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Heuristic Prioritization Of Emergency Evacuation Staging To Reduce Clearance Time

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HEURISTIC PRIORITIZATION OF EMERGENCY EVACUATION STAGING TO REDUCE CLEARANCE TIME

by

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ABSTRACT

A region's evacuation strategy encompasses a variety of areas and needs. Primary among these is the minimization of total evacuation time, represented in models as the clearance time estimate (CTE).

A generic testbed simulation network model was developed. An input/output (I/O) analysis was performed to establish a theoretical baseline CTE. Results were compared with simulations; analysis showed that the I/O method underestimated simulated CTE as a function of network size, with a correction factor range of 1.09 to 1.19.

A regression model was developed for the generic network. Predictors were total trips, and network size defined as a function of origin-destination distance. *Total Trips* ranged between 40,000 and 60,000. Holding size constant, R-squared values ranged from 97.1 to 99.3, indicating a high goodness of fit. Holding *Total Trips* constant, R-squared values ranged from 74.5 to 89.2. Finally, both *Total Trips* and size were used as predictors; the resulting regression model had an R-squared value of 97.3. This overall model is more useful, since real world situations are not fixed in nature.

The overall regression model was compared to a case network. The generic network regression model provided a close CTE approximation; deltas ranged from -4.7% to 8.6%. It was concluded that a generic network can serve as a surrogate for a case network over these ranges.

This study developed and evaluated heuristic strategies for evacuation using the generic network. Strategies were compared with a simultaneous departure loading scenario. Six different grouping strategies were evaluated. An initial evaluation was conducted using the generic network, and strategies that showed potential CTE reduction were implemented on the case study network. Analysis indicated that the HF-10 (half-far) grouping for 60k total trips showed potential reduction.

A complete simulation was conducted on the case network for all HF scenarios; an ANOVA was run using Dunnett's comparison. Results indicated that the HF grouping with 20% and 30% departure shifts showed potential for CTE reduction. From this it was concluded that the generic network could be used as a testbed for strategies that would show success on a case network.

A PhD is a collective endeavor, requiring the help and support of many people. This dissertation is dedicated first and foremost to my mother, who unfortunately was not around to see me graduate, and to my father, who together started me on this path so long ago, and are probably wondering when I will stop going to school – never. It is also dedicated to my wife Leslee, who allowed me to be a student when she didn’t have to. And her mom would have wanted her to marry a doctor.

ACKNOWLEDGMENTS

Huge thanks go out to my dissertation committee, and to those professors who have taught me much about finding the answers to questions I hadn’t yet thought to ask. Specifically I would like to thank Dr. Essam Radwan, Dr. Mansooreh Molloghasemi, Dr. Jose Sepulveda, Dr. Roger Wayson, and Dr. Abdel-Aty. I would also like to acknowledge Celia Williams, who started me on the “road” to studying transportation late one second shift.

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LIST OF ACRONYMS

CBD	Central Business District
CLEAR	Calculates Logical Evacuation And Response
CSEPP	Chemical Stockpile Emergency Preparedness Program
CTE	Clearance Time Estimate
DTA	Dynamic Traffic Assignment
DYMOD	Dynamic Model
DYNEV	Dynamic Network Evacuation Model
EPZ	Emergency Planning Zone
ETDFS	Evacuation Travel Demand Forecasting System
FEMA	Federal Emergency Management Agency
I/O	Input/Output
IDYNEV	Interactive Dynamic Network Evacuation Model
IRZ	Immediate Response Zone
ITS	Intelligent Transportation Systems
KPH	Kilometers Per Hour
MPH	Miles Per Hour
NRC	Nuclear Regulatory Commission
OD	Origin-Destination
OET	Office of Emergency Transportation
OREMS	Oak Ridge Evacuation Modeling System
PAZ	Protective Action Zone
PC	Personal Computer
PZ	Precautionary Zone
TAZ	Traffic Analysis Zone
TEDSS	Transportation Evacuation Decision Support System
USACE	US Army Corps of Engineers

INTRODUCTION

Communities throughout the world today face tremendous risks from many hazardous events, both natural and man-made. The range and scale of these types of events are wide, encompassing everything from hurricanes and forest fires to nuclear releases and chemical spills. At-risk populations can vary as well, both in numbers and demographics. Small scale events, such as hazardous spills along a freeway, may impact only a few motorists and businesses in the near vicinity. Larger scale disasters, such as hurricanes, can impact large rural and urban areas, affecting thousands or millions of people in the estimated area of effect.

These events typically necessitate the evacuation of local or regional populations to safe destinations or shelters, and have warning times ranging from minutes to many hours. Some events are predictable in either location or potential impacts; others are quite random and can vary in size and duration. For example, communities in close proximity to a nuclear power plant face a known and understood risk. Failure modes are documented, warning times are calculable, and the results of these failures have recognized boundaries and impacts. In the other extreme are transportation-related incidents such as freeway accidents and train derailments involving hazardous materials. The size and scope of these events are somewhat predictable, but the timing, location, and warning times are highly variable.

Underlying the mechanics of emergency evacuation is the regional transportation network. Transportation agencies face ever-increasing concerns regarding traffic and congestion. More lane miles, signalization, Intelligent Transportation Systems (ITS), and implementation of mass transit systems are all tools available to reduce recurring and non-recurring congestion problems.

The measures taken to address day-to-day recurring congestion, however, do not allow for the potential need for local and regional agencies when faced with the need to relocate large segments of a regional population in response to various emergency situations, such as hurricanes or chemical spills. Many roadways are overburdened as it is; a factor increase in traffic levels only creates more serious traffic situations.

Agencies today are familiar with the needs and techniques for addressing traffic incidents, as well as the impacts of such events, and many have plans in place to manage both the clearing of and the potential detour of traffic around the incident. These plans provide a handbook of procedures in response to previously identified emergency conditions, enabling emergency management personnel to focus on moving people to safety rather than having to develop strategies real-time, with potentially harmful results. Interjurisdictional coordination, public-private cooperation, and integrated communications all contribute to the implementation of such plans. However, in many cases these plans are inadequate to larger scale management operations, such as those required during disaster events. Consequently, many emergency management agencies, specifically transportation agencies, and particularly those with jurisdiction over high-risk areas, spend great amounts of time and effort in developing emergency response plans to guide evacuation in the event of disaster.

While state agencies have no control over the size and impact of an evacuation event, they can to certain extents control the two factors that determine congestion levels, and consequently total clearing time – supply and demand.

Control of supply entails both short-term and long-term solutions. Increased lane miles, advanced transportation management systems, and upgraded facilities are all examples of long-term solutions, and represent significant capital expenditures that may not be feasible or reasonable. Furthermore, these types of solutions do not provide immediate impact in the event of an evacuation, at least not until they are in place.

Making more effective use of existing supply through short-term solutions can be highly cost effective, and provide immediate benefits. Examples that are receiving more attention include contraflow lanes, signal retiming, and implementation of various ITS solutions such as video surveillance and dynamic message signs. Mobile resources can be quickly deployed to provide information to traffic agencies, allowing agency personnel to better control supply.

On the demand side, the critical point is controlling the number of vehicles and their departure times regarding use of the road network. Agencies have available to them a number of options, including use of existing transit resources in lieu of individual vehicles. This option is limited, however, in that many areas do not have sufficient transit vehicles in place to provide the reduction in traffic volume necessary to achieve network-wide congestion relief. A second option that is significantly easier and more cost effective to implement is the scheduling or staging of regions for evacuation. Proper coordination of vehicle departure, through the use of all available communications media, can potentially provide for more efficient use of existing facilities, reducing congestion and improving overall clearance time. Often evacuation plans are advisory and voluntary in nature, though even when plans require evacuation, enforcement of these plans continues to be a challenge.

A region's evacuation strategy encompasses a variety of areas and needs, many of these interdependent and interrelated. Primary among these is the minimization of total evacuation time, often represented in models as the *clearance time estimate* (CTE) (Church and Sexton 2002). This measure provides an indication of how long it will take to clear an identified population from a specific region.

RESEARCH OBJECTIVE

Emergency management personnel have many decisions to make regarding the best methods and actions to take to evacuate at-risk populations in an effective and timely manner. The primary objective of this dissertation is to develop improved strategies for coordinating and scheduling of local and regional populations to reduce clearance times in the event of an evacuation situation. In addition, these improved strategies will be evaluated using a real-life case study network, to determine the potential viability of the identified strategies, or conditions under which they may be most effective. Finally, given the involved and time-consuming nature of developing traffic simulation models, this dissertation will evaluate the use of a generic traffic model as a surrogate for a real-life network.

LITERATURE REVIEW

A variety of research has been done regarding emergency evacuation and the various aspects of moving populations to safe areas. This research covers a variety of aspects of the evacuation event, from types of hazard to evacuee behavior to modeling strategies.

An evacuation event creates a unique situation for traditional traffic simulation models. Traffic volumes vary over time, but also change in conjunction with the evacuation event. Loading will be at heightened levels for the duration of the emergency as residents relocate to safe areas, and subsequently return home once the situation is over. Time of day also influences origin and destination; daytime events find higher population densities in business districts, whereas most people are at home during evening and nighttime events. Current traffic simulation models can require significant modifications to model evacuation situations; this can include changes in model operation, adjustments to assumptions and network parameters, and input changes both prior to and during an evacuation simulation.

Evacuation Components

Review of existing literature indicates that for the purposes of this project the concept of evacuation can be broken down into three specific components: behavior, hazards, and decision support policies. In addition, there is an infrastructure component, or consideration of the underlying transportation network, that supports evacuation events. In conjunction with this infrastructure component is the aspect of computer modeling and simulation, and the tools and techniques available to test and evaluate various evacuation strategies in an efficient and cost-effective manner.

Behavior

Emergency events requiring evacuation can be terrifying experiences, causing a range of emotions and reactions from confusion to total panic. People's reactions vary depending on many different factors such as age, gender, and socioeconomic conditions. This varied reaction can influence the departure timing and loading levels of evacuation during an emergency event. This in turn impacts the design and implementation of policies and procedures for effective evacuation.

Age plays a significant role in the efforts to evacuate a population. The elderly are typically more vulnerable. According to Ngo (2001), "*certain attributes of the elderly population in the research were readily observed as being strong contributors to increased differential vulnerability. Foremost was increasing chronological age, mostly because increasing age above 65 years represented a growing constellation of significant risk factors, such as predisaster health and socioeconomic status.*"

The author further found that some patterns regarding the elderly did emerge. It describes five relationships that help to understand the disparities between elderly and nonelderly.

- Actual Loss versus Relative Need – Losses experienced by the elderly, while similar in level to the nonelderly, are relatively greater because elderly typically have fewer resources available to them to replace those losses.

- Perception of Loss – Those who suffer physical harm perceive their losses to be greater, and the elderly suffer disproportionate harm relative to the nonelderly.

- Service Stigma and Threats to Independence – The elderly view various means of assistance differently, perceiving some resources as welfare. Consequently they feel that to accept these services reveals a loss of independence.

- Psychological Vulnerability – The elderly find themselves in situations that place them a risk of greater psychological vulnerability. Some characteristics include living alone, fewer friends or smaller social circles, and (as mentioned earlier) fewer resources.

- Morbidity and Mortality – There is a fairly consistent relationship between increasing age and higher rates of morbidity and mortality. Disasters with shorter warning times seemed to result in the greatest "differential vulnerability."

Gender is also a factor in levels of evacuation. According to Bateman and Edwards (2002), "*Results from a series of bivariate and multivariate logistic regression analyses indicate that women are more likely to evacuate than men because of socially constructed gender differences in care-giving roles, access to evacuation incentives, exposure to risk, and perceived risk.*"

Past experience can also play an important role in people's decisions on when or whether to evacuate. Newcomers to an area may perhaps be more likely to leave when told to, given their expectations, or perhaps lack thereof, of the potential for injury. Long-time residents, on the other hand, may have been through a number of previous evacuation incidents, and may look upon future warnings with a touch of the “cry wolf” syndrome; i.e. they have yet to experience damage or injury, and so have reduced expectations. “When Hurricane Andrew approached Florida, previous experience with disasters influenced one elderly widow’s decision to not evacuate. She reasoned, ‘I figured we’d be okay. I’ve lived with storms all my life. There’s nothing you can do about them, so why worry.’”(Ngo 2001)

Despite the fact that human response to an emergency event can play an important role in determining the time necessary to evacuate, the number of studies that attempt to model this behavior is quite small. Fu (2004) provides a good overview of this work, and the author has developed a sequential logit model to attempt to simulate this behavior. Existing models are based on the concept of “loading curves.” These curves attempt to describe evacuee departure levels over time, and are typically “S” shaped in nature. Alsnih and Stopher (2004) have summarized the research on this, illustrating both a general model of evacuation behavior (Sorenson et al. 1987), as well as the response curves as illustrated in Figure 1 (Lewis 1985).

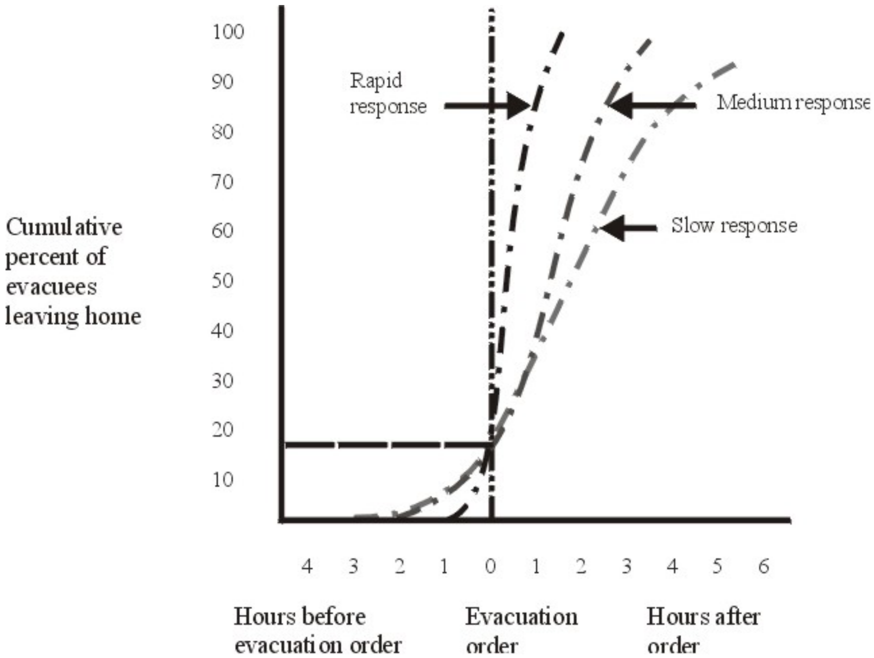

Figure 1 – Behavior Response Curves (© 1985 Institute of Transportation Engineers. Used by permission.)

Sattayhatewa (2000) has proposed two departure models for nuclear power plant evacuation, both fundamentally linear in nature. The goal of one model was to seek the shortest time to clear people from the origin, emphasizing departure time. The goal of the second model was to reduce system cost by penalizing arrival flows approaching their destinations. Later arrivals generate higher costs.

