and used for the *nD* network, assuming equal attraction at each destination zone, and will serve as a benchmark to evaluate the performance of the *1D* model during evacuation operations, in accordance with static or dynamic traffic assignment.

Simulated detectors were placed at the same position on the links where evacuees would exit the evacuation network, or EPZ, in real world, for both the *nD* and *1D* models. In this way, evacuation times were able to be measured and fairly compared. Statistical analyses were conducted to compare the evacuation times of different scenarios, including the time required to evacuate 25, 50, 75, and 95% of the evacuees and the network clearance time (100% evacuated), which is seldom achieved in reality but is provided, nevertheless, for reference purposes. Evacuation curves were also compared for different scenarios. A fixed random seed was used in all simulation runs to eliminate differences caused by stochastic variation so that the impact of various network setups could be fairly compared.

5.2.2.1 Static Traffic Assignment

The *1D* model was first evaluated for its potential to improve the evacuation efficiency against the *nD* model using static traffic assignment/routing, which does not provide real-time traffic information or allow en route routing. Assuming a steady state of the network conditions, evacuees were assigned to the best route available at the time that they were loaded onto the network. This is a typical evacuation planning strategy and the most viable practice for evacuation operations. The evacuation curves are plotted in Figure 5.6 and the evacuation times are summarized in Table 5.1.

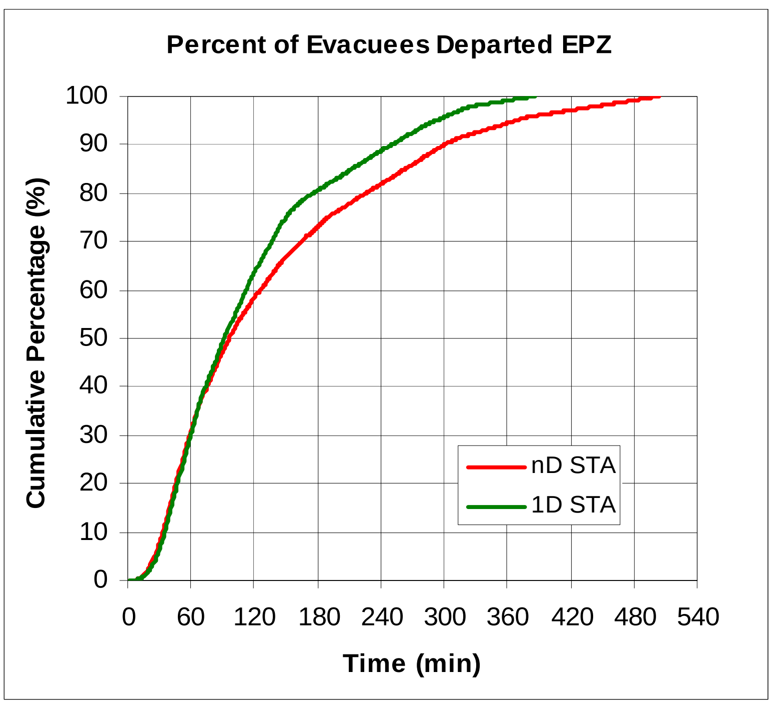


Figure 5.6 Evacuation Curves for Sequoyah Network Using STA

Table 5.1 Evacuation Times for Sequoyah Network Using STA

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
nD STA	52	97	190	369	504
1D STA	54	92	150	293	386

Using STA, the evacuation curves of the *1D* and the *nD* model basically match up until 50% of the population has been evacuated, as shown in Figure 5.6. However, as all evacuees loaded and as congestion on the network built up, the pre-specified destinations in the *nD* model could become inefficient, even ineffective, and the *nD* network performance became worse than the *1D* model, which affords flexibility in destination assignment and accordingly more leeway in traffic assignment and optimization. The *1D* model presents a substantial reduction in evacuation times compared to the *nD* model: the time required to evacuate 75% of the entire population was reduced by 21%, or 40 minutes, and the time required to evacuate 95% of the entire population was reduced by 21%, or 76 minutes, as shown in Table 5.1. The *1D* model also offers a substantial saving in total travel time, as indicated by a large area between two evacuation curves, and a lower overall time-based exposure, because many fewer evacuees were left in the network as time passed by and the evacuation risk became higher. One caveat relating to real-world use, however, is that because the evacuees were, in fact, assigned to the "best" destination at the time of departure, the *1D* model would require a certain level of real-time information for real-world implementation to be successful.

5.2.2.2 Dynamic Traffic Assignment

The *1D* model was then evaluated for its performance at the task of real-time operations and planning as against the conventional *nD* model using dynamic traffic assignment/routing. From the operational perspective, based on real-time traffic information, evacuees could be assigned to, perhaps, a better route, or diverted to different optimal routes toward the same destination. From the perspective of network modeling, DTA departs from the steady-state assumptions in STA to deal with time-varying flows, and therefore is more realistic and provides more accurate forecasts of the network conditions in the study period. Evacuation curves using DTA are plotted in Figure 5.7 and the evacuation times are summarized in Table 5.2.

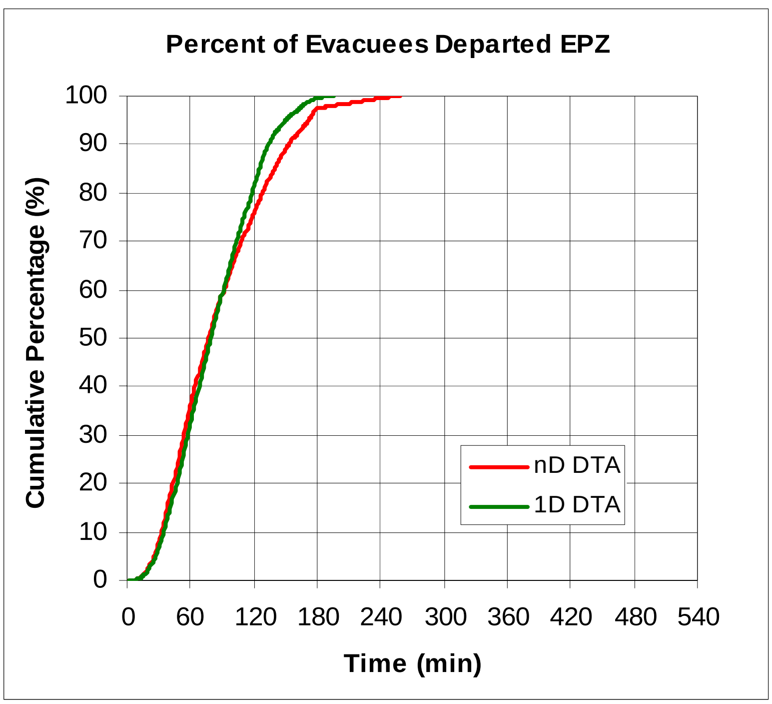


Figure 5.7 Evacuation Curves for Sequoyah Network Using DTA

Table 5.2 Evacuation Times for Sequoyah Network Using DTA

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
nD DTA	49	77	119	172	258
1D DTA	53	80	111	151	196

When implementing DTA in VISSIM, 10 iterations of simulation and assignment were executed; this showed that a stable and converged result was obtained with a small variation in evacuation times from iteration to iteration. Using DTA, the evacuation efficiency was greatly improved for both the *nD* and *1D* models: the time required to evacuate 95% of the entire population was reduced by 53%, or 197 minutes in the *nD* model, and that was reduced by 48%, or 142 minutes in the *1D* model, compared to the result when using STA. The benefits of DTA lie in its capability of finding more efficient routes for evacuees by taking into consideration of the network dynamics. Therefore, congestion on the network can be reduced or controlled. However, one should keep in mind that in order to implement DTA in the real-world and enjoy its benefits, some level of ITS infrastructure would have to be deployed. While using DTA the evacuation curves of the *1D* and *nD* models match up until 70% of the population has been evacuated, as shown in Figure 5.7, the *1D* model still outperformed the *nD* model, when all the evacuees were loaded and the congestion were built up. The time required to evacuate 95% of the population was reduced by 12%, or 21 minutes, and the network clearance time was reduced by 24% or 62 minutes, compared to the *nD* model.

5.2.2.3 Static Traffic Assignment with Improved OD Tables

To this end, the proposed *1D* model presents significant improvement over the conventional *nD* model. Based on the *1D* method, the overall evacuation time can be reduced by up to 20% and 60% using STA and DTA, respectively, compared to the *nD* model using STA. While the concept of ODE may be superior on paper, the benefit to the public is minimal if it cannot be implemented. The constraints in the real-world include: 1) evacuees would not appreciate being told to head for a dummy destination in a time of emergency and 2) ITS infrastructure is not readily deployed in all locales and, even when available, may not always be reliable under severe weather and other emergency conditions. Although limited by these constraints, the *1D* method and its optimal results are valuable for improving evacuation efficiency. Not only does the *1D* framework provide a foundation for planning real-time evacuation operations with future investment in and deployment of ITS, but the *1D* results (optimal destination assignment) can also serve to improve existing evacuation plans, as discussed in Chapter 4.

Using the *1D* assignment results, a new *nD*-based OD table can be constructed for the study area. Based on the real-world exit used by most evacuees from the same origin zone in the *1D* network, a specific destination zone (network exit) can be decided for each origin zone (all evacuees in the same origin zone are instructed to evacuate towards the same destination, the typical planning strategy). The resultant *nD*-based OD table presents, potentially, an improvement over the OD table used in the existing evacuation plans, which is mainly based on the criterion of geographical proximity. The efficiency of the improved OD table can be measured, using STA, against the planning OD table adapted from the up-to-date emergency response plan (ERP) for the Sequoyah plant prepared by the Tennessee Valley Authority (TVA, 2005). In TVA's ERP, the 10-mile EPZ is divided into sectors, as shown in Figure 5.8, and a specific evacuation route and destination are designated for each sector. This information was used to find the planning OD table for the study area. The evacuation curves with improved OD tables are plotted in Figure 5.9, and the evacuation times are compared in Table 5.3.

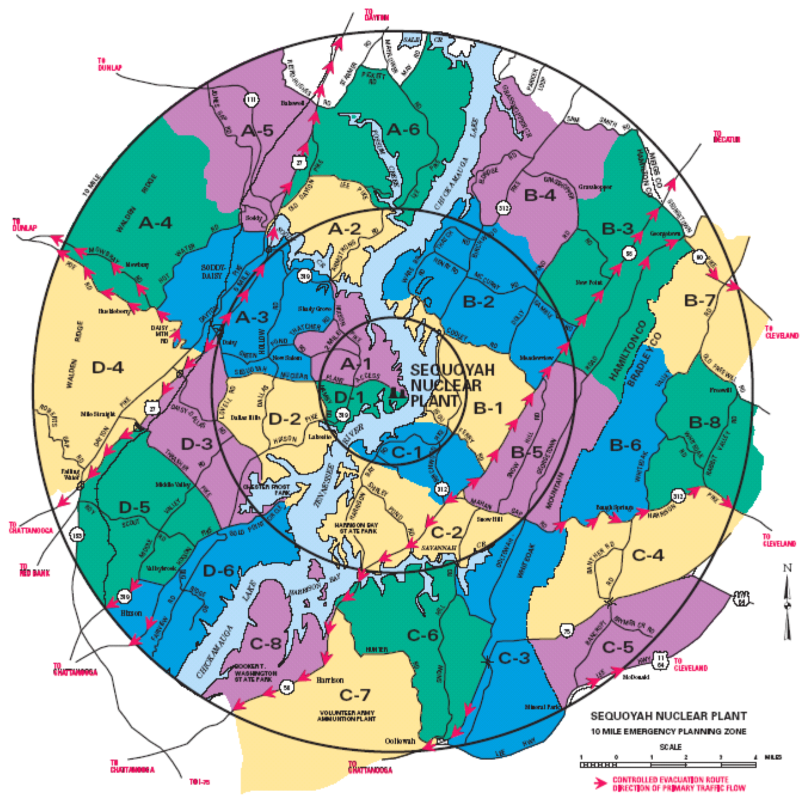


Figure 5.8 Sequoyah Evacuation Map and Routes (from TVA, 2005)

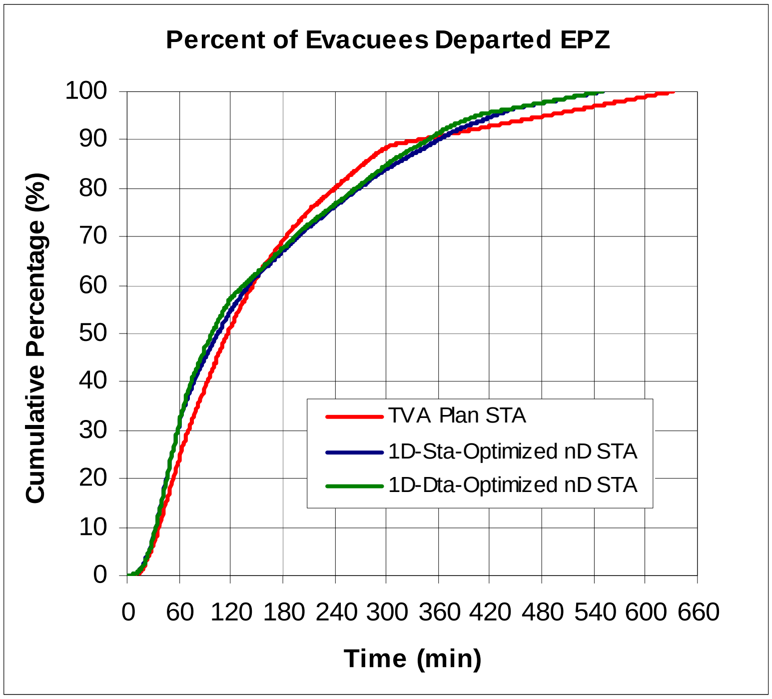


Figure 5.9 Evacuation Curves for Sequoyah Network with Improved OD Tables and STA

Table 5.3 Evacuation Times for Sequoyah Network with Improved OD Tables and STA

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
TVA Plan STA	62	117	209	484	631
1D-STA-Optimized *nD* STA	52	105	232	425	550
1D-DTA-Optimized *nD* STA	52	99	229	405	549

The simulation results clearly support the notion that the *1D* assignment results can be used to optimize the destination assignment (the OD table) at the evacuation planning stage. Based on the improved OD tables, the time required to evacuate 95% of the entire population was reduced by up to 16%, or 79 minutes. As shown in Figure 5.9, the evacuation curves based on the improved OD tables outperform the evacuation curve based on the existing planning OD table most of the time, except for during the middle stage of the evacuation process. For instance, the time required to evacuate 75% of the population was increased by 10%, or 20 minutes, based on the improved OD table. It was also noticed that while the total travel time might not be substantially reduced with the improved OD tables (indicated by a small difference in the areas defined by different evacuation curves, referring to the same loading curve used), the overall time-based risk exposure was obviously reduced. As discussed in Chapter 3, the evacuation operations based on the improved OD tables were more efficient because fewer evacuees were trapped in higher-risk situations at the late stage of the evacuation.

The evacuation curves based on two different OD tables, obtained from the *1D* optimization using STA and DTA respectively, almost match, as shown in Figure 5.9. The 1D-and-DTA optimized OD table only presents a very small reduction (5% or 20 minutes) in the time required to evacuate 95% of the entire population, compared to the 1D-and-STA optimized OD table. In fact, a comparison of these two OD tables shows that only eight out of 29 origin zones were assigned to different destination zones. Such a small difference in the destination assignment might have a very limited impact to the evacuation performance in terms of the overall evacuation time, as suggested in the simulation results. However, when compared to the planning OD table, 16 out of 29 origin zones were assigned to different destination zones based on the *1D* assignment results, and thus the evacuation performance was substantially altered. Therefore, one can conclude that the ODE concept itself presents great potential for improving the evacuation efficiency, even at the planning stage, no matter which assignment method is used, STA or DTA.

5.3 Knoxville Network

In the second case, the *1D* model was implemented to model a county-wide special-event evacuation by DYNASMART_P. The site of the study is Knox County, Tennessee. Two major interstates, I-40 and I-75, cross through the study area, as shown in Figure 5.10. Evacuation of the entire county was modeled. Two network setups, *nD* and *1D*, were simulated and compared for their effectiveness.

5.3.1 Network Setup

In this study, the simulation network was developed based on an example input file for DYNASMART_P prepared by the University of Maryland. The road network, shown in Figure 5.11, was geo-coded with detailed geographic representation including on-ramps, off-ramps, and interchanges, as well as control information. The network consists of 263 zones, 1006 links and 2179 nodes, of which 120 are signalized.

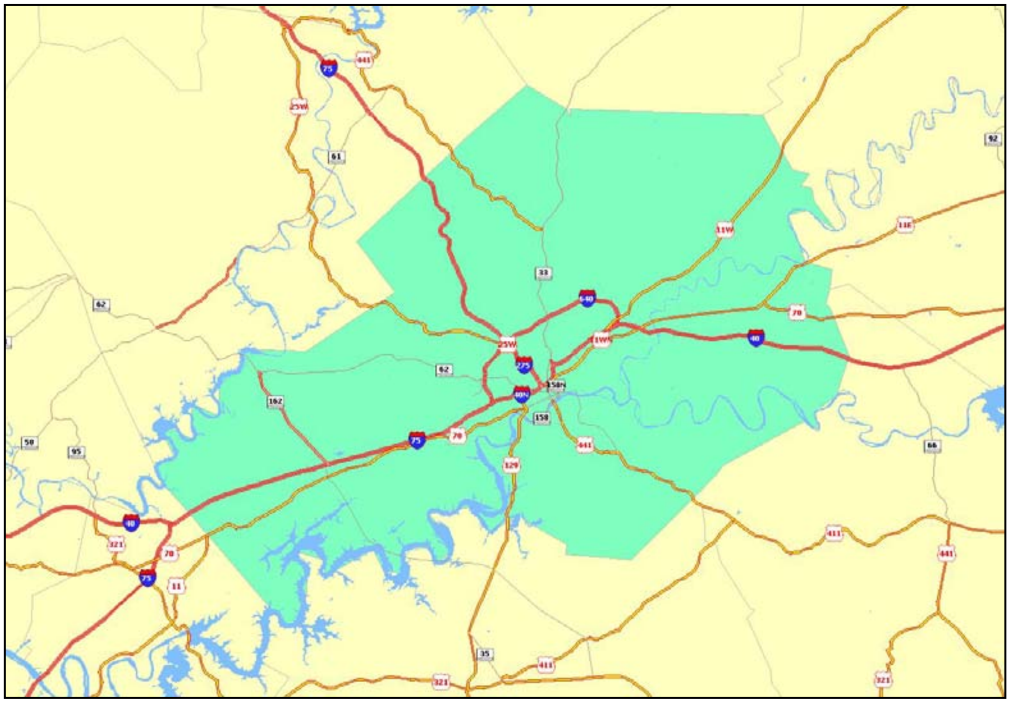


Figure 5.10 Study Area for Knox County

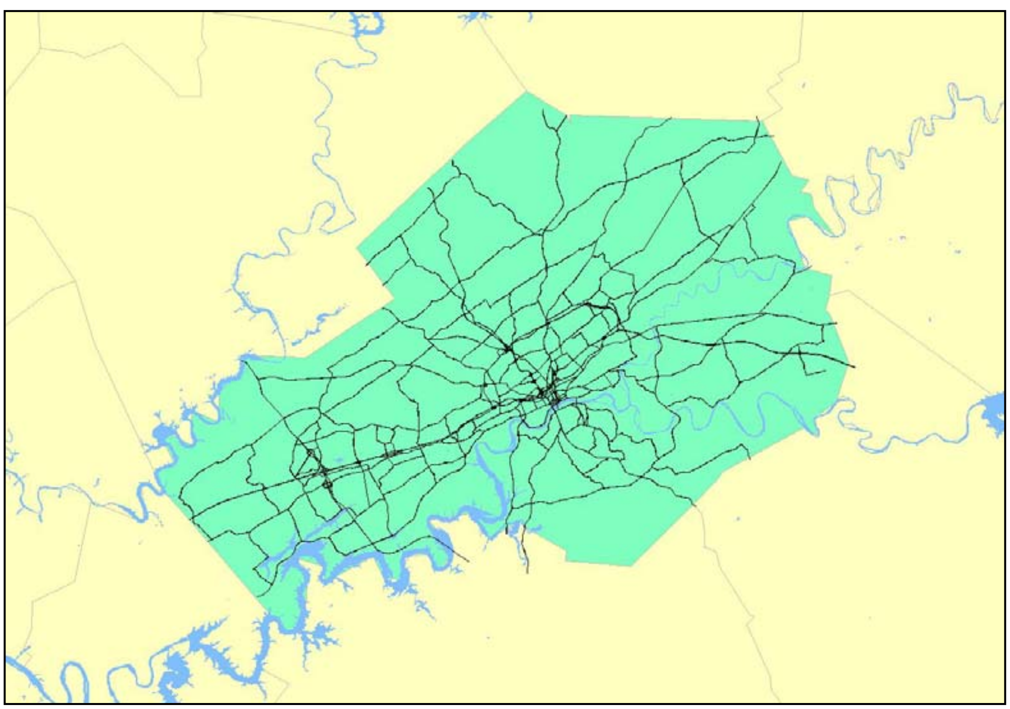


Figure 5.11 Geo-coded Highway Network for Knox County

The transportation analysis zones (TAZs) defined for the study area generally follow the transportation analysis zones formulated by the Knoxville and Knox County Metropolitan Planning Commission (MPC). Evacuation demand was estimated based on the number of households in each TAZ. According to the 2000 U.S. Census data, the number of households was aggregated at TAZ level and shown in Figure 5.12. Approximately, there are 158,000 households in the Knox County, and about 12,000 (7.7%) of these households do not possess personal-use vehicles (mainly concentrated in the inner city, i.e. the downtown area). In total, 157,733 vehicle trips were estimated and modeled for the study area for a hypothetical county-wide evacuation event.