Hazards

In general, evacuation hazards fall into two categories – natural and man-made. Natural hazards include hurricanes, earthquakes, tsunamis, and forest fires, and are generally regional and region-specific in nature. For example, the threat of a hurricane is limited to coastal regions, and for the United States, the highest probability of occurrence is along the Gulf and Atlantic coasts. Forest fires, on the other hand, can occur virtually anywhere that conditions are favorable; for example, areas of Southern California recently experienced widespread forest fires. Figure 2 shows the widespread impact of these wildfires.

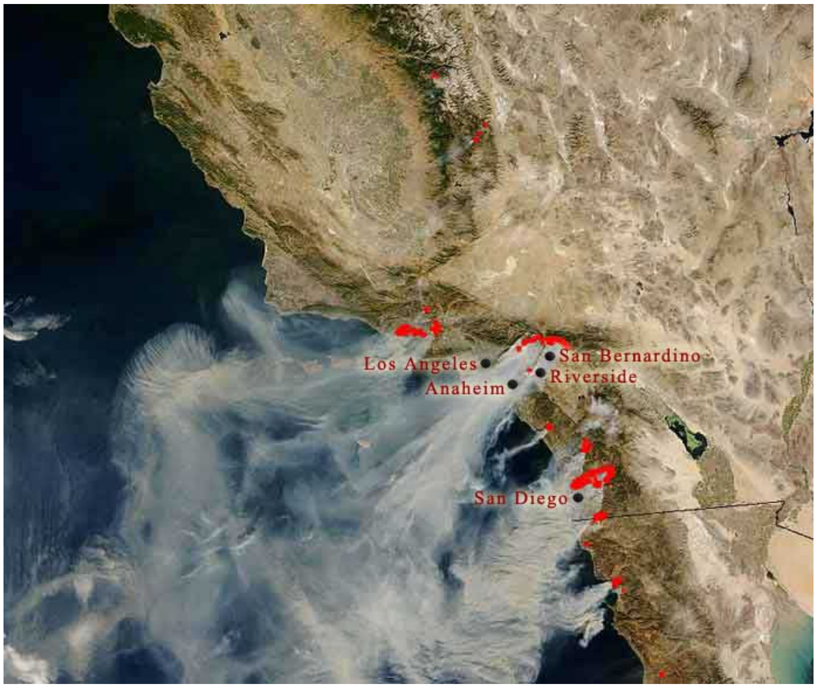

Figure 2 – Southern California Wildfires (Courtesy of NASA)

Florida is not immune to the potential for wildfire devastation. Since 1998, more than 15,000 Florida wildfires have devastated over one million acres and destroyed more than 750 structures.[1]

In contrast, earthquakes occur mostly in specific regions where the threat is well known, though the scale of the hazard can vary significantly. The San Andreas Fault, which

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[1] http://www.floridadisaster.org/hwaw/day5/wildfire.htm

extends through a substantial portion of California, is highly susceptible to fault shifts, generating earthquakes in the vicinity of the fault, and shockwaves that can be felt to a radius of many miles. While the threat of damage diminishes with distance, as does the need for evacuation, this does not absolve regions from taking preparatory steps.

Natural hazards are highly unpredictable, be it in location, duration, size, or advance warning time. Man-made disasters, on the other hand, are highly predictable in nature, particularly as regards location, duration, and size. Warning times, however, are typically short given the nature of their causes. Table 1 lists some recent natural hazards that required evacuation, and their locations.

Table 1 – Recent Evacuations

Site	Event	Comment
Southern California	Wildfires	A number of municipalities experienced wildfires and threats in the October 2003 timeframe.
Central Oregon	Wildfires	
Southwestern Colorado	Wildfires	Locations near Cortez and Durango experienced wildfires in summer of 2003.
South Carolina coast	Hurricane	In 1999, Hurricane Floyd caused what has been called the largest peacetime evacuation in US history (more than 700,000 people).[2]
New Orleans, LA	Hurricane	Hurricane Katrina
Houston, TX	Hurricane	Hurricane Rita
Cerro Grande, NM	Wildfires	Los Alamos / Bandelier National Monument
Fort Collins, CO	Flash Flood	City experienced a flash flood in July 1997
Kelowna, BC	Wildfires	Believed to be the largest evacuation in the shortest period of time in Canada's history. Nearly 20,000 residents were evacuated.[3]

Regions in the vicinity of nuclear power plants, chemical weapons storage locations, and major industrial facilities (oil and gas refineries, chemical production plants) are most at risk and most in need of preplanned evacuation procedures. Not all man-made hazards, however, have known locations. Each year thousands of tons of hazardous materials are transported along the nation's highways and rail networks, placing hundreds of thousands, possibly millions of people at risk in the event of a traffic accident or train derailment. According to the 1997 Commodity Flow Survey[4], almost 870 million tons of hazardous materials were transported along the nation's highways, and almost 97 million

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[2] http://www.govtech.net/magazine/story.print.php?id=8023

[3] http://forestry.about.com/b/a/021619.htm

[4] http://www.census.gov/econ/www/97tcf-hz.pdf, pg 9, Table 1

tons was carried by the nation's railroads. Based on average truck and rail trip lengths, this was equal to approximately 150 billion ton-miles, a substantial risk throughout the entire nation.

As can be seen, there are inherent differences between natural and man-made disasters. These differences must be taken into consideration when developing generic strategies for addressing emergency evacuation.

Decision Support Systems

While decision support policies are an important aspect of evacuation, their implementation varies from region to region, and from situation to situation. The necessary infrastructure may not always be present to institute some of the more effective policies. Therefore, decision support policies were not included as part of this investigation.

Evacuation Strategies

Order and timing of evacuation can have an impact on congestion levels that a road network will suffer during an emergency event. Many hazards have side effects that must be taken into account when developing evacuation plans. For example, storm surge is a leading effect of an approaching hurricane, and typically occurs within the few hours prior to storm landfall (Farahmand 1997). Low-lying areas along coastal regions are particularly susceptible to storm surge, as rising tides will flow inland farther than normal, flooding normally dry areas of land and creating impassable roads that may lie within the susceptible regions.

Similarly, wildfires can create severe disruptions in evacuation routes. Smoke and fire can result in the reduction in capacity or complete closure of critical road links that provide evacuee access to shelters or other safe destinations (Keller 2002).

Church and Sexton (2002) examined a method of estimating risks to such areas by estimating the time it would take to clear a neighborhood in the event of an evacuation. This risk estimate is embodied in the CTE, and simple formulae have been proposed that base this value upon a determination of bulk lane demand, or the total vehicles leaving an area compared to the available number of egress lanes. CTE values were derived from a simulation for 100% vehicle departures from the designated evacuation area.

Chen (2004) investigated the effectiveness of simultaneous versus staged evacuation strategies as applied to a number of road network configurations. The paper compared the effectiveness of each strategy by measuring the total time needed to evacuate. This time value is calculated from the simulation.

Church and Cova (2000) proposed a “critical cluster model” to identify small areas that have high population to exit capacity values, analogous to the CTE defined above. They use this value to classify the degree of evacuation difficulty, and then apply the model numerous times across the network to map evacuation vulnerability.

One additional evacuation strategy is contraflow operation. Under contraflow, some or all inbound lanes of a freeway are used for outbound evacuation. This strategy has many advantages and disadvantages; for example, an increase in capacity at the expense of more complex and resource-intense implementation (Wolshon 2001). It has been demonstrated that reversal of two inbound lanes of a four lane freeway can increase capacity by 70%, and single lane strategies have shown a capacity increase of 30% (Wolshon 2005).

Computer Simulation

With the advancements in computer hardware and software, computers are finding greater application in traffic modeling and simulation. Early developments in evacuation modeling include CLEAR (Calculates Logical Evacuation And Response) (Moeller et al. 1981) in 1980. The CLEAR model was developed in response to the Three Mile Island incident, at which point the US Nuclear Regulatory Commission (NRC) increased the radius for determining evacuation time estimates. Existing models were not up to the task, and so a more generic model was needed.

Nuclear plants are typically located in low density rural regions, with correspondingly low evacuation requirements. Urban areas, however, are also subject to emergency events, with greater evacuation network loading levels. In response to those realizations the MASSVAC evacuation model was developed by Hobeika (1985). This model evaluated evacuation plans through the calculation of highway clearance times.

This model was applied in the development of TEDSS (Transportation Evacuation Decision Support System) (Hobeika 1987), and specifically targeted nuclear power plant evacuation.

Traffic Simulation

Currently there are a number of traffic simulation packages that function on standalone personal computers (PC) and have established capabilities for conducting large-scale network evacuation modeling. A number of these packages are proprietary and in general developed especially for evacuation modeling. According to a recent study conducted by the Office of Emergency Transportation (OET) (Luo et al. 2002), there are three packages specific to evacuation; these are DYNEV (Dynamic Network Evacuation Model, KLD Associate 1979), OREMS (Oak Ridge Evacuation Modeling System, ORNL 1998), and ETDFS (Evacuation Travel Demand Forecasting System, PBS&J 1999). The ETDFS forms the basis for Florida's HEADSUP system.

Franzese and Han (2000) have implemented the OREMS model to analyze and evaluate the implications of large-scale evacuations. OREMS is an advancement over the original DYMOD (Dynamic Model) mass evacuation planning model developed during the late 1980s (Southworth et al. 1991). Application of OREMS requires the delineation of Emergency Planning Zones (EPZ), or a determination of the area at risk, and was used by Perkins in modeling transit issues during evacuation in North Carolina (Perkins 2001).

DYNEV, and its current incarnation IDYNEV (Interactive DYNEV), was originally developed for the Federal Emergency Management Agency (FEMA) for use in development of evacuation plans around nuclear power plants (Luo et al. 2002). It has since been enhanced to enable hurricane evacuation planning.

Further investigation into these packages indicated that they would not be made available or would be but on a limited basis. Therefore no further consideration was given to their possible use and other packages were considered for use in this project. Primary considerations included availability, flexibility, power and previous experience.

Beyond these evacuation-specific packages are the standard traffic simulation models. These models are more generic and more flexible in nature, developed to enable modeling any number of traffic or transportation situations.

Boxill and Yu (2000) conducted an evaluation of a number of traffic models to support ITS development. The objective of this report was to "*evaluate traffic simulation models to determine their suitability as an evaluation tool in the framework of ITS benefits assessments*." The study examined 65 microscopic, three mesoscopic and sixteen macroscopic traffic models. The study narrowed the field to nine models and evaluated them in more depth. The ability to address ITS in evacuation is important; information and management systems play key roles in managing traffic, particularly during high-volume evacuations.

This report concluded that CORSIM and INTEGRATION are currently the best suited to modeling ITS and traffic. Regarding these two packages the report states:

> CORSIM: This model appears to be the leading model for testing most of the scenarios involving alternative geometric configurations (weaving, merging, diverging), incident and work zone impacts, and various ramp metering options. It also appears to be the leading model for testing scenarios involving intersection design, signal coordination options, and transit modeling for exclusive lanes or mixed in traffic. CORSIM can assess advanced traffic control scenarios in which the route is fixed (adaptive traffic signal control on arterials, and traffic responsive ramp metering without diversion). Figure 3 shows an example screen shot of the CORSIM software package.

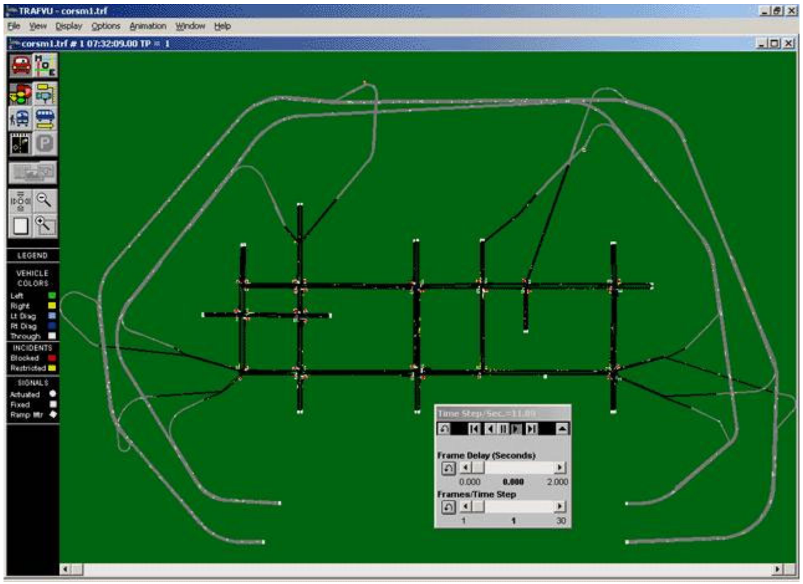

Figure 3 – CORSIM Screen Shot

> INTEGRATION: This model appears to be the leading model for evaluating ITS scenarios along corridors that involve effects of real-time route guidance systems, or changes in traffic patterns as a result of

freeway ramp metering options. Several studies have been documented that demonstrate most of the model features. Figure 4 shows an example screen shot of the INTEGRATION software package.

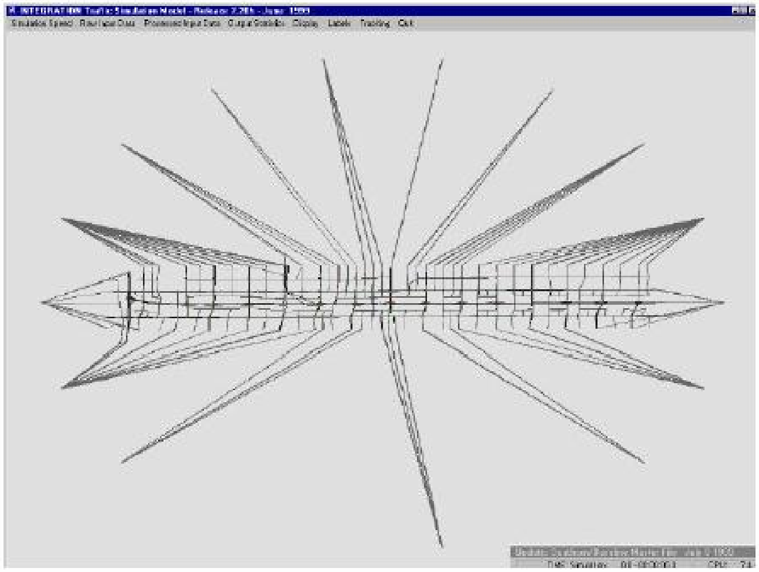

Figure 4 – Integration Screen Shot (courtesy of Virginia Tech)

In addition, three other packages were potentially viable for this project: PARAMICS, WATSIM, and VISSIM. Each of these provides a microscopic level of traffic modeling, though do not implicitly include the capabilities for modeling ITS. This, however, does not necessarily eliminate them from consideration.

Dynasmart-P was also considered for this project; however, it was in beta test at the time and so not generally available to the public. Therefore it was not included in subsequent decision-making evaluations.

Discrete Simulation

Simulation models can be classified as discrete, continuous or mixed continuous-discrete simulation models. In a discrete simulation model, the state of the system under consideration changes at discrete points in time by events such as a highway traffic system with possible events including vehicles entering into or leaving out of a particular road segment, traffic lights changing into red, yellow, and green, an occurrence of a traffic accident, etc., at some discrete point in time which in turn change some system state variables such as the number of vehicles along a road segment waiting for the lights to pass, number of vehicles traveling along the road segment or accumulated due to a blocking. In a continuous model, system state change occurs continuously such as level of a dam reservoir as water flows in and is let out. The mixed models incorporate elements of both discrete and continuous change in the same model. Discrete event traffic simulation can be used to analyze the behavior of the system under various conditions, to provide insight into what-if questions, evaluate different strategies and scenarios, improve traffic control, provide measures of consequences of traffic jams and blockages, etc.