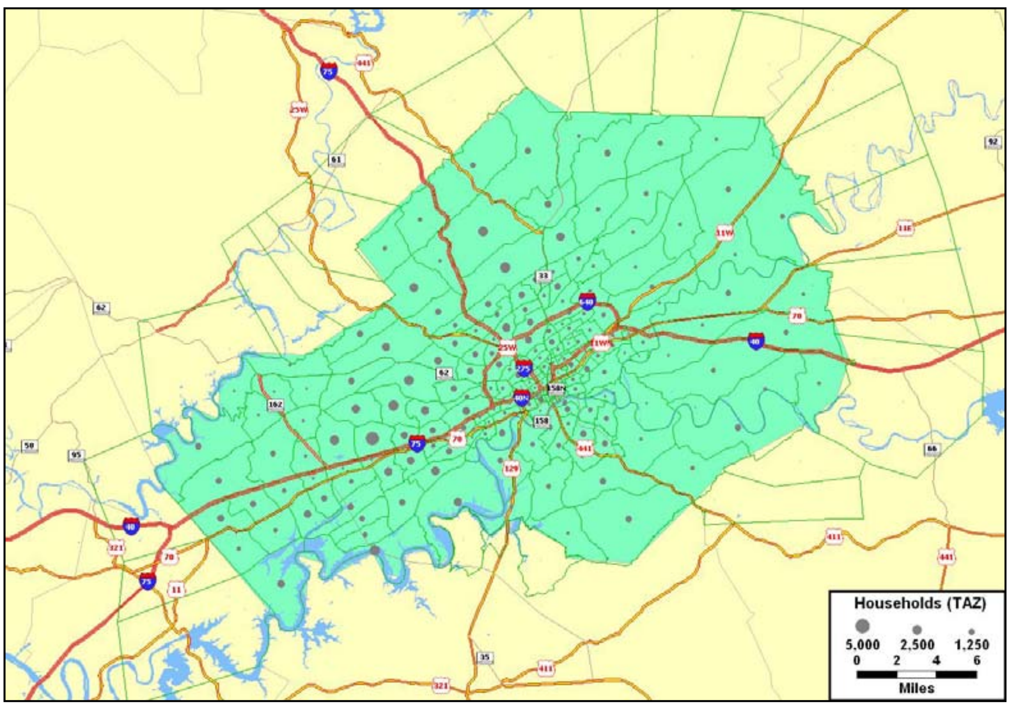


Figure 5.12 Traffic Zones and Households by TAZ in Knox County

In this simulated case, evacuation trips are generally directed outwards in order to leave the EPZ and seek safety. A total of 24 highway exits exist leading out of the evacuation area. Using the conventional methods, individual destination zones are defined at the end of each network exit, and thus an *nD* evacuation network is formed. For this *nD* network, two strategies, nearest-exit (proximity) assignment and interstates-biased assignment, were implemented; see Figures 5.13 and 5.14 respectively. All evacuees from the same TAZ are assumed to evacuate toward the same destination zone (the nearest exit, whatever its classification, or the nearest interstate end) in accordance with the assignment strategies. The performance of the *nD* model based on these two different exiting strategies is to be compared with that of the *1D* model.

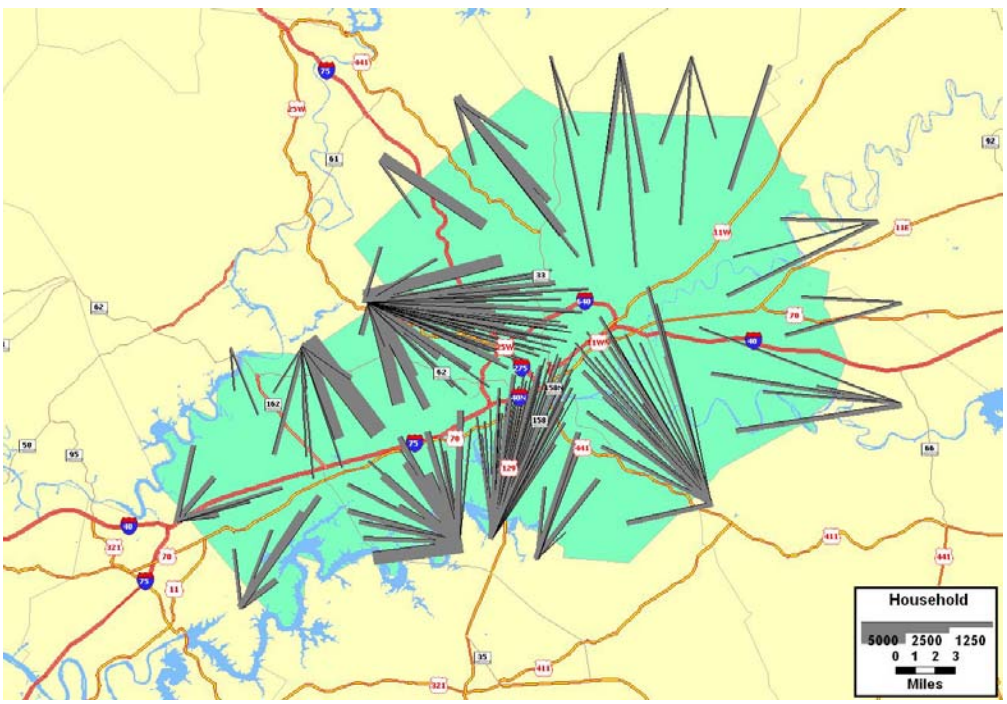


Figure 5.13 Nearest Exit Based Destination Assignment

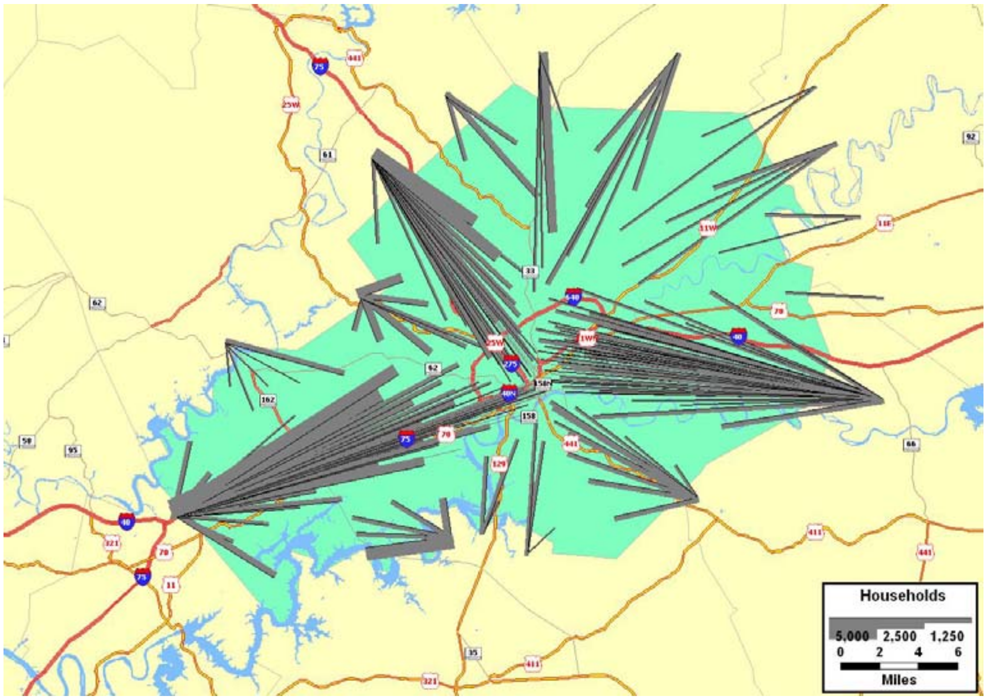


Figure 5.14 Interstates-Biased Destination Assignment

The *1D* model was constructed by connecting the 24 actual exit points in the real world to one “dummy destination” that all evacuees head for via whatever routes. In DYNASMART_P, vehicles exit the network via destination nodes, in much the same way as in conventional planning model, such that vehicles are considered to have finished their trips and been removed from the system once they have reached the specified exiting points. Therefore, by specifying all of the real-world exit points as the destination nodes of the dummy destination zone defined in the *1D* model, the evacuation time and the solution computational time can be exactly measured and fairly compared between the *1D* and *nD* models.

5.3.2 Scenarios and Simulation Results

Various scenarios, representing various destination/route assignment strategies, were investigated by using DYNASMART_P to evaluate the performance of the *1D* model against the conventional *nD* model during a large-scale evacuation on the Knoxville network. The evacuation traffic was loaded onto the network in a uniform fashion during the first hour of the simulation. Due to the hefty computational effort required to simulation hundreds of thousands vehicles in a large network, all evacuation durations were capped at 20 hours. Based on the vehicle statistics outputted by DYNSMASRT_P, the times required to evacuate 25, 50, 75, and 95% of the evacuees are tabulated together with the time required to evacuate 100% of the population, wherever applicable. Evacuation curves are also plotted to compare these two models in different simulation scenarios.

5.3.2.1 Static Traffic Assignment

The *1D* network and the *nD* network, based on two different exiting strategies, nearest-exit assignment and interstate-biased assignment, were first compared using static traffic assignment/routing (STA or SR), which is the typical evacuation planning strategy. During simulations, vehicles were assigned to the current best path between an OD pair at their departure time. The resultant evacuation curves are plotted in Figure 5.15, and the evacuation times are summarized in Table 5.4.

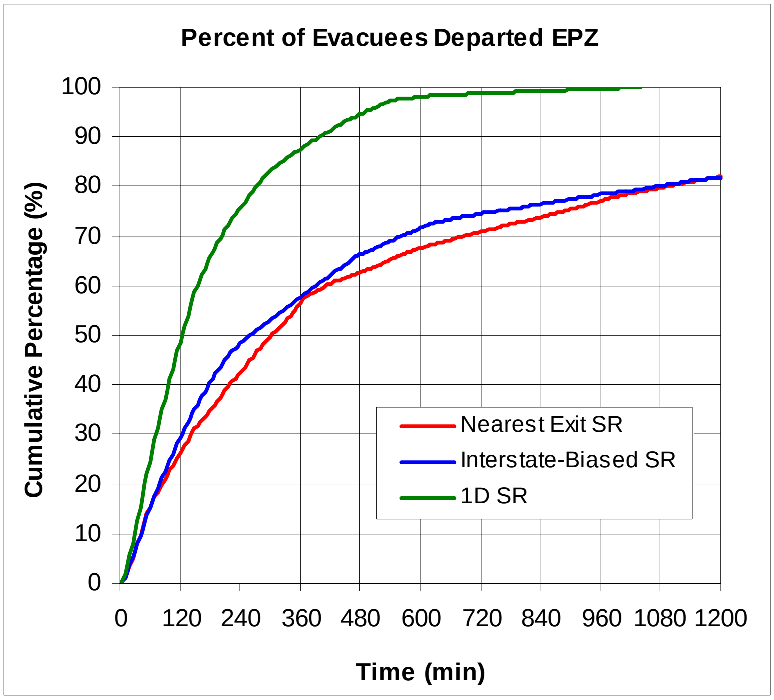


Figure 5.15 Evacuation Curves for Knoxville Network Using SR

Table 5.4 Evacuation Times for Knoxville Network Using SR

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
Nearest Exit SR[(1)]	115	305	890	\	\
Interstates-Biased SR[(2)]	105	260	755	\	\
1D SR	65	125	235	490	1040

[(1)] Only 82.1% of the population was evacuated within 20 hours.
[(2)] Only 81.7% of the population was evacuated within 20 hours.

For the *nD* network, the nearest exit assignment where evacuees are assigned to the nearest of the 24 exits is the base case. For this scenario, the simulation results using SR indicate a very long evacuation process that would leave about 18%, or close to 70,000 people, stranded in the EPZ 20 hours after the evacuation operation commenced. The evacuation curve is shown in red in Figure 5.15. Interstate highways are perceived to have desirable access control, faster operational speed, higher roadway capacity, superior geometric design, and more dependability in time of emergency. By assigning most evacuees to the nearest of the four interstate highway exits, it was hoped that some level of improvement to the evacuation efficiency can be achieved. For this interstates-biased *nD* assignment using SR, the simulation results suggest a slightly better evacuation curve at first, (see blue line in Figure 5.15), which, however, did not outperform the nearest exit assignment at the end of the 20-hour period, when around 18% of the population was still stranded in the EPZ.

For the *1D* network, every evacuee is assigned to the same "dummy destination," to which all 24 exit points lead. However, as in all static traffic assignments/routing, once vehicles are en route, they do not have access to real-time traffic information for rerouting, which practically "fixes" the real-world destination for each vehicle. The simulation results, shown in green in Figure 5.15, suggest a remarkable improvement in evacuation efficiency over the conventional *nD* approaches using either the nearest exit or interstates-biased assignment, which can barely evacuate 80% of the population in 20 hours; in contrast, the *1D* approach moves 95% of the population, the typical measure of effectiveness for evacuation operations, in about 8 hours. In general, the *1D* model enjoys a 60% or so saving of time in evacuating the EPZ population, just using SR. However, one should keep in mind that because the evacuees were, in effect, assigned to the "best" destination along with the "best" route at the time of departure, the *1D* model requires real-time information and, hence, makes it difficult to implement in areas without deployed/matured ITS infrastructure.

Overall, one can foresee that it would require a very long time to evacuate the entire population in the EPZ. This could be a problem inherent in the STA procedure on a large network. Using STA, evacuees were assigned to the "best" path at their departure time, but all in the first hour; the average trip time to depart the EPZ would be more than five hours instead, based on the simulation outputs. Therefore, the STA procedure used here is really based on a myopic view of the network conditions beyond the loading period. It is hoped that the evacuation operations will be improved by using DTA.

5.3.2.2 Dynamic Traffic Assignment

The *1D* model was then evaluated for its performance during real-time evacuation operations against the conventional *nD* model using dynamic traffic assignment/routing. As mentioned earlier, an iterative simulation-assignment procedure is deployed in DYNASMART_P to solve a system optimal or user optimal dynamic traffic assignment problem. However, the computational burden associated with the use of a simulator as part of an iterative mechanism to capture the complex vehicle interactions and project the future can be operationally restrictive. In fact, the iterative simulation-based DTA is not feasible for the large network and long planning horizon modeled in this study, due to the software and hardware constraints. However, DYNAMSART_P also provides a function to emulate the effects of the Advanced Traveler Information System (ATIS), including dynamic routing (DR), even via a one-step simulation-assignment procedure. Travelers with the ATIS equipments can be modeled, and during simulations they will be able to update their travel paths at each intersection based on the prevailing shortest path tree (reroute to a faster route). This function is designed to replicate the en route information and model the rational behavior of the travelers. However, when DR is modeled via this function and implemented in the one-step simulation-assignment mode, it does not guarantee that travelers will have the overall best path at the end of simulation as in the system optimal dynamic assignment case implemented in the iterative simulation-assignment mode. However, the DR scenario thus modeled is more operationally realistic and adequate from the standpoint of modeling and control under ATIS in response to unpredicted variations in network conditions.

In this study, the performance of the *1D* network is further compared with the *nD* network, based on two different exiting strategies, the nearest exit assignment and the interstates-biased assignment, at real-time evacuation operations in the content of ATIS, using DR. For these three different network setups and destination assignments, the evacuation curves are plotted and compared in Figure 5.16. The evacuation times are summarized in Table 5.5.

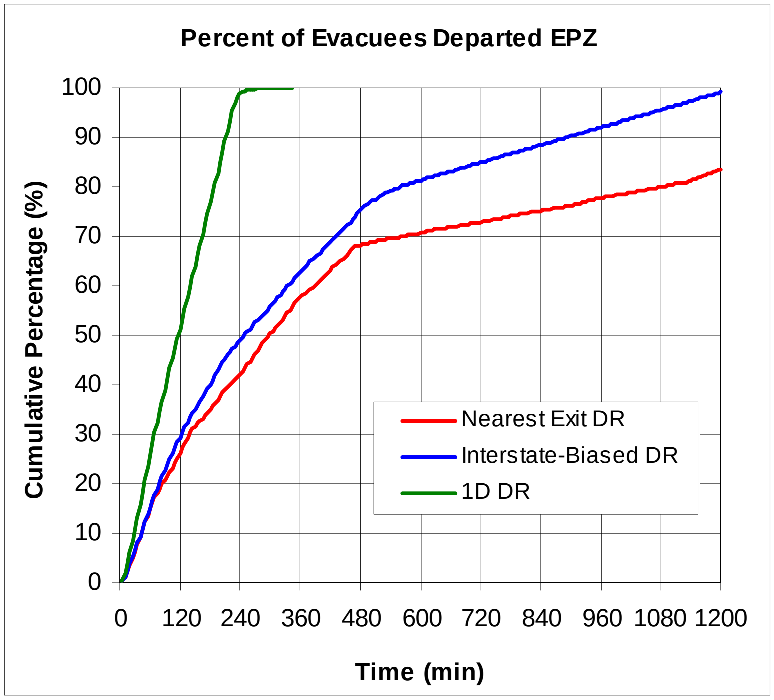


Figure 5.16 Evacuation Curves for Knoxville Network Using DR

Table 5.5 Evacuation Times for Knoxville Network Using DR

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
Nearest Exit DR(1)	115	300	835	\	\
Interstates-Biased DR(2)	105	250	480	1065	\
1D DR	60	120	180	225	345

(1) Only 83.7% of the population was evacuated within 20 hours.
(2) Only 99.1% of the population was evacuated within 20 hours.

For the *nD* network with the nearest-exit assignment and DR, the evacuation curve is shown in red in Figure 5.16. It is somewhat surprising that DR did not seem to help to reduce the evacuation time in a noticeable fashion. At the end of the 20-hour evacuation period more than 60,000 people were still stranded in the EPZ. This is, perhaps, an indication of the weakness of the conventional proximity-based destination assignment approach, which would not gain much efficiency, even if provided with expensive ITS infrastructures and sophisticated routing schemes because of the less-than-optimal destination assignment at the outset. For the *nD* network with the interstates-biased assignment and DR, the results shown in blue in Figure 5.16 are more promising as 95% of the population was evacuated in about 16 hours. About 3,000 people were still stranded in the EPZ at the end of the 20-hour evacuation period, but this is already a significant reduction from the 60,000 cited above in static traffic assignment/dynamic. It appears that the DR approach is more effective when most evacuees are destined for interstate exits. But once again, to implement DR in the real-world and enjoy its benefits, some level of ITS infrastructure would have to be deployed for real-time traffic information gathering and dissemination.

For the *1D* network with DR, intuitively, one would consider this scenario the most efficient of all strategies because it simultaneously optimizes the destination and route assignment based on real-time information for all evacuees. The results as shown in green in Figure 5.16 certainly support this notion. The large population that the *nD* network could not clear in 20 hours even though DR was also deployed, was easily evacuated in just over 4 hours, an astonishing time saving of more than 80%. Such an improvement presents the maximal improvement that could be achieved during evacuation operations using ITS technologies to reassign destinations and reroute evacuation traffic based on the proposed *1D* framework. While the implementation of DR require ITS and, hence, makes this optimal strategy rather challenging to realize, the results could still provide valuable insights for improving non-DR strategies. The short evacuation time serves as a "lower bound" that other scenarios can be measured against and should strive to achieve. More importantly, the resultant OD table can be used for implementation in the *nD* network without dynamic routing or en route information.

5.3.2.3 Static Traffic Assignment with Improved OD Tables

The *1D* assignment results can be used to determine a new *nD*-based OD table for the study area. In the new OD table, all evacuees from the same origin zone are assigned to the same destination zone (a specific exit in the real world), which was taken by most evacuees from that origin zone in the *1D* network. This is the easiest way to implement the optimal destination assignment of the *1D* network in the existing evacuation plan without changing the zone partition. Two different *nD*-based OD tables were constructed based on the *1D* results using static or dynamic routing respectively, as depicted in Figures 5.17 and 5.18. The efficiency of these two resultant OD tables are compared with the nearest-exit and interstates-biased destination assignment, using static traffic assignment/routing. The evacuation curves based on different OD tables are compared in Figure 5.19, and the evacuation times are summarized in Table 5.6.