The use of discrete event simulation in modeling the curbside vehicular traffic as well as pedestrian flow entering and exiting the terminal building and the parking garage was used to aid in planning and design of the Austin-Bergstrom International Airport in the city of Austin, Texas (Tunasar et al. 1998). This study does not incorporate hazard scenarios or traffic evacuation plans, but mainly presents the newly started traffic simulation project covering the conceptual level modeling issues in a relatively small-sized traffic system. Another study (Van Burgsteden et al. 2000) describes the development of a traffic template as a new template for the ARENA software to be used in traffic simulations. They provide an implementation of the discrete event simulation approach using the developed template on the premises of Amsterdam Airport, in which they compared several layouts for bus routes to improve the traffic flow and analyzed the consequences of putting a lighting system at an intersection. Again, this study focuses on a relatively small-sized system and does not incorporate evacuation scenarios. However, it displays the capabilities of the ARENA software to incorporate user-designed specific templates (which is not a simple task though) and also the usage of discrete event simulation for transportation systems.

RESEARCH METHODOLOGY

A primary objective of this dissertation was to examine the relationship between clearance time, total number of trips, and size of region to be evacuated. This would provide emergency planners with a method for quickly estimating clearance time given these two factors, one which is known, the other which could be easily determined.

Given the large range of populations and regional network sizes, it was important to identify values that were representative of an emergency evacuation situation, and in the case of this work as related to hurricanes. Therefore a convenient urban area within the Central Florida region was selected. From this a case study network was developed, with corresponding roadway and origin-destination characteristics. Trips were determined by examining land use and dwelling densities using the regional planning projections for this urban area. This served as a baseline for developing a trips range.

The range of network sizes was established based on an arbitrary selection of total origin/destinations (100), and a nominal block and inter-signal spacing. From this a total area per origin was determined. This served as a baseline for developing a range of sizes. To vary size, network topology was kept constant, and block sizes were increased to develop the range.

The US Army Corps of Engineers (USACE) and FEMA manage the Hurricane Evacuation Study (HES) Program. This program develops tools to assist state and county emergency management personnel. A number of post-hurricane assessment studies have been conducted under this program, including behavior evaluations. Of particular interest in these studies is the response of evacuees over the multiple days that a hurricane evacuation typically occurs. As discussed earlier, behavior follows an ‘S’ curve. This can be seen in the HES studies. Figure 5, Figure 6, and Figure 7 show the evacuation curves for hurricanes Charley, Frances, and Jeanne.

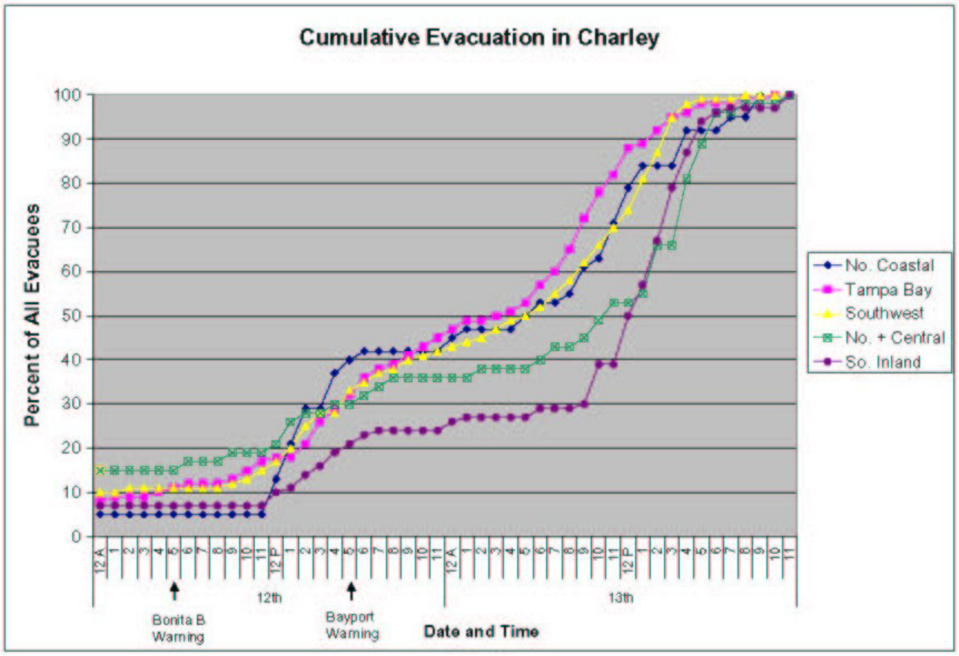

Figure 5 – Hurricane Charley Cumulative Evacuation (Figure 54 from HES Study[5])

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[5] http://chps.sam.usace.army.mil/USHESdata/Assessments/2004Storms/PDFfiles/Charley%20Behave%20FinalPDF.pdf

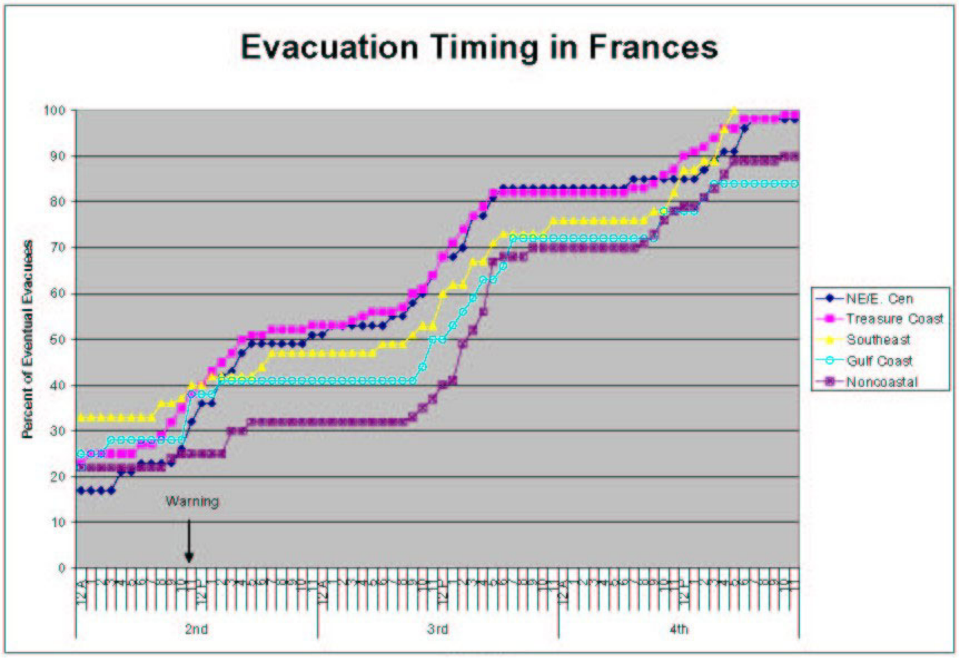

Figure 6 – Hurricane Frances Cumulative Evacuation (Figure 60 from HES Study[6])

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[6] http://chps.sam.usace.army.mil/USHESdata/Assessments/2004Storms/PDFfiles/Frances%20Behave%20FinalPDF.pdf

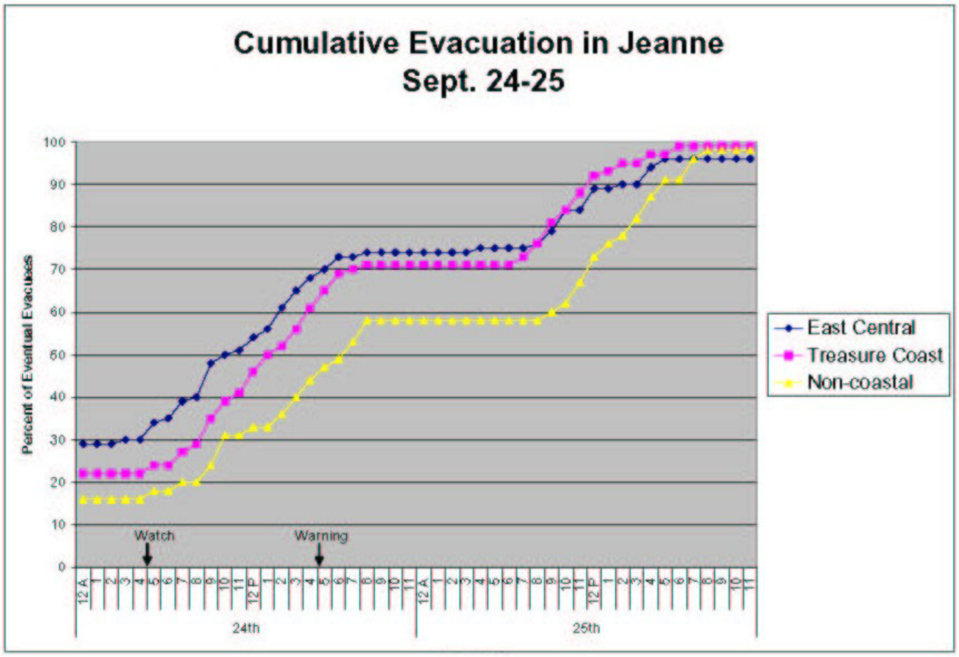

Figure 7 – Hurricane Jeanne Cumulative Evacuation (Figure 60 from HES Study[7])

As can be seen in these figures, evacuation tends to follow the ‘S’ curve behavior within days. People stop evacuating sometime in the evening, and then resume the next morning. Hurricane Charley showed the results of a short notice; Charley altered course at the last minute. Consequently, a high percentage of evacuees departed in the final day.

The combination of these behaviors led to the decision to utilize a 12-hour departure window for the evacuation analysis in this dissertation. This would be representative of a single day’s evacuation loading; future analysis could examine the interaction between days, and the effects of multi-day evacuations more closely.

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[7] http://chps.sam.usace.army.mil/USHESdata/Assessments/2004Storms/PDFfiles/Jeanne%20Behave%20finalPDF.pdf

An additional consideration for this dissertation was the high amount of simulation time and resources required to conduct the replications. Due to these limitations certain evaluations were necessarily limited in scope. Particularly affected were the staging scenarios; given the trip and size ranges, plus the forecast number of staging strategies, there were many potential scenarios, each with the requirement of a minimum number of replications. Therefore, various methods were considered to reduce the simulation requirements while still maintaining an effective analysis.

One of the factors influencing clearance time is network size. As the total distance that a vehicle must travel from origin to destination increases, the corresponding implicit travel time increases. Consequently, one would expect larger networks to show increased clearance times for a constant number of total trips.

However, in parallel with this expectation is the fact that larger networks would tend to disperse vehicle arrivals at the departure intersections over both space and time. Figure 8 illustrates the effect of distance (or travel time delta) on arrivals. As can be seen, as the network size increases, the travel time for each origin increases, and the arrivals at a particularly destination or departure intersection disperse over time. Consequently, capacity may be under-utilized, indicating a potential for shifting departures to more efficiently utilize available capacities, and reduce clearance time.

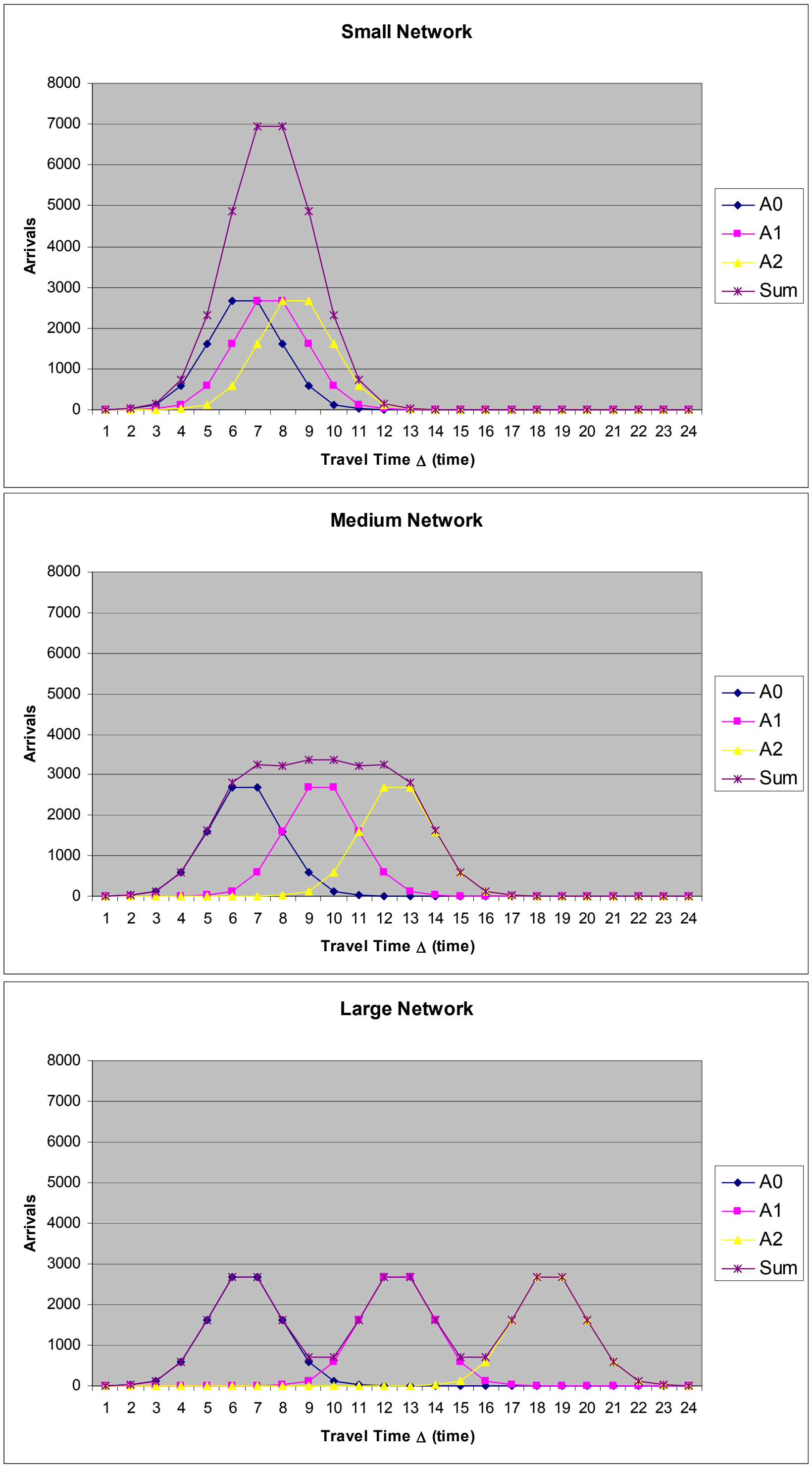

Figure 8 – Vehicle Arrivals by Network Size

MODELING LEVEL

Computer simulations of a generic transportation network were conducted using a traffic simulation package. Package selection was based on its ability to provide output data that can be used to evaluate evacuation strategies, specifically by providing a CTE. In addition, the package required a relatively low level of complexity so that model development, debugging, operation, and data extraction were infeasible based on the network size. Other selection criteria included model history, availability, user experience/ease of learning, and advanced capabilities to model ITS.

Software Package Decision

The following criteria were used in the package decision process. Each package was scored on a scale of 1 to 5, 1 being the least effective, and 5 being the most effective. Each factor was also weighted as to its importance regarding this project.

Table 2 – Software Decision Criteria

Criteria	Weighting	Comment
Ease of use/learning	.1	Software and model development learning curve
Model Complexity	.2	Level of detail required for acceptable model
Data Output	.5	Range and detail of available output data
ITS Capability	.2	Ease of implementing ITS modeling

The following matrix shows the scoring and totals for each software package considered.

Table 3 – Software Evaluation Matrix

Package	Ease of use	Complexity	Output	ITS Capable	Total
INTEGRATION	4	3	5	5	4.5
PARAMICS	4	4	4	3	3.8
VISSIM	4	3	4	2	3.4
CORSIM	3	4	2	4	2.9
WATSIM	4	4	3	1	2.9

INTEGRATION Software

The INTEGRATION model was initially conceived to simulate both freeways and arterials within a single software model. The original version also incorporated traffic assignment, and subsequent versions have added multiple routing algorithms and the ability to model ITS, emissions, and incidents and diversions (Van Aerde et al. 1996).

At the core of the INTEGRATION model is a microscopic representation of vehicles and traffic flow. Vehicle performance is governed by macroscopic traffic flow and assignments, as well as rules for individual car following and lane changing, and other vehicle interactions.

Time Varying Traffic

INTEGRATION has been designed in such a way as to model virtually continuous time varying traffic demands. Demand departure rates, link capacity changes, and traffic control elements (e.g. signals) are each defined over user-specified time periods, and are not restricted to explicit durations.

Each origin-destination input datum is comprised of the following defining factors:

- Origin
- Destination
- Departure rate (vph)
- Rate start time (sec)
- Rate end time (sec)
- Vehicle type percentages (1-5, total to 100%)

This structure enables the modeling of various time-varying loading curves, including the evacuation behavior "S" curve.

Within INTEGRATION, vehicle trips are initiated based upon the cumulative vehicle flow rates from an origin during a given time period. According to the INTEGRATION User's Guide (Rakha and Van Aerde 2004), the user specifies a degree of randomness for departure headways. This randomness value

> *"indicates the fraction of the headway that will be random. For example, if a value of 0.6 is entered, then the headway of a vehicle will consist of a constant component equal to 40% of the average headway (derived from the departure rate), plus an (negative) exponential component with a mean of 60% of the average headway."*

Routing

INTEGRATION provides eight basic traffic assignment/routing options. Two of these are generated through external, time-dependent routing files. A third is strictly distance based, routing vehicles based on the distance from the origin to the destination. The remaining five routing options implement various algorithms to determine vehicle paths.

Of these five options, four have the capability to use traffic information and real-time traffic data to update paths. In addition, the frequency of path updates is configurable, both pre-trip and en-route.

The fifth routing mechanism uses a Dynamic Traffic Assignment (DTA). According to the INTEGRATION User's Guide, this method "computes the minimum path for every scheduled vehicle departure, in view of the link travel times anticipated in the network at the time the vehicle will reach these specific links. The anticipated travel time for each link is estimated based on anticipated link traffic volumes and queue sizes."

INTEGRATION incorporates the ability to model various ITS capabilities, including advanced signal and information systems. These elements, combined with the routing options that are available in INTEGRATION, make it possible to model various pre-trip and en-route navigation mixes.

Output Data

The INTEGRATION program provides an extensive amount of output data. Output includes summary data, individual link and vehicle data, and time-series link and vehicle data. Output is written to a number of files that can be specified as needed.

In addition, detectors can be “placed” on links, which provide volume, speed and occupancy data for polling durations of up to 300 seconds. These detectors can output data on an individual lane basis, or cumulative for the entire link.

A number of the output files are formatted specifically for manipulation and processing within mathematical and spreadsheet software programs. This allows the user to implement a wide range of vehicle- and link-based analyses, and not be restricted to the simulation package output.

PILOT NETWORK STUDY

Since every traffic network is unique, a generic grid network was selected for testing. This layout is representative of an urban center or central business district (CBD), and has application throughout the world.

Network Assumptions

A grid network was created, with three major east-west routes, and three major north-south routes. Minor side streets run parallel both north-south and east-west, and within each block were connecting streets representing neighborhood access. Figure 9 illustrates the generic grid network.

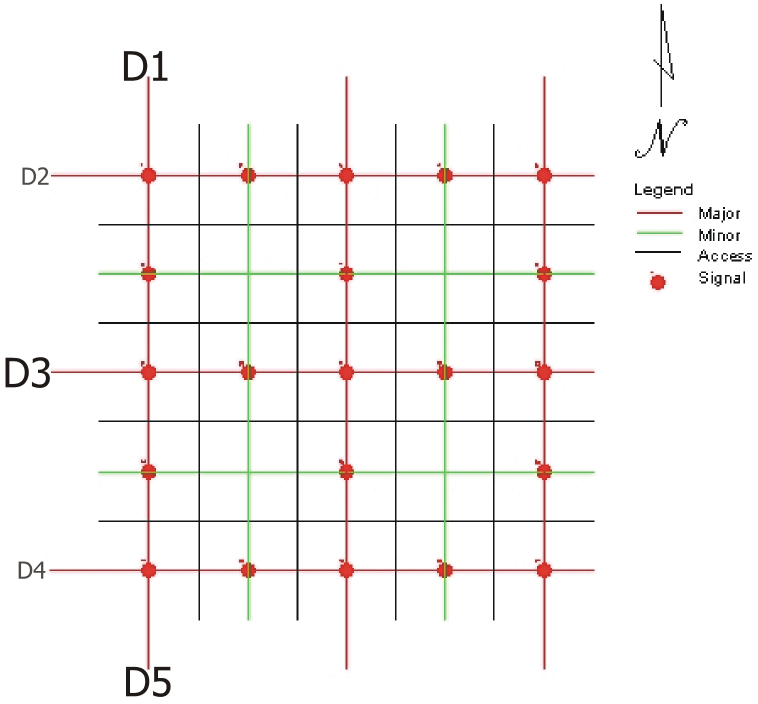

Figure 9 – Generic Traffic Network

The major routes consisted of two lanes in each direction; minor routes were a single lane in each direction. All intersections between major-major, major-minor, and minor-minor had single left turn lanes on each approach.

Each major-major and major-minor intersection was signalized. All signal timings were assumed to be two-phase, with cycle lengths of 180 seconds. Timing was divided equally between each phase (fifty-fifty split). No special phasing was used, and no offset progression was implemented.

The network consisted of 100 origin nodes; 64 internal nodes represented local neighborhoods, and 36 external nodes represented either incoming traffic from adjacent areas or potential evacuation destinations. The network layout has sixteen major blocks, each represented by four origin nodes.

System detectors were placed on each evacuation destination link. Total clearance time was determined by the final recorded detector output time. The detectors were set to output data in 30-second increments.

A number of assumptions were made regarding evacuee behavior, the network, and network traffic operations during the evacuation. These assumptions were independent of the scenarios and their development. In addition, the primary traffic movement was assumed to move from east to west, to reflect a hurricane evacuation situation.

Behavior

Evacuee departures were assumed to occur entirely within a 12-hour window. This demonstrated the impacts of attempting to evacuate a population within essentially the daylight window of a single day. Departure rates followed an “S” curve as shown in the literature. In addition, each origin had the same equal destination distribution: 1/3 to the northwest, 1/3 to the west, and 1/3 to the southwest. Figure 10 illustrates the mathematical estimation for the “S’ departure curve rates listed in Table 4.

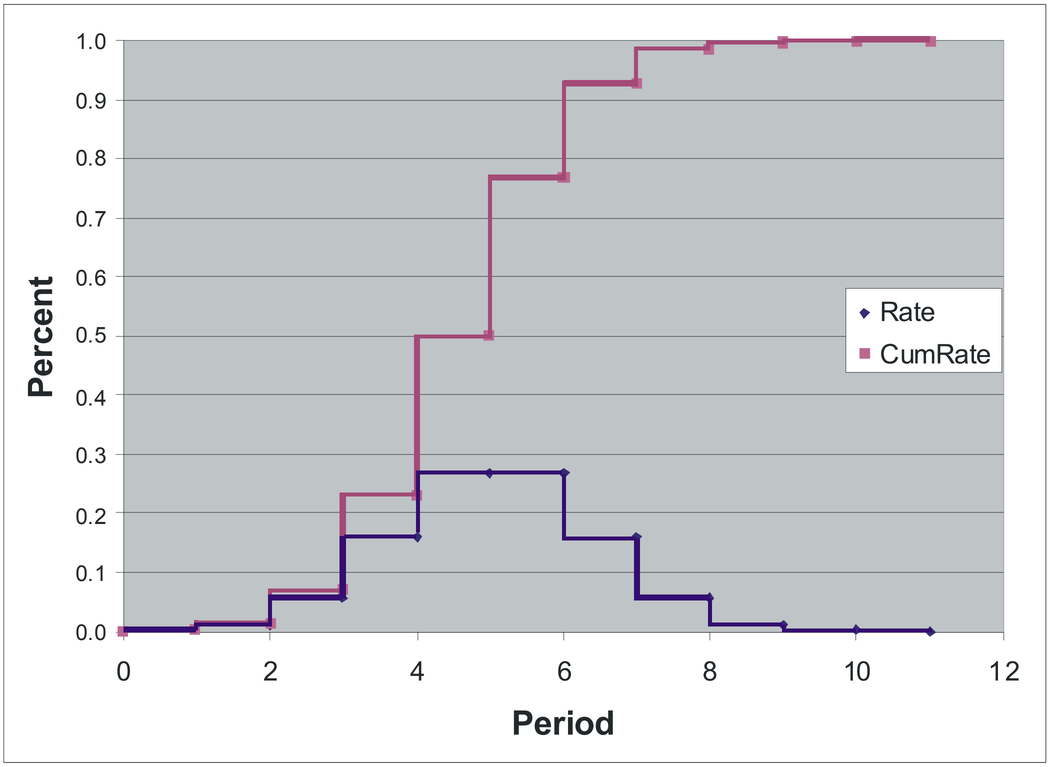

Figure 10 – Departure Rate Curves

Table 4 – Departure Rate Values

Period	Rate	Cumulative Rate
0	0.0001	0.0001
1	0.0016	0.0018
2	0.0125	0.0143
3	0.0579	0.0721
4	0.1605	0.2326
5	0.2674	0.5000
6	0.2674	0.7673
7	0.1605	0.9279
8	0.0579	0.9857
9	0.0125	0.9982
10	0.0016	0.9999
11	0.0001	1.0000

Network

The network had a uniform density; i.e. every origin had the same number of households. It was assumed that there was one vehicle/household evacuating.

In order to determine the effects of size, intersection spacing was varied to generate three different size networks. The default spacing was assumed at a nominal 500 meters, with signal spacing of 1000 meters along the major routes. Link lengths were increased to 1030 meters (2060 meter signal spacing) for the medium network, and to 1720 meters (3440 meter signal spacing) for the large network. This provided a diverse range of network sizes, classified as Small (~25 hectares/OD), Medium (~105 hectares/OD), and Large (~295 hectares/OD).

It was assumed that the network was empty upon the start of evacuation. This eliminated the impact of daily variations in traffic conditions, and provided a baseline for evaluation of these impacts at a later date.

Speed limits for each road segment type were set as follows:

Major :	72 kph (45 mph)
Minor :	56 kph (35 mph)
Access :	16 kph (10 mph)

Operations

As stated earlier, INTEGRATION utilizes different vehicle routing options. It was assumed that 20% of all vehicles would take advantage of pre-trip or en-route information and adjust their routes accordingly. The remaining vehicles selected their routes at departure, and made no en-route changes.

Also, no special considerations were made regarding signal timing over the duration of the evacuation. Identical timings were used for all simulations.

Network Development

The network was generated in AutoCAD, and then output to an entities database for analysis. Individual links were represented by LINE entities; each unique link configuration, for example number of lanes, was represented by various entity characteristics. Each direction was represented by separate entities. In addition, blocks were created to represent signals and origin-destination nodes.

The entities data was imported into Microsoft Excel. One macro, *acadcnvt*, was written to read through the entity data and strip out relevant information, such as type, handle, color, and linetype. These parameters were used to represent characteristics such as number of lanes (LineWeight) and link speeds (Color). Links, signals, and O-D blocks were output to separate worksheets.

A second macro, *ExtractNodes*, was written to read through these worksheets and create INTEGRATION-specific node, link, signal, and lanestripe (lane configuration) files. These files were then modified accordingly to include various input parameters required by INTEGRATION, or make unique changes not reflected in the AutoCAD model.

A third macro, *Signalize*, was written to read signal-timing data from another worksheet, and modify the link data accordingly. INTEGRATION stores signal phase and movement information in the link file.

OD Matrix

INTEGRATION requires an OD matrix as an input file. This matrix includes the following information:

1. Origin
2. Destination
3. Rate (vph)
4. Start time (for rate)
5. End time (for rate)

For small networks, managing this file requires some effort, but is not impractical to do manually. For larger networks, however, managing this file can become unwieldy, time-consuming, and prone to human error. Therefore a solution was implemented using Microsoft Excel, though any spreadsheet program would be sufficient.

Origin-destination information was broken down into two matrices. The first matrix defined rates over time for each origin, based on each origin trip total and a specified period length (e.g. one hour per period). The second matrix provided destination breakdown in percent for each origin. In this way, minute adjustments could be made for virtually any assumption or real-world value.

A macro, *CreateOD*, was written to process these two matrices, and output an INTEGRATION-specific formatted OD file. Additional macros were written to make adjustments to this file, such as vehicle class breakdowns and Start- and End-time shifts.

For the pilot network, these matrices were 100x12 and 100x100 respectively. The first matrix utilized the departure rate values shown in Table 4. The second matrix used the following destination percentages (for each respective destination illustrated in Figure 9):

D1: 0.33

D2: 0

D3: 0.34

D4: 0

D5: 0.33

Network Analysis

Two analyses were conducted using the pilot network. The first analysis evaluated key bottleneck intersections using the I/O analysis method. The second analysis involved computer simulation of the same network to determine the CTE. These two results were then compared. For all analyses, 45,000 total trips were assumed (approximately 474 trips/OD, or about five trips/hectare for this scale model). This value represented moderately dense land-use. A further I/O analysis was conducted utilizing the approach rate outputs of the simulation.

Input/Output Analysis

Input/Output (I/O) analysis compares the arrival rate for a roadway segment to its capacity and effective departure rate. From this, queue lengths, queue clearance times, and delayed vehicles can be calculated.

While this method is typically applied to a freeway segment, it can be adapted for use with intersections. However, in this case certain assumptions must be made when the intersection is not standalone, i.e. is part of an overall traffic network. Specific approach rates and turning movement counts are not known. Following are the assumptions made for analysis of a departure intersection for the generic network:

- Origin departure rates = intersection arrival rates
- Arrival percentages per approach
- No thru traffic, i.e. the intersection is the final transit point prior to exiting the network
- Travel times from all origins to intersection are equal

Intersection Analysis

Origin departure rates were derived for the base, or DO NOTHING, case. Table 5 lists the origin departure (intersection arrival) rates for each of the intersections shown in Figure 11. It should be pointed out that the departure rates for the first hour and the last hour were zero, and so those hours were not included in the analysis.