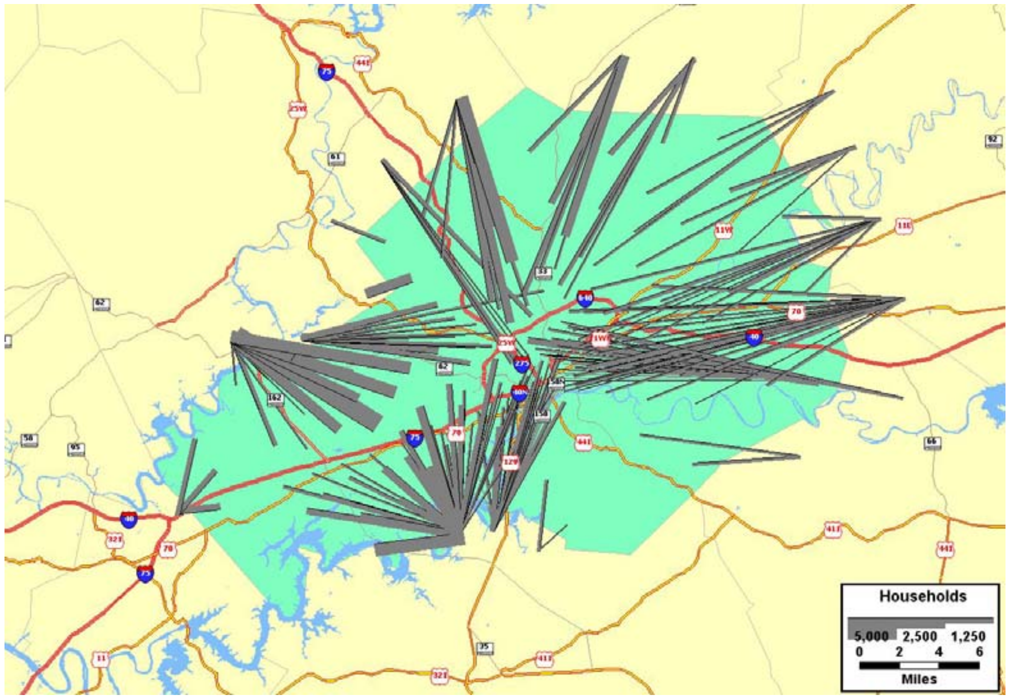


Figure 5.17 Destination Assignment from *1D* Optimization with SR

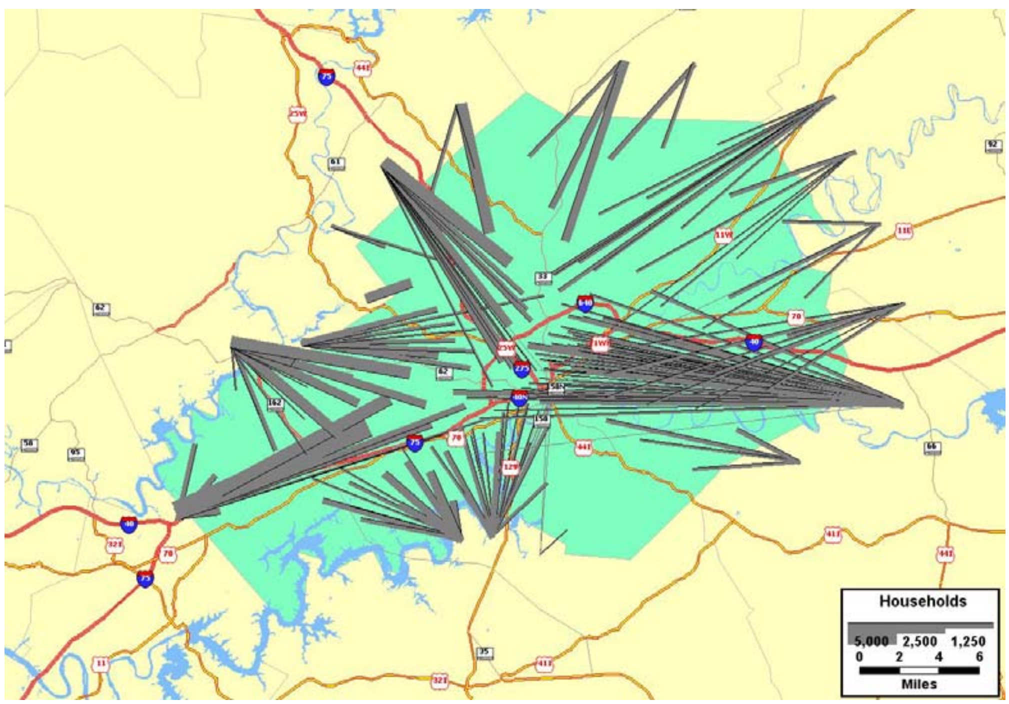


Figure 5.18 Destination Assignment from *1D* Optimization with DR

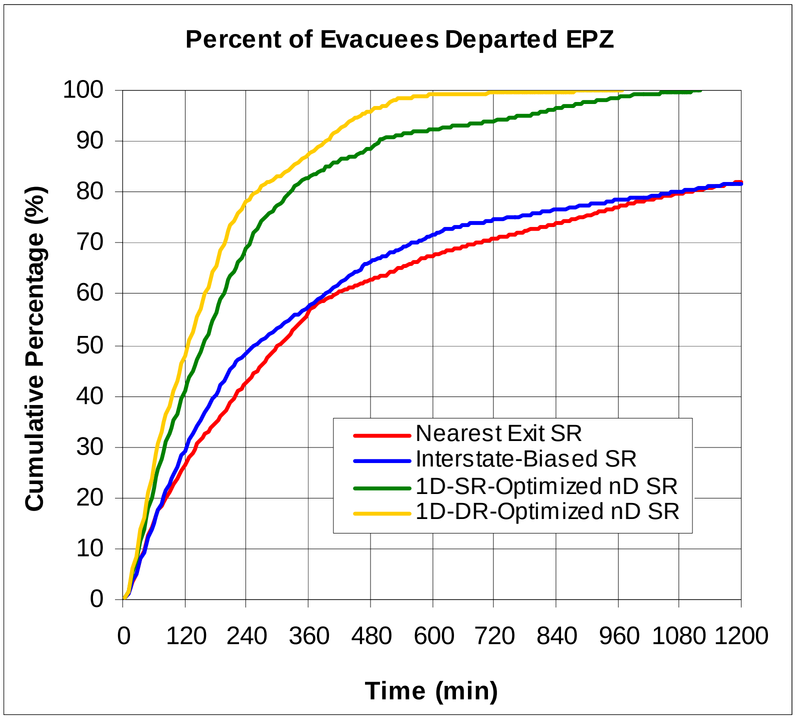


Figure 5.19 Evacuation Curves for Knoxville Network with Improved OD Tables and SR

Table 5.6 Evacuation Times for Knoxville Network with Improved OD Tables and SR

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
Nearest Exit SR[(1)]	115	305	890	\	\
Interstates-Biased SR[(2)]	105	260	755	\	\
1D-SR-optimized nD SR	70	160	280	820	1120
1D-DR-optimized nD SR	60	130	220	460	970

[(1)] Only 82.1% of the population was evacuated within 20 hours.
[(2)] Only 81.7% of the population was evacuated within 20 hours.

The results, shown in Figure 5.19 and also in Table 5.6, are reassuring. Without DR or real-time information, the *1D*-SR-optimized *nD* assignment was able to clear 95% of the population within 14 hours and, in general, exhibit a time saving of better than 30% in comparison with the traditional nearest exit or interstates-biased destination assignment. The *1D*-DR-optimized *nD* assignment is expected to be more efficient, as the *1D* DR scenario is the most efficient approach that simultaneously optimizes the destination and routing problems. A point the simulation results, shown in yellow in Figure 5.19, clearly support. Again, without using DR or real-time information, this *nD* traditional assignment was able to clear 95% of the population within 8 hours and, in general, exhibit a time saving of more than 60% in comparison with the traditional planning approaches. Most importantly, such a dramatic time saving can be actually achieved without any capital investment in ITS infrastructure, contra-flow control devices, etc., just by instructing evacuees to head for more efficient destinations determined from the 1D optimization performed beforehand.

To ensure the effectiveness and reliability of the *1D*-based *nD* OD tables in real-world implementation, multiple simulation runs were conducted using different random seeds to quantify the variation in the expected time saving based on the improved OD tables. This process shows that the time required to evacuate 95% of the population is only varied by 10% due to the stochastic variation in simulations. Figure 5.20 shows the typical variation in evacuation curves by different random seeds. It is clear that the *1D*-based destination optimization is effective and its improvement is reliable and predictable.

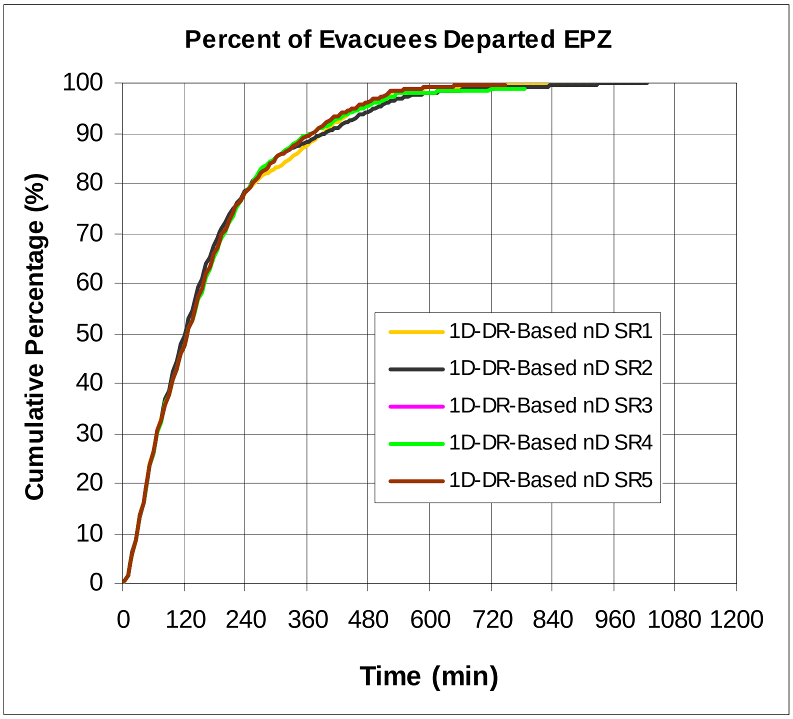


Figure 5.20 Evacuation Curves for *1D*-DR-Based *nD* SR with Different Random Seeds

CHAPTER 6

HYPOTHETICAL GRID NETWORK

When tested on real-world networks for evacuation studies, the proposed *1D* model demonstrates substantial improvement over the conventional *nD* model for both planning and operational purposes. For a county-wide special-event evacuation, a nearly 80% reduction in the overall evacuation time can be achieved when modeling of traffic routing with en route information in the *1D* framework, and the *1D* optimization results can also be used to improve the planning OD tables, resulting in a reduction of up to 60% in the overall evacuation time. For a regional evacuation due to a nuclear power plant mishap, a reduction of up to 60% in the overall evacuation time can be achieved by using the *1D* formulation with DTA, and the planning OD tables can also be improved based on the *1D* results with a near 16% reduction in the overall evacuation time.

Beyond this, it may also be worthwhile to test the *1D* model in some special cases in order to fully evaluate its feasibility and benefits. Therefore, further experiments and simulation analyses were conducted for evacuation operations from a point-source threat on a grid network under various demand distribution and network constraints. This hypothetical case assumes that the population within a 10-mile radius from the point source will be evacuated; the evacuation transportation network is represented by a ten-by-ten grid, as illustrated in Figure 6.1.

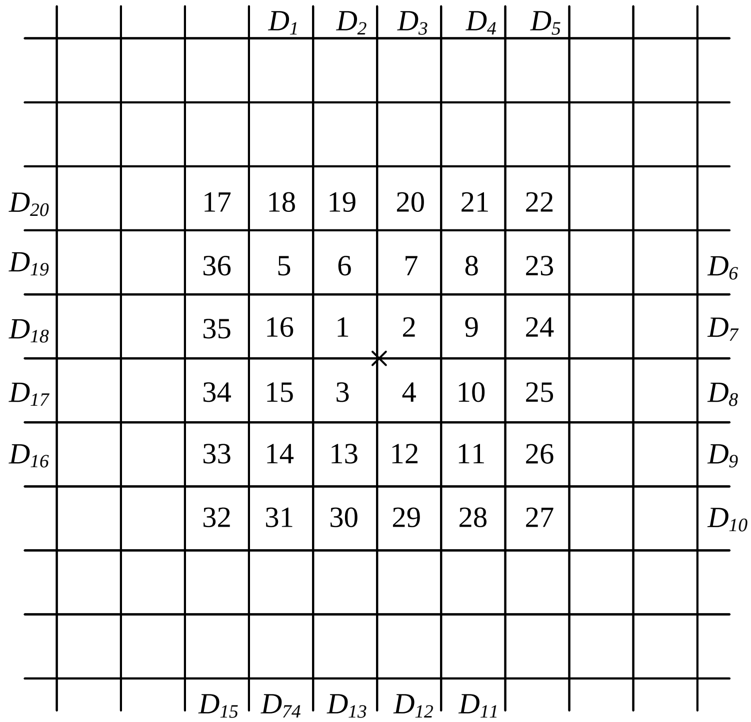


Figure 6.1 Hypothetical *nD* Grid Network

6.1 Network Setup

The hypothetical evacuation network was coded in VISSIM and consists of 1452 one-lane links and 121 non-signalized intersections. Each link was randomly assigned with a desired speed distribution (i.e., each vehicle will get a new speed from the relevant speed distribution as it crosses over the desired speed decision point on a link) to model varying traffic operating characteristics (e.g., posted speed limit or geometric changes) on the evacuation network. The area within each grid was defined as an evacuation planning zone. Evacuees were assumed to be located in the inner grids around the evacuation source, as marked in Figure 6.1. In total, 36 origin zones (where evacuation trips begin) were defined, as numbered in Figure 6.1. For these zones, it is more challenging to determine the optimal destination assignment compared with these zones at or closer to the network boundary, and therefore optimizing their destination assignment would yield more benefits. Any road exit out of the evacuation area is potentially an evacuation destination. In this study, two network setups (modeling strategies), multiple-destination (*nD*) and one-destination (*1D*), were simulated and compared for their effectiveness.