Table 5 – Departure Intersection Arrival Rates

				Rate (vph)	
Period	Start (sec)	End (sec)	A	B	C
1	1	3600	25	26	25
2	3601	7200	186	191	186
3	7201	10800	860	886	860
4	10801	14400	2383	2456	2383
5	14401	18000	3971	4091	3971
6	18001	21600	3971	4091	3971
7	21601	25200	2383	2456	2383
8	25201	28800	860	886	860
9	28801	32400	186	191	186
10	32401	36000	25	26	25

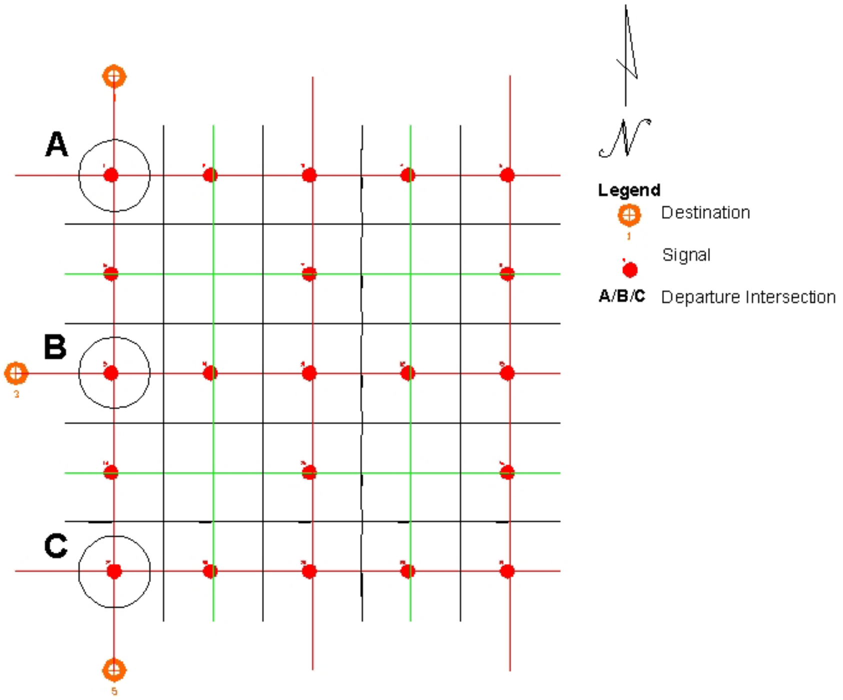

Figure 11 – Departure Intersections

Using the Highway Capacity Manual (HCM 2000) analysis for signalized intersections, capacity for each relevant approach was calculated. Table 6 lists the factors utilized for evaluating each departure intersection.

Table 6 – Intersection Capacity Analysis

	Int 'A'		Int 'B'			Int 'C'	
Factor	WBR	NBT	SBR	WBT	NBL	SBT	WBL
s_0	1900	1900	1900	1900	1900	1900	1900
N	$1^{\#}$	2	$1^{\#}$	2	1	2	1
f_{LT}	1.0	1.0	1.0	1.0	0.95	1.0	0.95
f_{RT}	0.85	1.0	0.89	1.0	1.0	1.0	1.0
Other*	1.0	1.0	1.0	1.0	1.0	1.0	1.0
G				- - - - - 85 - - - - -			
Y				- - - - - 4 - - - - -			
t_L				- - - - - 4 - - - - -			
C				- - - - - 180 - - - - -			
s (vph)	1615	3800	1691	3800	1805	3800	1805
c (vph)	763	1794	799	1794	852	1794	852

shared thru/right lane

* the remaining HCM capacity factors were assumed = 1.0, given the assumptions made for evacuation conditions and traffic movements at the intersection

Using the equations from Chapter 16 for saturation flow and lane group capacity

$$s = s_0 * N * f_w * f_{hv} * f_g * f_p * f_{bb} * f_{LU} * f_a * f_{LT} * f_{RT} * f_{Lpb} * f_{Rpb} \qquad (1)$$

$$c = s * (g / C) \qquad (2)$$

the capacity for each approach was calculated, and is also shown in Table 6. For the f_{RT} factors, intersection 'A' WRT was assumed to be an exclusive lane; based on traffic destinations, only right turn traffic would utilize this lane. For intersection ‘B’, since some thru traffic would be expected, with the majority using the median thru lane, the proportion of right turns (P_{RT}) for SBR was assumed to be 75%. Figure 12 illustrates traffic approaches for each departure intersection (A, B, and C).

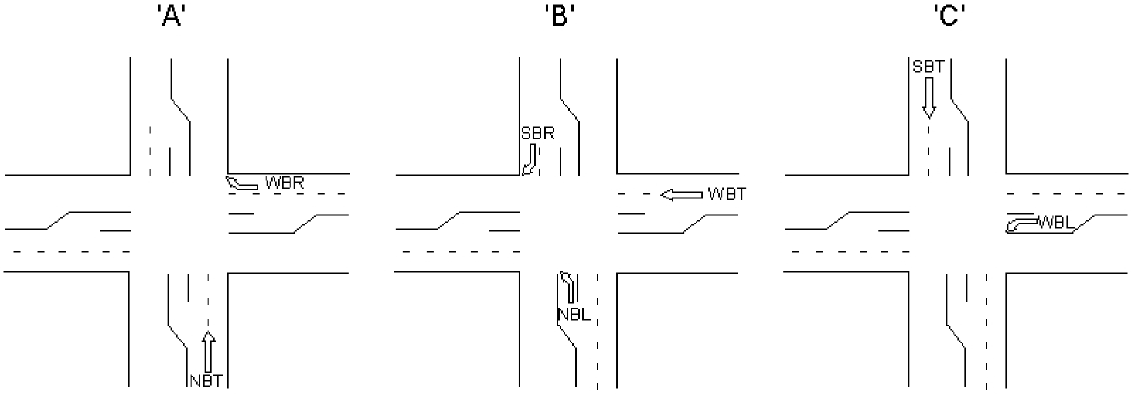

Figure 12 – Departure Intersections A, B, C

Since these intersections are part of an overall network, an assumption for arrival volume percentages for each approach must be assumed. Total approach volumes can then be calculated based on *Total Trips*. The following assumed approach percentages were used:

Intersection ‘A’:	WBR	0.50
	NBT	0.50
Intersection ‘B’:	SBR	0.25
	WBT	0.50
	NBL	0.25
Intersection ‘C’:	SBT	0.50
	WBL	0.50

Figure 13 shows the arrival rates and capacities for the NBT and WBR approaches for intersection 'A'. For this intersection, NBT-Arr indicates the arrival rate for, and NBT-Cap indicates the capacity of the NBT approach, and WBR-Arr indicates the arrival rate for, and WBR-Cap indicates the capacity of the WBR approach.

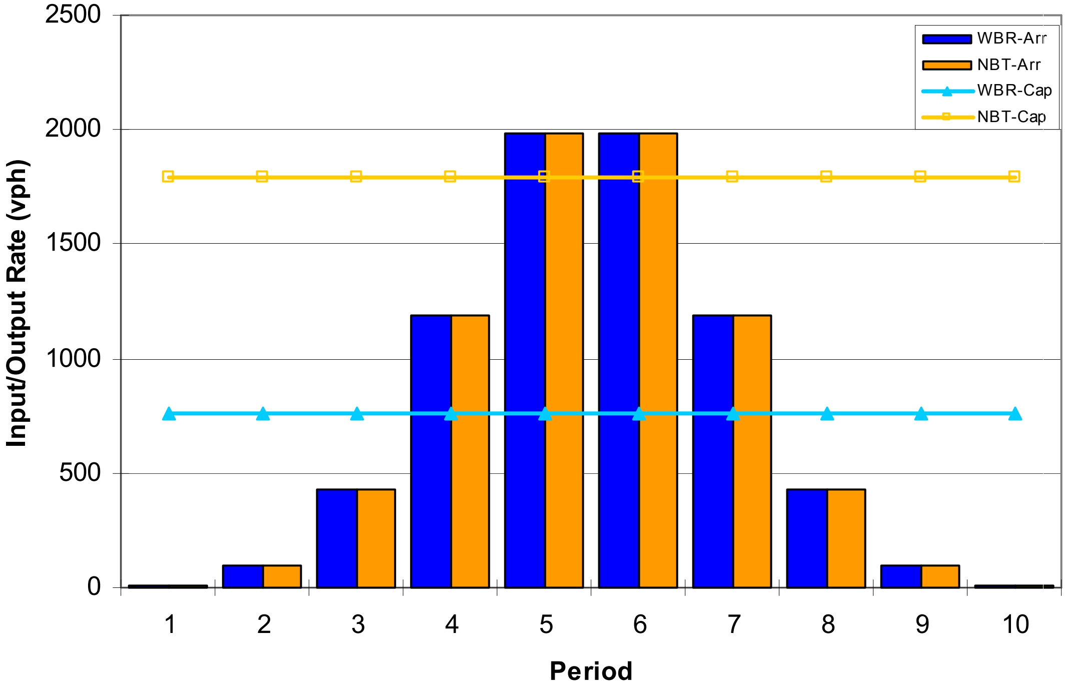

Figure 13 – Departure Intersection 'A' Input/Output Rate

As can be seen, the approach rate for the northbound approach (NBT-Arr) exceeds the capacity for periods 5 and 6. The approach rate for the westbound approach (WBR-Arr) exceeds the capacity for periods 4 through 7. From this, queue buildup is expected on both approaches, and an increase in clearance time is possible.

Figure 14 shows the arrival rates and capacities for the SBR, WBT and NBL approaches for intersection 'B'. For this intersection, SBR-Arr indicates the arrival rate for, and SBR-

Cap indicates the capacity of the SBR approach. Similarly, WBT-Arr and WBT-Cap are the arrival and capacity for the WBT approach, and NBL-Arr and NBL-Cap are the arrival and capacity for the NBL approach.

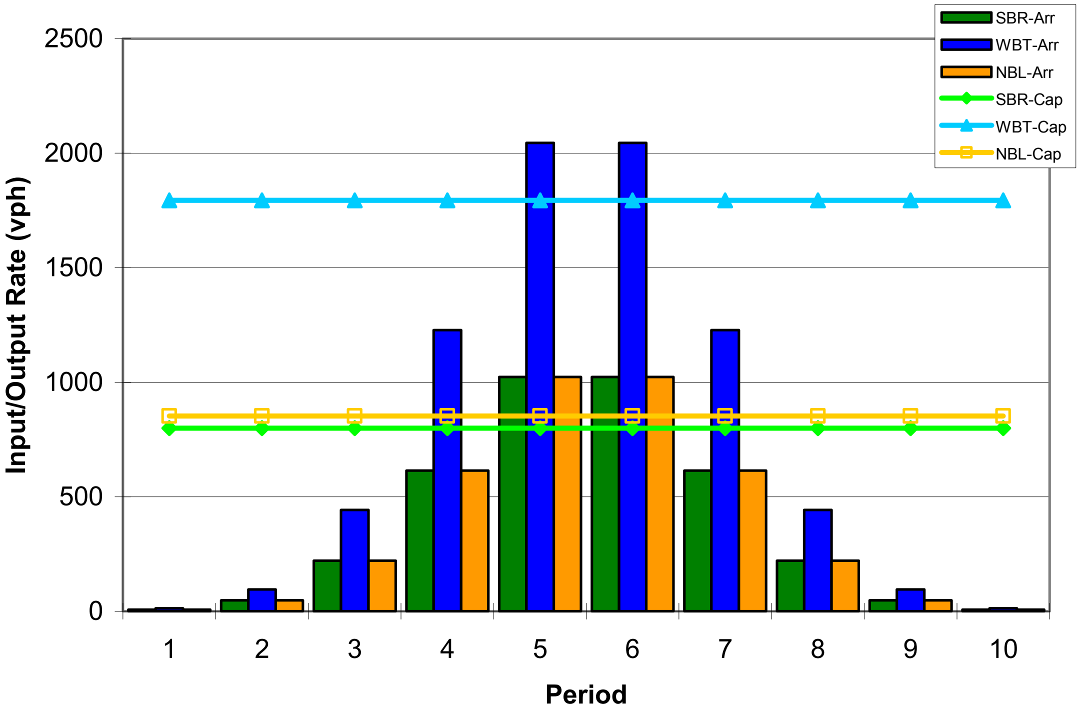

Figure 14 – Departure Intersection 'B' Input/Output Rate

As can be seen, the arrival rates for all three approaches exceed capacity; this occurs during periods 5 and 6 for all approaches. From this a queue is expected on each approach, and an increase in clearance time is possible.

Figure 15 shows the arrival rates and capacities for the SBT and WBL approaches for intersection 'C'. For this intersection, SBT-Arr indicates the arrival rate for, and SBT-Cap indicates the capacity of the SBT approach, and WBL-Arr indicates the arrival rate for, and WBL-Cap indicates the capacity of the WBL approach.

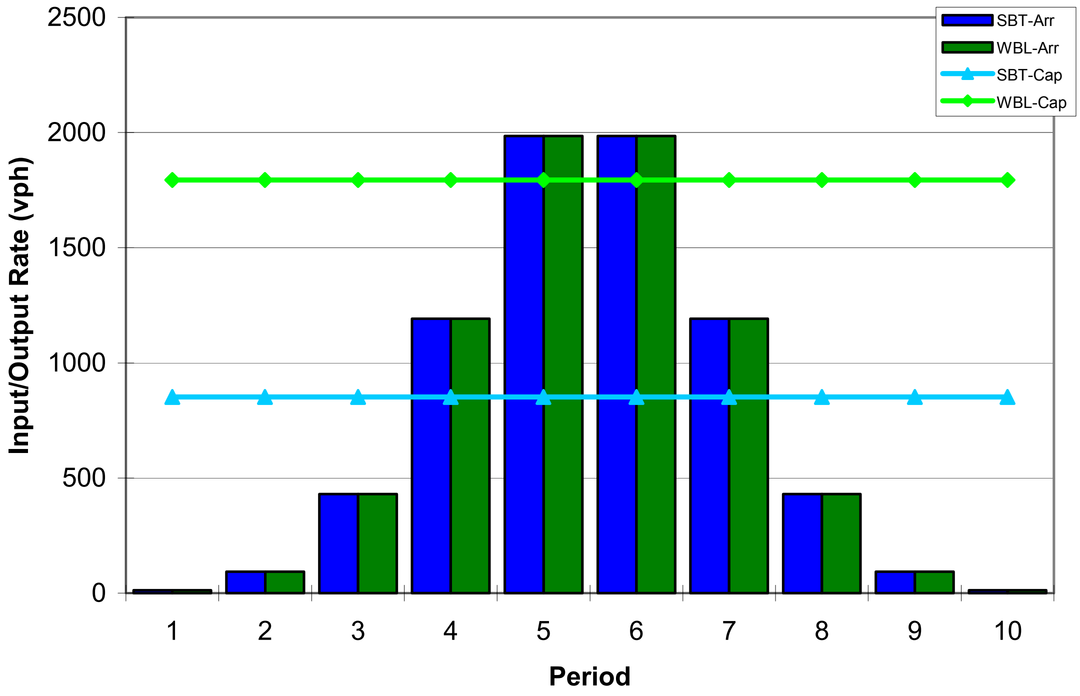

Figure 15 – Departure Intersection ‘C’ Input/Output Rate

As can be seen, the approach rate for the southbound approach (SBT-Arr) exceeds the capacity for periods 5 and 6. The approach rate for the westbound (WBL-Arr) exceeds the capacity for periods 4 through 7. From this, queue buildup is expected on both approaches, and an increase in clearance time is possible.

Queue Clearance Time

Queue clearance time (QCT) was calculated using the I/O method based on flow rate versus time. Figure 16 illustrates the methodology to determine queue buildup and clearance.

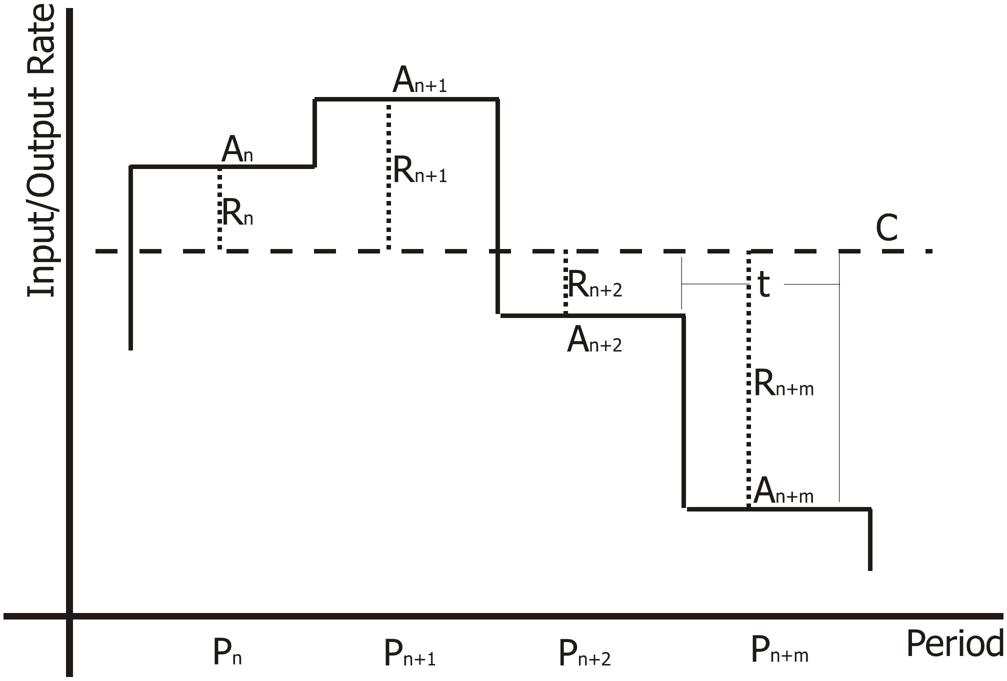

Figure 16 – Input/Output Analysis

The following are the variables represented in this figure:

A: Arrival rate

R: Accumulation rate

P: Time period

C: Capacity

n: Period counter

m: Future period counter

t: Queue clearance time (fractional)

The total vehicles in queue for period *n*, or Q_n, can be calculated using the following relationship:

$$Q_n = \int R_n dp = R_n p \tag{3}$$

where p = length of period Pn

Using an iterative approach, the queue clearance time t within period P_{n+m} can be determined. The cumulative queue is shown as ΣQ.

Table 7 – Intersection ‘A’ WBR Approach

Period	A (vph)	C (vph)	R (vph)	P (hr)	ΔQ (veh)	ΣQ
1	13	763	-750	1	-750	0
2	93	763	-670	1	-670	0
3	430	763	-333	1	-333	0
4	1192	763	429	1	429	429
5	1985	763	1222	1	1222	1651
6	1985	763	1222	1	1222	2873
7	1192	763	429	1	429	3302
8	430	763	-333	1	-333	2969
9	93	763	-670	1	-670	2299
10	13	763	-750	1	-750	1549

At the end of the departure window (period 10), there is a queue remaining (ΣQ=1549). From this point on, the arrival rate is zero, and the time to clear the queue can be calculated by

$$t = Q / C \tag{4}$$

For the WBR approach, the queue clearance time is 1549 / 763 or 2.03 hours (7309 sec). Applying this methodology to each of the approaches, clearance times were calculated, and are summarized in Table 8. In addition, the overall CTE (in seconds) is shown.

Table 8 – Approach Queue Clearance Times

Intersection	Approach	ΣQ	C (vph)	T (sec)	CTE (sec)
A	WBR	1549	763	7309	43309
A	NBT	0	1794	0	36000
B	SBR	0	799	0	36000
B	WBT	0	1794	0	36000
B	NBL	0	852	0	36000
C	SBT	0	1794	0	36000
C	WBL	926	852	3913	39913

Sensitivity Analysis

Using the above methodology, each intersection can be evaluated by varying the assumed arrival percentages by approach. Table 9 shows the estimated increase in CTE based on varying the approach arrival percentages. As the approach volumes shift from the thru to the turn movements, the standing queues resulting from insufficient capacity shift as well. Based on these results, the overall network clearance time is highly sensitive to the approach split percentage. For intersection 'B', turn percentages were split equally between the SBR and the NBL approaches.

Table 9 – Queue Clearance Time by Approach %

QCT (s)	Int 'A'			Int 'B'		Int 'C'	
Thru %	WBR	NBT	SBR	WBT	NBL	SBT	WBL
100	0	2450	0	3289	0	2450	0
90	0	0	0	437	0	0	0
80	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0
60	797	0	0	0	0	0	0
50	7309	0	0	0	0	0	3913
40	13810	0	0	0	0	0	9735
30	20312	0	0	0	0	0	15558
20	26818	0	378	0	0	0	21385
10	33367	0	3586	0	1796	0	27203
0	40270	0	6790	0	4800	0	33055

I/O Summary

Since the calculation method does not account for interaction between intersections, intersection independence was assumed. The CTE for this network, using the I/O method, was determined by taking the worst case intersection. From Table 8, the overall network CTE is 43309 seconds. It is interesting to note that, in contradiction to the intuitive conclusion, the WBR approach at intersection 'A' (not the WBL approach at intersection 'C') resulted in the longest time to clear, and therefore set the overall CTE for the network. This was due to the right turn capacity factor (f_{RT}) of 0.85 utilized in the HCM being lower than the left turn factor (f_{LT}) of 0.95. Right-turn-on-red (RTOR) vehicles are essentially ignored in the HCM analysis.

Computer Simulation

The Medium network was used for this analysis. Table 10 lists the CTE (in seconds) by intersection, maximum of the CTE values, and completed trips for the DO NOTHING scenario. Also shown are the mean and standard deviation values. CTE by intersection was defined as the time at which the last vehicle passed through the intersection and exited the network. It did not include vehicles passing through the intersection on the way to their final departure intersection.

Table 10 – DO NOTHING CTE Results for Medium Network

	CTE (seconds)			Max	
Run	A	B	C	CTE	Trips
1	53760	54210	54840	54840	45399
2	54360	54120	55800	55800	45397
3	53220	52950	54690	54690	45400
4	54450	55830	55980	55980	45402
5	53250	52890	54840	54840	45401
Mean	53808	54000	55230	55230	45400
StDev	586.6	1198.1	608.9	608.9	2.2
C.I. (α=0.05)	[53377, 54240]	[53119, 54881]	[54782, 55678]	-	-

Replications were stopped at five, using an accepted rule of thumb that states that if the half-width of the confidence interval is within 10% of the mean, then no further replications are necessary. For intersections A, B, and C the half-widths are 431.5, 881.3, and 447.9 respectively (less than 10% of the means 5381, 5400, and 5523). The variation in trips is due to the vehicle generation algorithm and origin-destination matrix in

INTEGRATION. Each simulation was within 99.993% (+/- 3 trips) of the overall mean, and had negligible impacts on the overall results.

Comparison

INTEGRATION provides the capability to output vehicle performance data by link. This allows for extensive routing and path analysis. From this data, the approach and turning movement volumes for any link can be determined.

Using a database software program (for this project Microsoft Access was used), simple SQL queries were written to extract link approach volumes for those links representing the departure intersection approaches. This data was broken down by period to correspond with the I/O analysis to facilitate two methods of comparison.

Table 11 lists the simulated approach volumes for a single replication. This served as a representative case for comparison with the I/O analysis. The ratio value indicates the percentage of vehicles at each intersection that utilize the corresponding approach.

Table 11 – Simulated Approach Volumes

Intersection	Approach	Volume	Ratio
A	WBR	8462	0.56
A	NBT	6544	0.44
B	SBR	3293	0.21
B	WBT	8579	0.56
B	NBL	3516	0.23
C	SBT	7160	0.48
C	WBL	7845	0.52

The first comparison method involved simply comparing the approach percentage breakdowns to the sensitivity analysis shown in Table 9. Inspection showed that the worst case CTE involved the WBR approach for intersection 'A'. Interpolating the values resulted in an expected queue clearance time of 11210 seconds, and an overall CTE of 47210 seconds. This calculated I/O value was significantly less than the simulated CTE of 55230 seconds (final vehicle exit time from link), indicating that other network factors, such as interactions with vehicles headed to other destinations, affected the vehicle arrivals and queue accumulations for this destination intersection. In addition, arrival rate assumptions and internal travel time assumptions from each OD also likely contribute to the differences.

The second method for comparison involved using the simulated throughputs. A direct comparison of arrival rates was not possible, since the simulation output does not provide the information necessary to extract approach arrival rates. Therefore, a comparison of throughput and derived queue clearance (period of final vehicle departure) was done. Table 12 lists these throughput volumes by period.

Table 12 – Simulated Throughput (vehicles per period)

	Int 'A'		Int 'B'		Int 'C'			
Period	WBR	NBT	SBR	WBT	NBL	SBT	WBL	Total
1	50	41	14	60	21	39	52	277
2	116	51	24	121	36	54	116	518
3	493	224	101	471	145	226	471	2131
4	900	603	263	827	439	761	587	4380
5	747	960	647	760	331	1180	561	5186
6	692	926	656	695	353	1072	537	4931
7	771	855	483	739	380	831	555	4614
8	726	702	454	737	433	713	574	4339
9	804	767	356	587	453	694	551	4212
10	887	472	182	339	368	415	553	3216
11	602	255	35	577	144	270	594	2477
12	421	163	17	604	190	144	560	2099
13	557	209	0	1001	120	290	612	2789
14	548	223	61	855	69	151	638	2545
15	118	60	0	167	27	316	641	1329
16	30	33	0	39	7	4	243	356
17	0	0	0	0	0	0	0	0
Total	8462	6544	3293	8579	3516	7160	7845	45399
Pct	0.56	0.44	0.21	0.56	0.23	0.48	0.52	-

Using the approach numbers from Table 12, new I/O rates were derived. Throughput rate was determined as the lesser either of the approach arrival volume or the approach capacity, allowing for the presence of any standing queue. Table 13 shows the throughput volumes for the I/O analysis based on the simulated approach percentages and volume (using the 'S' curve).

Table 13 – I/O Throughput Analysis

	Int 'A'			Int 'B'		Int 'C'		
Period	WBR	NBT	SBR	WBT	NBL	SBT	WBL	Total
1	14	11	6	15	6	12	13	77
2	105	82	41	108	44	90	97	567
3	486	382	188	500	206	416	451	2629
4	763	1058	520	1387	570	1154	852	6304
5	763	1763	799	1794	852	1794	852	8617
6	763	1763	799	1794	852	1794	852	8617
7	763	1058	656	1794	764	1412	852	7299
8	763	382	188	1127	206	416	852	3934
9	763	82	41	108	44	90	852	1980
10	763	11	6	15	6	12	852	1665
11	763	0	0	0	0	0	852	1615
12	763	0	0	0	0	0	411	1174
13	763	0	0	0	0	0	0	763
14	155	0	0	0	0	0	0	155
15	0	0	0	0	0	0	0	0
Total	8390	6592	3244	8642	3550	7190	7788	45396
Pct	0.56	0.44	0.21	0.56	0.23	0.48	0.52	-

From Table 10, the deviations in approach volumes are due to rounding in the approach percentages; however, the largest difference is 1.5% and was deemed insignificant to this analysis. The differences between the I/O analysis and the simulated clearance are immediately evident. Whereas the I/O analysis assumed approach arrival rates reflective of the departure rate curve, the simulation approach arrival rates were subject to internal network routing calculations and upstream bottlenecks. Consequently, the actual arrival rates and corresponding throughputs were dissimilar to those assumed in the I/O analysis. In addition, the simulated approach capacities varied slightly from the HCM calculations, though their impacts cannot be adequately determined from this analysis. Figure 17, Figure 18, and Figure 19 show each intersection throughput by approach.