For the *nD* network, all evacuees in the same zone were assumed to evacuate toward the nearest destination zone, measured by the distance from the vehicle loading point in an origin zone (with one entrance per zone) to the exit point in a destination zone. In this case, a total of 20 destination zones were defined at the network boundary, as marked in Figure 6.1. Each destination zone consists of two exit points that outgoing traffic can use equally. If an origin zone lies at the same distance to two different destination zones, all evacuees in this origin zone were randomly assigned to one of these destination zones. Therefore, all evacuees from the same origin zone should travel toward the fixed exits in a pre-specified destination zone, and the travel routes would be determined by a traffic assignment procedure using a 36-by-20 OD table. For the *1D* network, the grid network was augmented by additional 44 links, each connecting from an exit point on the original grid network to one dummy point, *D**, as shown in Figure 6.2. All these new links were designed with the same length and a desired high speed. Accordingly, only one destination zone was defined and used by all the evacuees.

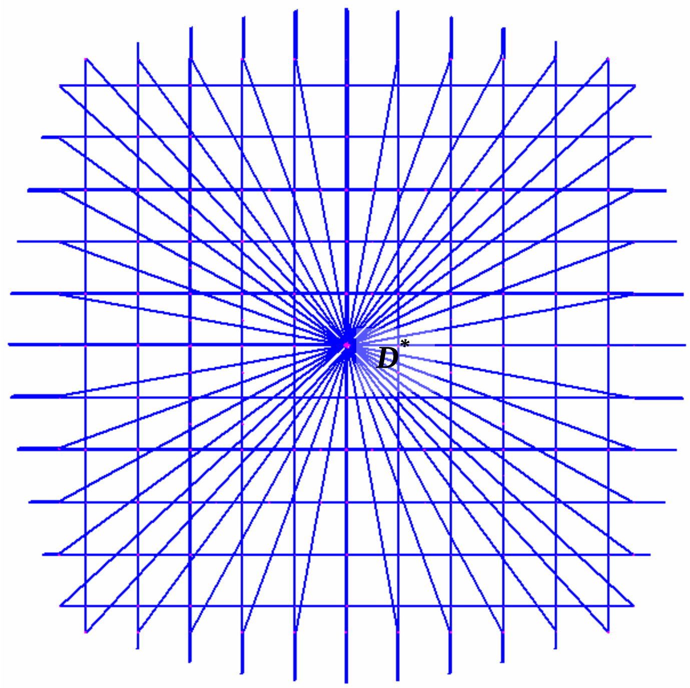


Figure 6.2 Hypothetical *1D* Grid Network

For both the *nD* and *1D* network, simulated detectors were placed at the same position on the links where vehicles depart the evacuation area in real world. Vehicle counts were collected and aggregated at one-minute intervals. For the *1D* network, the evacuation times were actually measured by the time vehicles crossed over the detectors (that is, left the "real-world" evacuation area), though they remained in the network until they reached the final destination, i.e. the "dummy point". As a result, the actual evacuation time was able to be collected and fairly compared between these two networks.

For this hypothetical case, the evacuation demand can be assumed, but it needs to be designed carefully. In real-world evacuations, the transportation system is usually operating at or near its maximum capacity, and in many cases, the evacuation demand far exceeds the capacity. Therefore, it is necessary for practical reasons to compare the *nD* and *1D* models assuming a reasonably high evacuation demand. A range of evacuation demand levels was tested and compared using evacuation times. The evacuation demand was assumed to be from 500 to 2000 vehicle trips per zone and to be uniformly loaded in the first hour of the simulation. These demands were first tested on the *nD* network using STA. The resulting evacuation curves are plotted and compared in Figure 6.3.

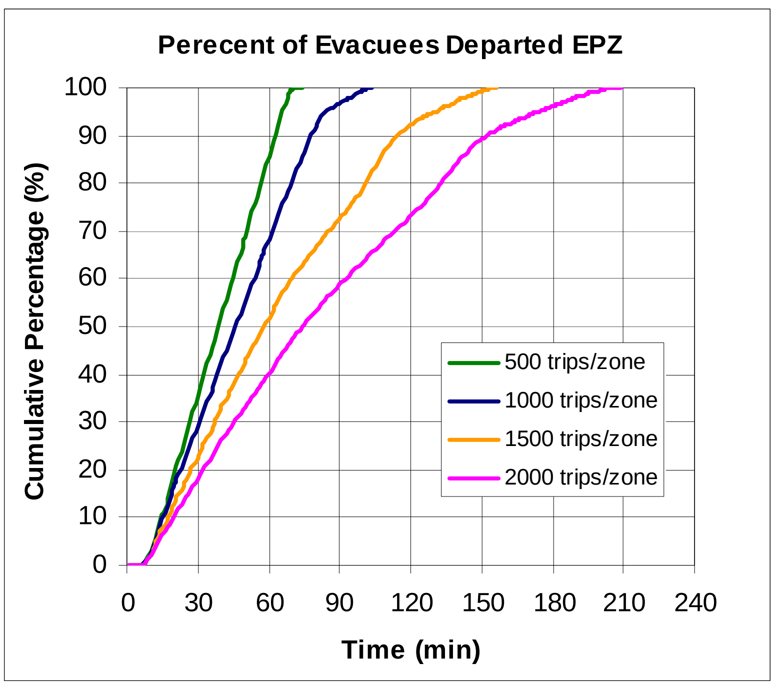
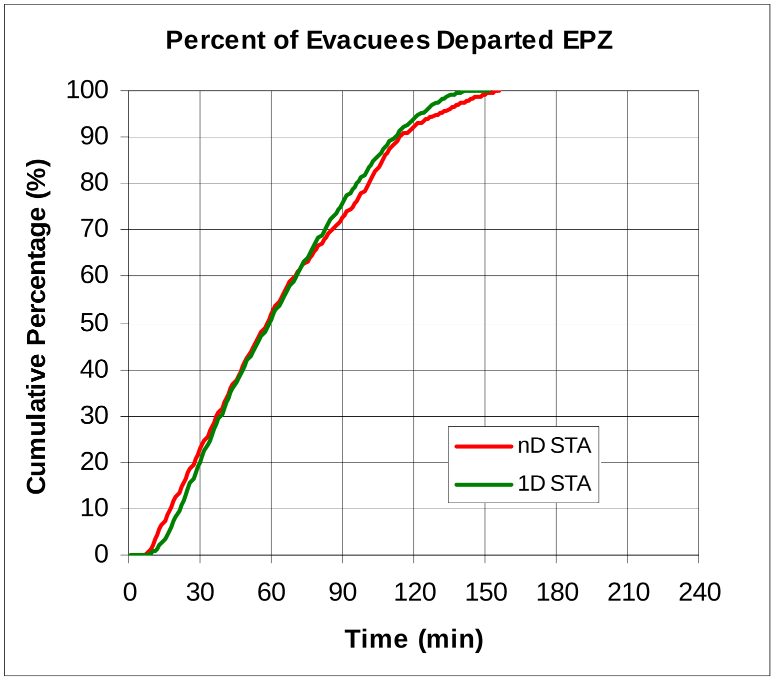


Figure 6.3 Evacuation Curves for Grid Network under Different Demands

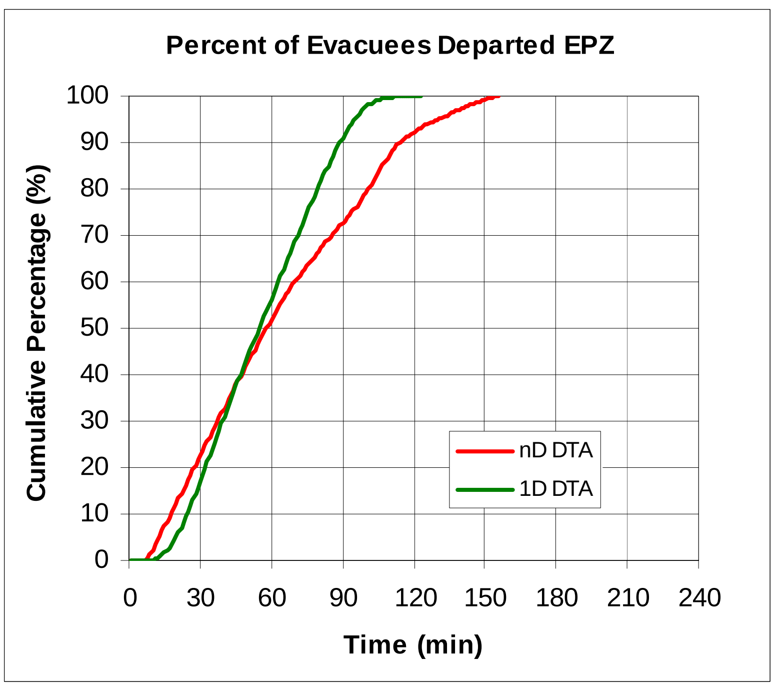
After examining the evacuation times under different demands, an evacuation demand of 1500 vehicle trips per zone was selected as the basis for further simulations. At this demand level, a large part of the evacuation road network would experience congestion, and more efficient traffic operations and optimization would therefore be required in order to reduce delay and total evacuation time. A total of 54,000 evacuation trips would be simulated, with a uniform or non-uniform distribution within the origin zones, to compare the effectiveness of the *1D* and *nD* networks.

6.2.1 Uniform Demand Distribution

First, it was assumed that the evacuees were uniformly distributed within the origin zones at an amount of 1500 vehicle trips per zone and also that the evacuees were loaded in a uniform fashion during the first hour of the simulation. Evacuation curves for the *nD* and *1D* networks were plotted and compared (see Figure 6.4), using STA and DTA respectively. When using DTA, 10 iterations of simulation and assignment were conducted until a stable and converged result was obtained with a small variation in evacuation times from iteration to iteration. The statistics in terms of the time required to evacuate 25, 50, 75, and 95% of the entire population are compared in Table 6.1, and the network clearance time is also listed for reference purposes.