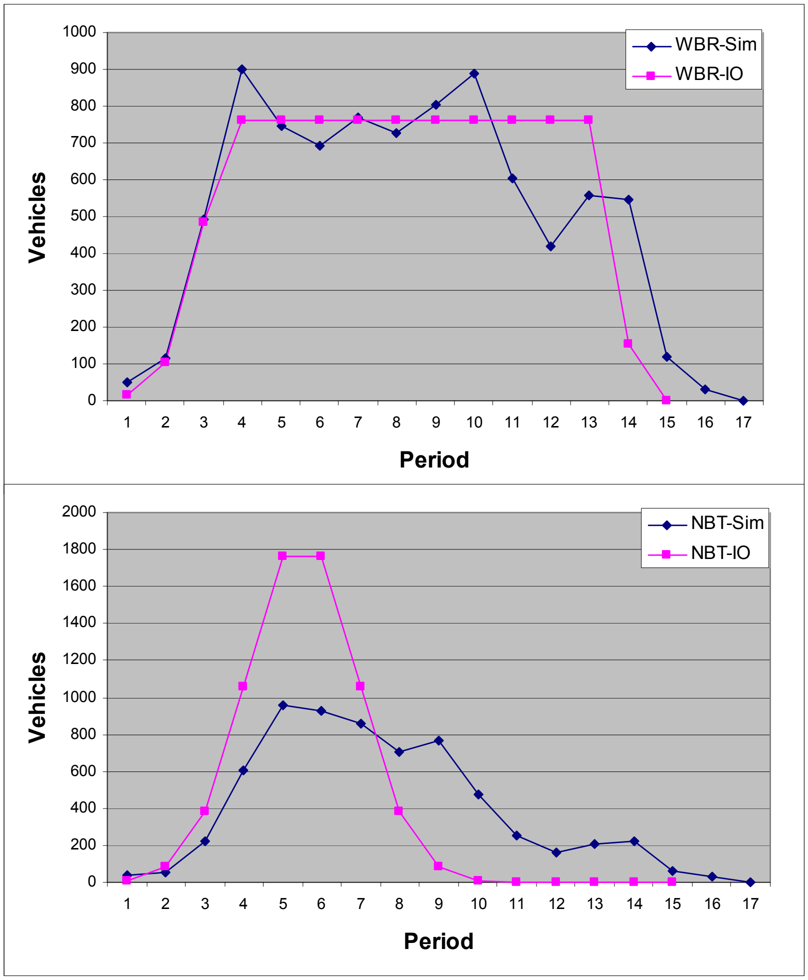

Figure 17 – Int 'A' Throughput by Approach

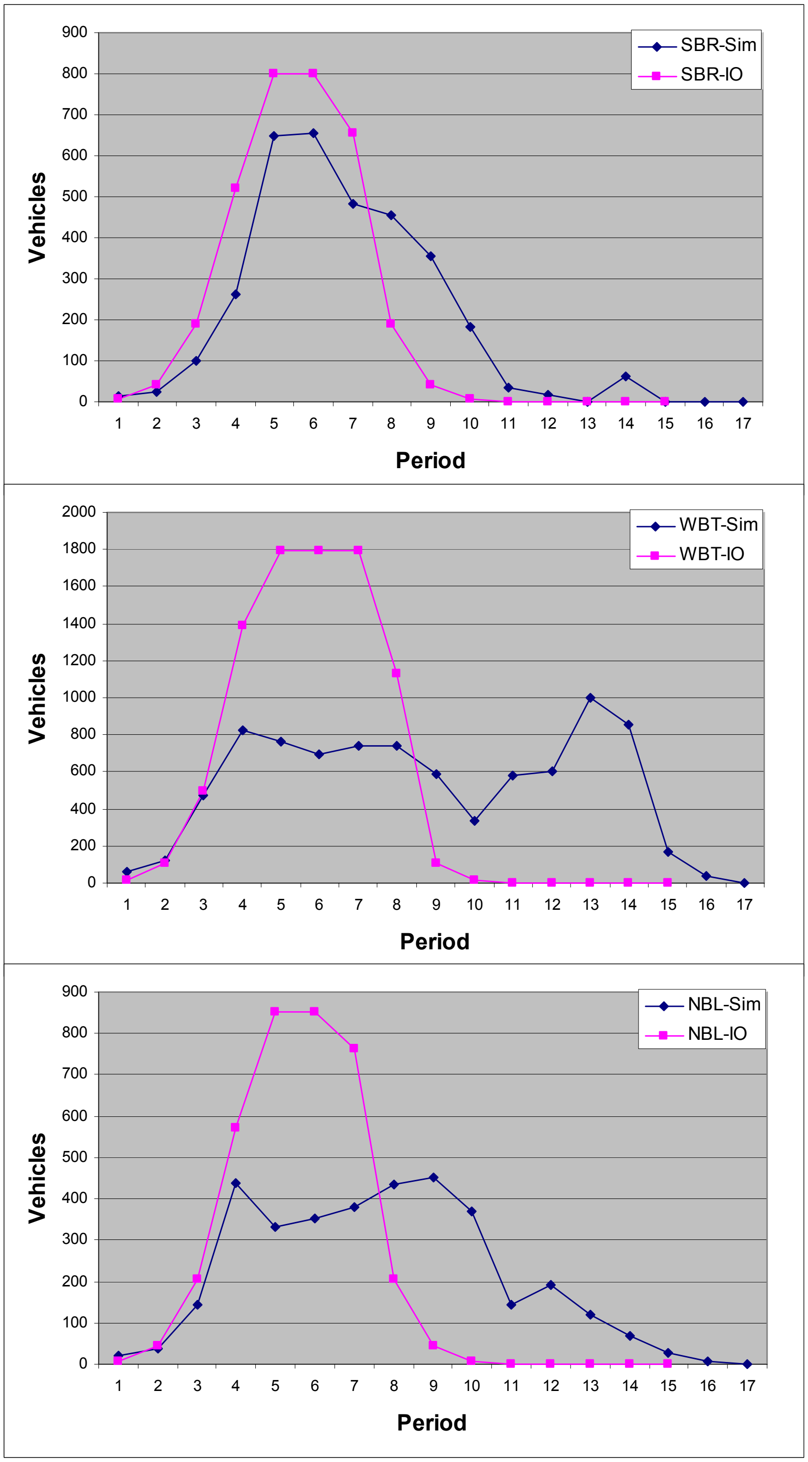

Figure 18 – Int 'B' Throughput by Approach

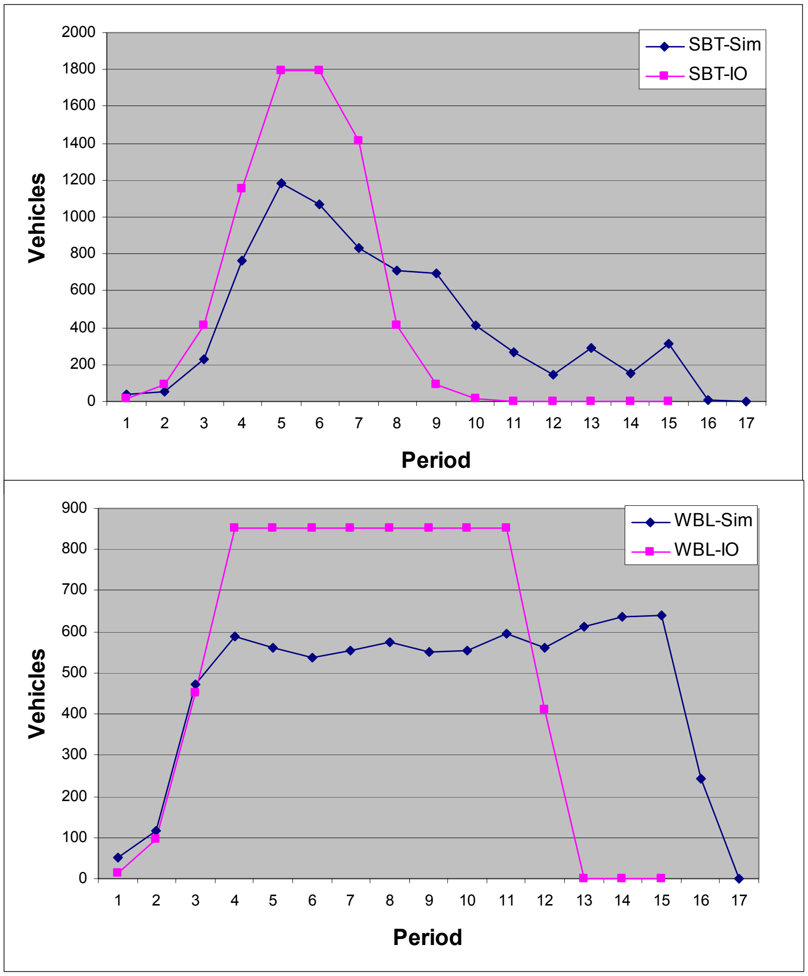

Figure 19 – Int ‘C’ Throughput by Approach

REGRESSION MODEL

A primary objective of this dissertation was to examine the relationship between clearance time, total number of trips, and size of region to be evacuated. This would provide emergency planners with a method for quickly estimating clearance time given these two factors, one which is known, the other which could be easily determined.

In order to develop a linear regression model, the varying factor must be determined. Obviously, *Total Trips* plays an important part in the overall clearance time, and therefore should be included. However, network size would also seem to play a role; the larger the network, the greater the implicit travel time for vehicles to travel from origin to destination, resulting in a larger clearance time. Therefore, network size in some form must also be evaluated.

Size

Network size is a nebulous characteristic, and so something more definitive was necessary. Area is an insufficient gauge, since very low trip density regions can artificially skew the overall area value higher, whereas very high density urban sections could severely underweight any area measurement. In addition, defining the coverage area can be highly subjective and inaccurate, and does not reflect anything regarding the underlying network.

A more specific measurement of network size was required. This measurement needed to be reasonably easy to calculate consistently, have little variation in its method of calculation, and still reasonably reflect both the overall coverage area and underlying roadway network. The logical characteristic was total roadway distance (kilometers). However, since not all roads within a region are vital or influence the network performance, a more limited definition was needed. One defining characteristic of an evacuation is that the destinations are known and likely few in number. Therefore, a function of origin to destination distance was chosen. Since more possible destinations could skew this value, an average of each origin to all destinations was used, summed over all origins. This was called average internal travel distance, or *ITDA*:

$$ITDA = \sum_{i=1}^{m} \frac{\sum_{j=1}^{n} dist\left(o_i, d_j\right)}{n} \tag{5}$$

where

dist: distance from origin i to destination j

o_i: origin i (m = total origins)

d_j: destination j (n = total destinations)

The *ITDA*, along with total network trips, results in an estimate of the expected total vehicle distance traveled within the network. This value is relatively easy to calculate for a given network. Using this relationship, three different network sizes were calculated, Small, Medium, and Large. These sizes were selected to provide a range of representative regional networks.

Trips

A range of trips was selected to reflect small and medium sized populations requiring evacuation. Larger populations could have been modeled, but due to the time requirements for microscopic simulation, a different simulation program would be needed out of practicality. A range of 40k to 60k trips, in increments of five thousand, was selected. Table 14 shows the number of trips per OD and area (in hectares).

Table 14 – Trip Generation Statistics

Total Trips	OD (trips/OD)	Model Size (trips/ha) Small	Medium	Large
40k	421	16.8	4.0	1.4
45k	474	19.0	4.5	1.6
50k	526	21.0	5.0	1.8
55k	579	23.1	5.5	2.0
60k	632	25.2	6.0	2.1

Model Analysis

Simulations were run, and Table 15 lists the results of those DO NOTHING runs. Shown are CTE (in seconds) and *Total Trips* for each of five runs, for each of the three network sizes (Small, Medium, Large).

Table 15 – Generic Network DO NOTHING Results

	Total Trips	40k		45k		50k		55k		60k	
Network	Replication	CTE	Trips	CTE	Trips	CTE	Trips	CTE	Trips	CTE	Trips
Small	1	48690	40840	52650	45397	57270	50720	60930	55467	64140	61173
	2	49230	40834	51390	45405	56610	50724	60030	55471	62910	61170
	3	48840	40845	53190	45402	56370	50720	60210	55475	67020	61165
	4	49170	40840	52770	45401	57090	50722	59790	55473	67170	61166
	5	48840	40838	52770	45402	56370	50721	60030	55466	64110	61167
Medium	1	51120	40840	54840	45399	60360	50717	65190	55470	70050	61173
	2	51300	40843	55800	45397	60240	50719	65370	55467	69510	61166
	3	51300	40841	54690	45400	61410	50720	64110	55467	69150	61160
	4	50580	40845	55980	45402	59580	50720	65670	55466	70140	61155
	5	51450	40840	54840	45401	59430	50722	65370	55467	70410	61167
Large	1	52770	40840	56370	45399	61620	50719	64830	55467	71700	61173
	2	51540	40843	56190	45397	62880	50720	65970	55467	70860	61170
	3	52410	40841	56250	45400	61770	50720	66150	55466	72030	61165
	4	52770	40845	56580	45402	61080	50724	66270	55467	71370	61165
	5	52260	40840	56760	45401	61410	50721	65580	55467	72750	61167

Table 16 shows the ITDA values that correspond to each size used in the analysis.

Table 16 – ITDA Values

Size	ITDA (km)
Small	490
Medium	880
Large	1385

A more in-depth comparison with the I/O analysis was made, looking at the full range of trips. Assuming the same simulated approach rates as shown in Table 11, the I/O values were calculated and overall CTE for each trip total was determined. Table 17 shows the calculated standing queues at the end of the departure window, and Table 18 shows the resulting CTE for each intersection approach by trip total. It also shows the mean CTE based on the results in Table 15. Note that the trip values used for the I/O analysis were the mean values from the simulation runs also shown in Table 15.

Table 17 – Queue Accumulation by Approach and Total Trips

		ΣQ				
Intersection	Approach	40k	45k	50k	55k	60k
A	WBR	1661	2444	3355	4170	5147
A	NBT	0	0	0	0	0
B	SBR	0	0	0	0	0
B	WBT	0	0	0	0	0
B	NBL	0	0	0	0	0
C	SBT	0	0	0	0	0
C	WBL	540	1263	2112	2868	3777

Table 18 – Calculated versus Simulated CTE Results

				CTE (seconds)		
Intersection	Approach	40k	45k	50k	55k	60k
A	WBR	43867	47531	51830	55675	60285
A	NBT	36000	36000	36000	36000	36000
B	SBR	36000	36000	36000	36000	36000
B	WBT	36000	36000	36000	36000	36000
B	NBL	36000	36000	36000	36000	36000
C	SBT	36000	36000	36000	36000	36000
C	WBL	38282	41337	44924	48118	51959
Max CTE (calculated):		43867	47531	51830	55675	60285
CTE (simulated)	Small:	48954	52554	56742	60198	65070
	Medium:	51150	55230	60204	65142	69852
	Large:	52350	56430	61752	65760	71742

It should be noted that the I/O analysis is not a function of network size; therefore the use of correction factors requires that the network under evaluation be taken into account. A linear regression analysis was conducted to identify the relationship between the I/O analysis, trips (*Trips*), and size (*ITDA*). Since the result sought was the scalar factor for the I/O analysis, the response variable for this analysis was the ratio of the I/O analysis and the simulated results; the predictors were *Trips* and *ITDA*. Table 19 shows the ratios used as the response variable.

Table 19 – I/O Analysis Correction Factor

	Correction Factor				
	40k	45k	50k	55k	60k
Small	1.12	1.11	1.09	1.08	1.08
Medium	1.17	1.16	1.16	1.17	1.16
Large	1.19	1.19	1.19	1.18	1.19

A regression analysis using Minitab v13 results in the following equation to calculate the correction factor (*CF*). The final analysis included size in the regression analysis; a stepwise regression analysis on the two predictors indicated that only size (*ITDA*) should be included, with a p-value of 0.0. ITDA values used are from Table 16.

$$CF = 1.06 + 0.0001\, ITDA \tag{6}$$

R-squared measures the proportion of the variability in Y that is explained by X, and is a direct function of the correlation between the variables. An R-squared value closer to one indicates a strong relationship between the two variables. The R-squared value for this equation is 83.1, indicating a strong relationship between the predictor variable (*ITDA*) and response (*CF*). Figure 20 shows both the calculated (from the data) and the estimated (from the regression equation) correction factors by model size over the trip total range.