(a) Static Traffic Assignment



(b) Dynamic Traffic Assignment

Figure 6.4 Evacuation Curves for Grid Network with Uniform Demand Distribution

Table 6.1 Evacuation Times for Grid Network with Uniform Demand Distribution

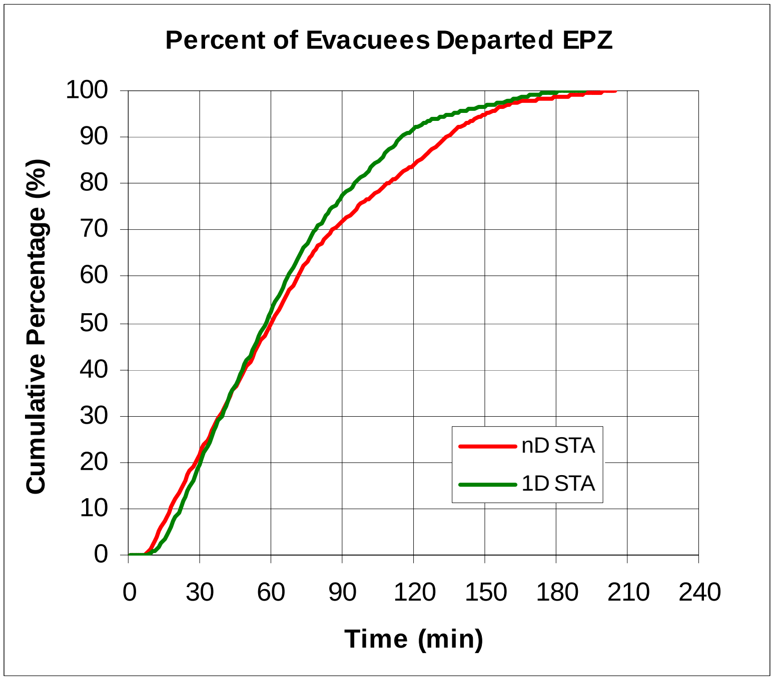
Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
nD STA	33	59	94	131	156
1D STA	35	60	89	123	152
nD DTA	33	58	93	131	156
1D DTA	36	55	76	96	123

Using STA the overall difference in evacuation times between the *1D* and *nD* model is trivial. The evacuation curves of the *1D* and *nD* models basically mach up until 90% of the population was evacuated. The *1D* model only presents a slight improvement at the late stage of the evacuation: the time required to evacuate 95% of the population was reduced by 6%, or 8 minutes, compared to the *nD* model. This limited improvement may be related to this particular network and demand setup. When the evacuee demand was uniformly distributed over a symmetric grid network, in something more like a homogeneous condition, there was probably not much room for optimization in terms of destination or route choice. Although different desired speeds were assigned to different links, that was unlikely to make much difference statistically in the average speed (travel time) on different travel directions and paths. Using STA, therefore, the destination and route assignment in the *1D* model tend to be similar to that in the *nD* model.

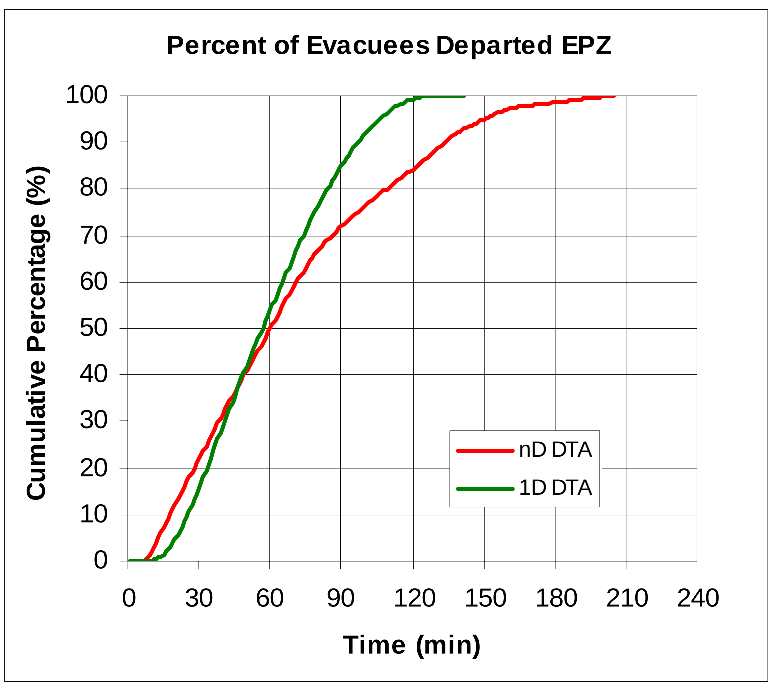
Using DTA, the *1D* model presents substantial improvement over the *nD* model: the time required to evacuate 95% of the population was reduced by 27%, or 35 minutes, compared to the *nD* model. The *1D* model also enjoys a substantial reduction in the total travel time and overall time-based exposure, as discussed in Chapter 3. In fact, even with the implementation of DTA, which is supposed to find the best routes for evacuees by taking into consideration of changing traffic conditions, efficiency was not improved for the *nD* network but was significantly improved for the *1D* network. For the *nD* network, with more destinations defined at the network boundary and accordingly more restrictions imposed on route choice, the traffic tends to be assigned to limited routes within a limited area of the network (Wang, H. 2002). Hence, the fixed OD table can be quite inefficient, and even with DTA it is unlikely to find new and more efficient routes. However, for the *1D* network, with its flexibility that affords evacuees the option to head for other destinations, there is much more room for route optimization. By implementing DTA in the *1D* framework, more efficient routes can be found, and the traffic will tend to be distributed to a wider area of the network, maximizing the network usage.

6.2.2 Non-Uniform Demand Distribution

The effectiveness of the *1D* and *nD* networks was then compared under a non-uniform demand distribution. Dividing the grids by a vertical line across the center of the grid network, 2000 vehicle trips per zone were assumed for the left-hand-side origin zones, and 1000 vehicle trips per zone were assumed for the right-hand-side zones. All evacuees were uniformly loaded during the first hour of the simulation. The evacuation curves are plotted in Figure 6.5, and the evacuation times are compared in Table 6.2.



(a) Static Traffic Assignment



(b) Dynamic Traffic Assignment

Figure 6.5 Evacuation Curves for Grid Network with Non-Uniform Demand Distribution

Table 6.2 Evacuation Times for Grid Network with Non-Uniform Demand Distribution

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
nD STA	34	61	97	151	205
1D STA	35	58	87	137	192
nD DTA	34	61	96	150	205
1D DTA	38	57	79	107	141

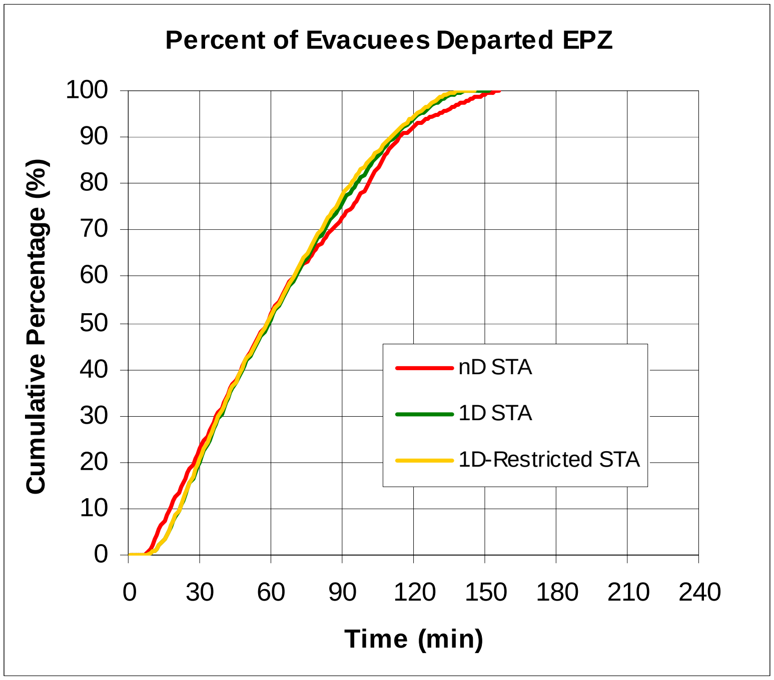
When evacuation demand was non-uniformly distributed on the grid network, the improvement resulting from the *1D* formulation is more pronounced compared to the case with uniform demand distribution. Using STA, the two evacuation curves match until 50% of the population was evacuated, but the *1D* model was more efficient at the late stage: the time required to evacuate 95% of the population was reduced by 9% or 14 minutes, compared to the *nD* model. Even using the DTA, the efficiency was not improved for the *nD* network, but substantially improved for the *1D* network. The *1D* model exhibits a time savings of 29% or 43 minutes in evacuating 95% of the evacuees.

Therefore, the *1D* model has been shown to provide different benefits at different sites and scenarios, including this hypothetical network with simple topology and demand. Generally, one could conclude that for more complex network and demand conditions (e.g. large network, irregular topology, and non-uniform demand distribution) there would be even more benefits from the flexibility provided in the *1D* model. In contrast, without this flexibility, the conventional *nD* model would not gain much efficiency even when afforded with sophisticated routing schemes (e.g. DTA) because of the fixed but less-than-optimal destination assignment at the outset. Therefore, the *1D* formulation is a more efficient method to optimize network flow patterns and reduce evacuation time in complex real-world situations.

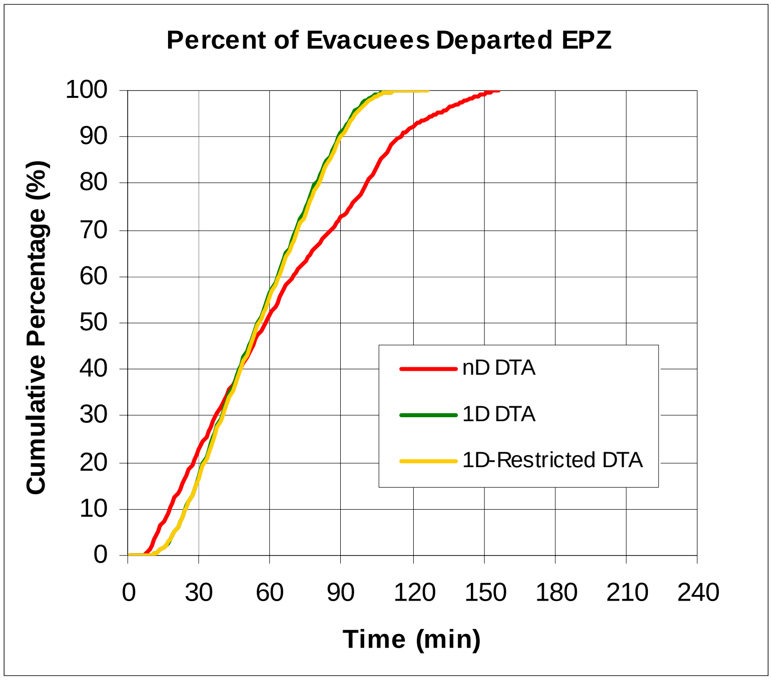
6.2.3 Link Restrictions

As mentioned in Chapter 4, there are route and destination preferences that need to be considered and properly modeled when applying the *1D* formulation. For instance, due to safety concerns, evacuees should not travel through the emergency source and then journey outwards to gain safety. Evacuees must be steered away from any link across the source, but this restriction may be violated in the traffic assignment process on the *1D* network. Detectors were placed on four links that lead toward the source to measure the number of violations. For the *1D* network with uniform demand distribution, it was found that 1,962 vehicles (3.6%) were assigned to travel across the source using STA, and that 3,297 vehicles (6.1%) were assigned to travel across the source using DTA.

As discussed in Chapter 4, this violation may be eliminated by adding a very high cost to those high-risk links in order to influence/bias the traffic assignment results. This strategy was also tested in this Chapter. Assuming a uniform demand distribution, the evacuation curves for the *1D* network with link restrictions are compared with those for the *1D* and *nD* networks without link restriction, using STA and DTA respectively, as in Figure 6.6. The resultant evacuation times are summarized in Table 6.3.



(a) Static Traffic Assignment



(b) Dynamic Traffic Assignment

Figure 6.6 Evacuation Curves for Grid Network with Link Restrictions

Table 6.3 Evacuation Times for Grid Network with Link Restrictions

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
1D STA	35	60	89	123	152
1D-Restricted STA	34	59	87	122	146
1D DTA	36	55	76	96	123
1D-Restricted DTA	36	56	77	97	126

According to Figure 6.6, it is clear that the performance of the *1D* model was not impacted by the link restrictions, but that the route assignment became more reliable in terms of safety. No vehicles were assigned to travel across the emergency source.

6.2.4 Improved OD Table

As demonstrated in Chapter 5, the *1D* assignment results can be used to formulate a new *nD*-based OD table for the study area; this new table should outperform the conventional planning OD table based on the proximity-based destination assignment. Based on the network exit taken by most evacuees from the same origin zone in the *1D* network, the destination assignment can be refined, and the destination zones may also be redefined for the *nD* network. Using STA, simulations analyses were applied to evaluate the efficiency of the OD table determined from the *1D* optimization with link restrictions. For the grid network with uniform demand distribution, the resulting evacuation curve is plotted in Figure 6.7, and the evacuation times are compared in Table 6.4.

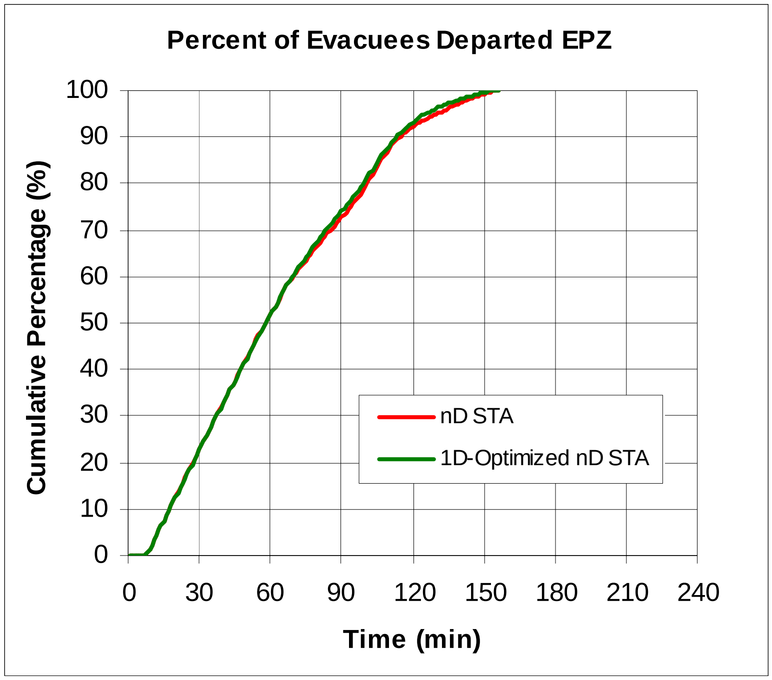


Figure 6.7 Evacuation Curves for Grid Network with Improved OD Table

Table 6.4 Evacuation Times for Grid Network with Improved OD Table

Scenario	Percent Evacuated				
	25%	50%	75%	95%	100%
	Evacuation Times in Minutes				
1D STA	33	59	94	131	156
1D-Optimized nD STA	33	59	93	126	155

As shown in Figure 6.7 and Table 6.4, the improvement is trivial based on the *1D*-optimized *nD* OD table. The evacuation curves based on two different OD tables almost match, and the time required to evacuate 95% of the population was reduced by 4% or 5 minutes after modification of the destination assignment. In fact, when comparing these two OD tables, it shows that only two origin zones were assigned to different destinations zones. The impact of such a small change is very limited. When more complex network and demand conditions are involved, it becomes more difficult to decide the optimal destination assignment, and the *1D* assignment results would then be more beneficial for the planning purposes, as indicated in Chapter 5 in real-world applications.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

A framework for the simultaneous optimization of evacuation traffic distribution and assignment is proposed in this study. Based on the concept of ODE, the optimal destination and route assignment can be obtained by solving a one-destination traffic assignment problem on a modified network representation. To demonstrate the feasibility and benefits of the proposed *1D* model for improving evacuation efficiency and to showcase its applicability, case studies of real-world evacuation operations at different locales were conducted using two widely used traffic simulation and assignment packages, VISSIM and DYNAMSART_P. Different scenarios representing various destination and route assignment strategies were investigated, and the evacuation efficiency based on the proposed *1D* model was measured and evaluated against the conventional *nD* model. To guide the optimization process and evaluate its benefits, a four-tier framework of MOEs is also proposed to take into consideration, in a comprehensive fashion, evacuation time, cumulative exposure, and risk factors.

Through simulation analyses, the *1D* model has been shown to provide different benefits at different sites and in different scenarios. For two real-world cases/sites, the proposed *1D* model presents substantial improvement over the conventional *nD* model for both planning and operational purposes. For instance, for a regional evacuation due to a nuclear power plant mishap, an up to 60% reduction in the overall evacuation time can be achieved by using the *1D* formulation with DTA, and the *1D* optimization results can also be used to improve the planning OD table, resulting in an up to 16% reduction in the overall evacuation time; for a county-wide special-event evacuation, a nearly 80% reduction in the overall evacuation can be achieved when modeling of traffic routing with en route information in the *1D* framework, and the planning OD tables can also be improved based on the *1D* assignment results, with a nearly 60% reduction in the overall evacuation time. For a hypothetical case, evacuation from a point-source threat on a grid network, the improvement by the *1D* optimization appears to relate to the complexity of the network and demand conditions, but overall the *1D* model outperforms the *nD* model by reducing the overall evacuation time up to 30%. In contrast, the *nD* model based on a fixed OD table can be quite inefficient and would not gain much efficiency even if provided with sophisticated routing schemes using DTA. All these results demonstrate that the *1D* modeling strategy is an efficient method for optimizing network flow patterns and reducing evacuation time by providing flexibility in destination selection and, consequently, route selection.

The *1D* results obtained in this study are not only superior on paper but are also valuable to the current practices of evacuation planning and operations. Ultimately, the *1D* model can be implemented in real time by taking advantage of the ITS infrastructure in the EPZ. An astonishing time saving, up to 80% for a large network, could be achieved at evacuation operations by employing dynamic traffic routing and destination reassignment in the *1D* framework. Though real-world constraints might make this optimal strategy rather challenging to realize, the results could still provide valuable insights for improving the evacuation efficiency. The short evacuation time serves as a “lower bound” that current evacuation plans and operational strategies can be measured against and should strive to achieve. Even at the planning level, the *1D* model provides a tool for greatly enhancing existing evacuation plans. The *1D* framework can actually be implemented without real-time en route information, and its efficiency enhancement can be realized simply by instructing evacuees to head for destinations that have been determined to be more or most efficient based on the results from the *1D* optimization performed beforehand.

In this study, the *1D* modeling strategy was implemented and tested via a simulation approach using two different traffic simulation and assignment models, and both STA and DTA were employed as different optimization methods in order to improve the evacuation destination and route assignment, satisfying different needs during both evacuation planning and operations. However, the applicability of the *1D* model is not limited to any particular software, assignment method, or infrastructure (e.g. availability of ITS in the EPZ). A wide range of analytical methods or simulation tools can be adapted to formulate and solve the *1D* optimization problem and improve evacuation efficiency to some extent. When implemented via simulation, solving a *1D* assignment problem appeared to be very efficient in terms of solution time and convergence. For instance, the *1D* optimization did not require a longer computational time for a large network in the Knoxville case compared to the conventional *nD* formulation. For the Sequoyah network and grid network modeled by VISSIM, the *1D* formulation only presents slight increases in computational time and memory usage, due to the software constraints, since all simulated vehicles would remain on the network and travel for additional distances until they reached the dummy destination. Therefore, besides the theoretical advantages of the *1D* formulation, the *1D* method is also easy and efficient for implementation in real-world situations, with a great potential for improving evacuation efficiency for both planning and operational purposes.

7.2 Recommendations for Future Research

In this study, the *1D* model was implemented via simulations, but these analytical methods (Lam and Huang, 1995; Ziliaskopoulos, 2000) can also be applied to solve the *1D* optimization problem, and therefore are worthwhile investigating in future research. Theoretically, analytical approaches to the traffic assignment problem have a better-defined solution algorithm and better solution properties. Also, the *1D* setup makes it easier to formulate, especially for the DTA problem, as some difficulties in DTA formulation from a mathematical programming standpoint, such as the FIFO requirements, are easily satisfied in the *1D* formulation. In the future research, mathematical formulation of the *1D* optimization problem and efficient solution algorithms need to be identified and evaluated, including efficient best-path searching algorithms, especially for real-time implementation purposes.

According to the MOE and optimization formulation as defined upon evacuation curve, as discussed in Chapter 3, in order to minimize the total travel time, formulating and solving the *1D* optimization problem as a system-optimal traffic assignment problem would be more appropriate and effective. Due to software and hardware constraints, the traffic assignment procedure employed in this study was essentially based on the user-optimal formulation. Therefore, in future research, it would be worthwhile to implement and test the system optimal static or dynamic traffic assignment in the *1D* framework in order to fully reveal the benefits of the *1D* model for improving evacuation efficiency.

As mentioned in Chapter 4, in the course of implementing the *1D* formulation in real-world situations, some preferences in destination and route selection need to be considered and properly modeled. One potential solution is to represent these preferences as additional costs in link cost function for some critical links such as the dummy links connected with real-world destinations (for the destination preference) and the high-risk links to steer evacuees away from (for the route preference). This method was only tested for modeling of the route preferences (restrictions) away from the links across the hazard, and the results appear to be effective on the grid network. Other preferential treatments in destination and route assignment need to be examined in future research. As was also discussed in Chapter 4, two hybrid network configurations could be considered, beyond the *1D* setup, in order to improve the efficiency of the *1D* optimization in real-world applications. It will be worthwhile to test and evaluate these hybrid network configurations in future research.

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VITA

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