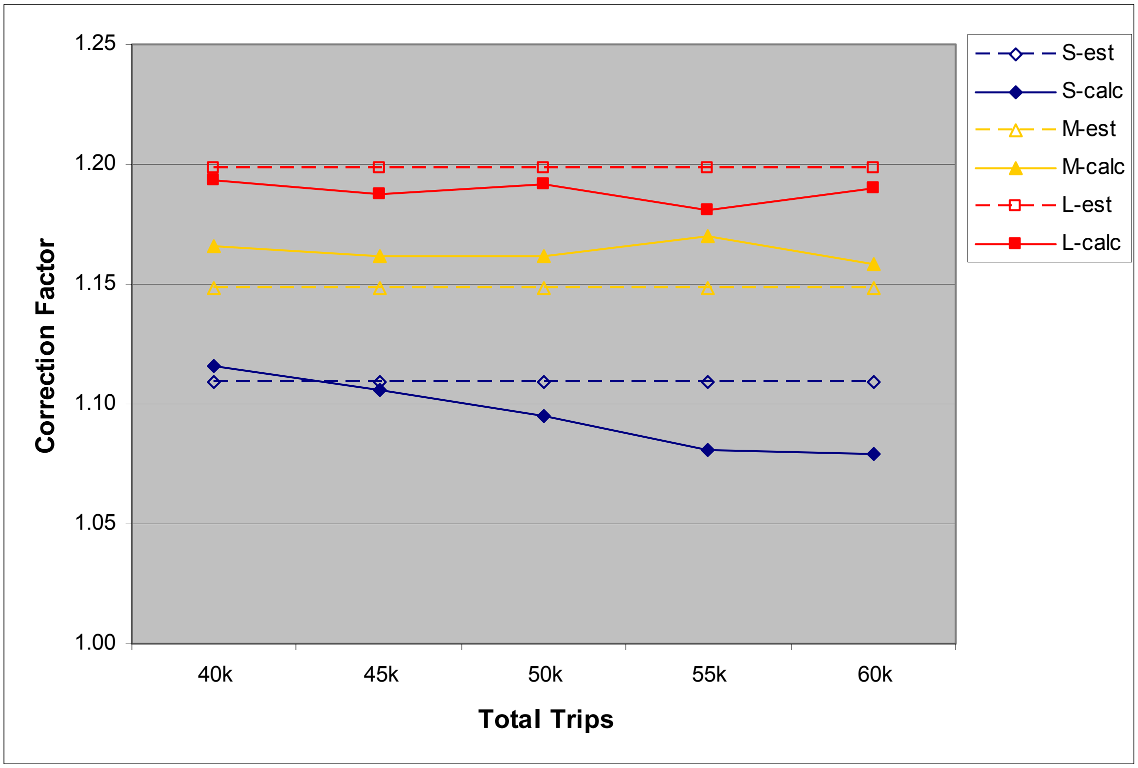

Figure 20 – Calculated and Estimated Correction Factors

Nine regression analyses were conducted for the generic grid network, using CTE as the response variable, and *ITDA* and *Trips* as predictors. Four of the analyses held size constant while varying total trips. For four other analyses, trips were held constant while network size was varied. The final analysis included both size and trips in the regression analysis. Table 20 lists each of the resulting regression equations, as calculated using Minitab v13. A stepwise regression analysis on the two predictors indicated that both should be included, with p-values of 0.0 for each.

Table 20 – Generic Network Regression Analyses

Constant	Regression Equation	R-sq (%)	Obs
Size (Small)	$CTE = 16810 + 0.787\,\mathit{Trips}$	97.1	25
Size (Med)	$CTE = 13023 + 0.932\,\mathit{Trips}$	99.3	25
Size (Large)	$CTE = 13445 + 0.950\,\mathit{Trips}$	99.3	25
Trips (40k)	$CTE = 47396 + 3.73\,\mathit{ITDA}$	89.2	20
Trips (45k)	$CTE = 50847 + 4.24\,\mathit{ITDA}$	84.2	20
Trips (50k)	$CTE = 54537 + 5.48\,\mathit{ITDA}$	85.3	20
Trips (55k)	$CTE = 58213 + 5.97\,\mathit{ITDA}$	74.5	20
Trips (60k)	$CTE = 62206 + 7.28\,\mathit{ITDA}$	78.4	20
(none)	$CTE = 9524 + 0.890\,\mathit{Trips} + 5.34\,\mathit{ITDA}$	97.3	100

As can be seen in Table 20, the R-squared values for each equation are quite high, indicating a strong relationship between the predictor variables (either *Trips* or *ITDA*) and CTE. It is interesting to note that the slopes of the regression equations increase as network size increases, and as *Total Trips* increase. This could be indicative of a curvilinear (non-linear or polynomial) relationship between CTE and size and trips individually. At higher or lower sizes and trips, a linear regression may not be an adequate model, though over the ranges in this study it is sufficient.

Figure 21 shows the regression analysis using *Trips* as the predictor (*Trips* held constant). Both the raw data and the regression plot are illustrated.

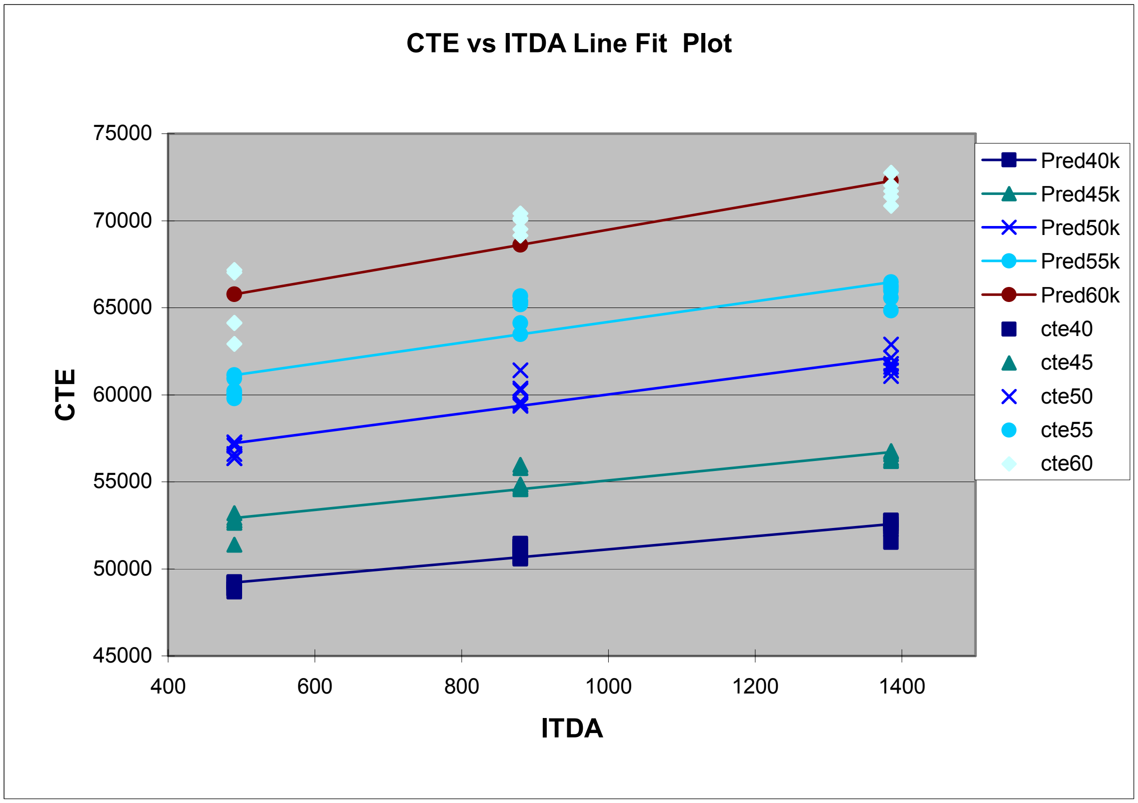

Figure 21 – Regression Analysis with *Trips* as the Predictor

Figure 22 shows the regression analysis using *ITDA* (network size) as the predictor (*ITDA* held constant). *ITDA* values used are shown in Table 16. The slight increase in slope for each regression is discernible in this plot. Both the raw data and the regression plot are illustrated.

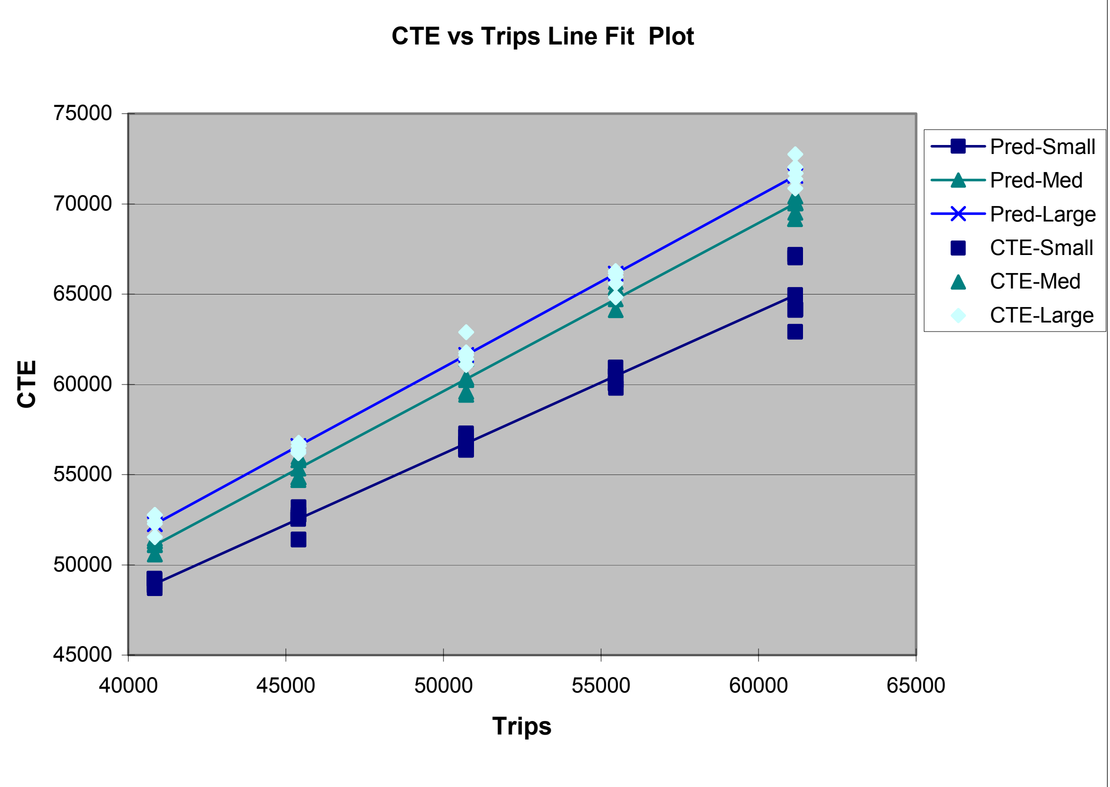

Figure 22 – Regression Analysis with *ITDA* as a Predictor

In addition to evaluating the relationships individually, a regression analysis was conducted using both predictors. The R-squared value for this equation was 97.1, indicating that the two predictors, *Trips* and *ITDA*, account for virtually all of the variation in the response variable CTE. This overall regression equation represents the generic network with a high degree of confidence, and will be used for later comparison with the case study network.

CASE STUDY

The case study network was modeled on a real-life urban area that is subject to hurricane evacuations. The region represents a medium sized population center with a variation of urban and rural densities, a well-structured transportation network with a range of roadway types and configurations, and an extensive level of signalization. Figure 23 shows the case study roadway network.

Generally a municipality or county will have established guidelines specifically for hurricane evacuation, though those requirements could be interpreted as necessary for other emergency events. Guideline implementation varies among municipalities, often based on the expected hazards. Some representative requirements for a region subject to hurricane evacuation include:

- Live in a mobile or manufactured home
- Live in a low-lying or flood-prone area
- Live in other specifically identified at-risk regions

Consideration must also be given to various procedures that the municipality may implement prior to expected hazard. For example, in the event of hurricane landfall, bridges and low-lying roadways may be closed due to winds or potential flooding.

The strategies developed in this case study will be generally applicable to locations susceptible to hurricanes. Future work would involve evaluating and modifying these strategies to other natural disasters such as wildfires.

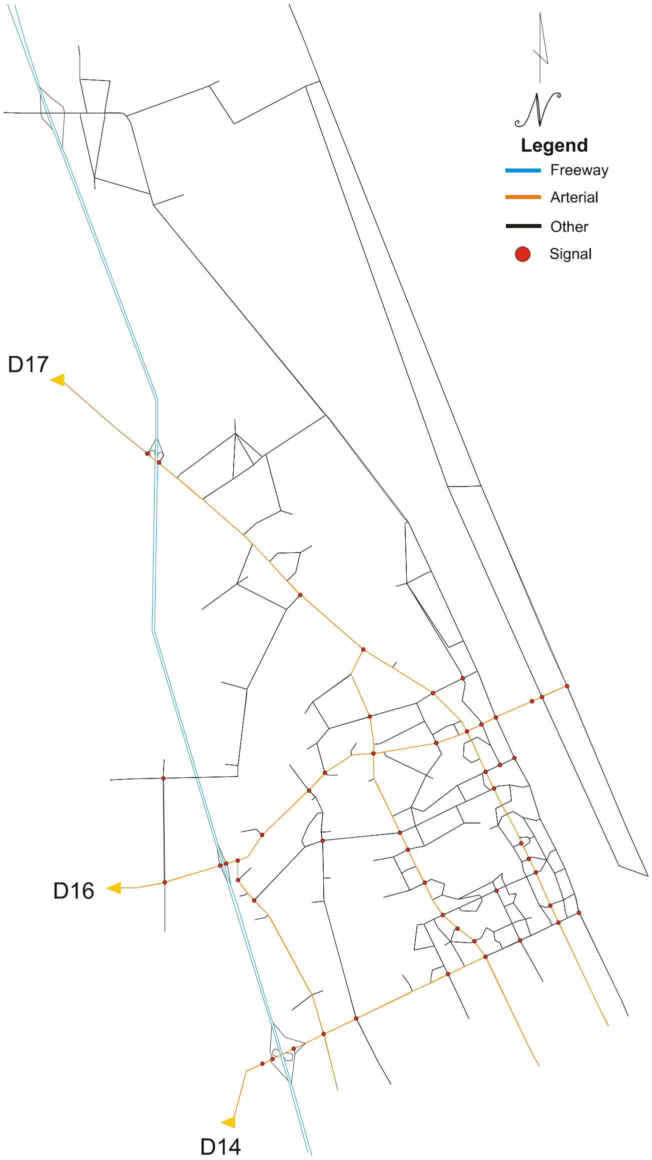

Figure 23 – Ormondsville Roadway Network

Network Assumptions

Given that this network was based on a real-world system, fewer assumptions regarding the physical characteristics and layout were necessary. However, many assumptions were necessary as related to behavior and operations.

Behavior

As with the previous analyses, evacuee departures were assumed to occur entirely within a 12-hour window, to correspond with the pilot network study. Departure rates followed the same “S” curve used for the pilot network.

Weightings were assumed equal for three physical destinations. This model most closely resembled the pilot network assumptions, and its results were used for subsequent analyses.

Network

It was assumed that there was one vehicle per household evacuating.

Operations

As stated earlier, INTEGRATION utilizes different vehicle routing options. It was assumed that 20% of all vehicles would take advantage of pre-trip or en-route information and adjust their routes accordingly. The remaining vehicles selected their routes at departure, and would not adjust. However, in order to simplify simulation runs, origins with single or relatively short paths to their destinations utilized DTA routing.

Signal timings were implemented to favor the primary east-west movement. Offsets were adjusted to provide green bands along the primary evacuation routes. Phasing in some cases was simplified, eliminating turn phases that were assumed would not be utilized and consequently not necessary.

Under the scenario conditions, it was assumed that no specific TAZ (origin) was treated differently due to hazard level or other circumstance.

Network Development

As with the pilot network, the case network was developed using AutoCAD. An ArcGIS file for the roadway system was imported and converted to an AutoCAD file. Links were then modified, added, or deleted as necessary to reduce the complexity of the model. The process discussed for the pilot network was utilized here as well.

Roadway characteristics for the underlying region were used in the development of the traffic network model. Number of lanes, turn lanes, speed limits, and turning movement restrictions were implemented based on existing data.

Origins within this network were identified based on TAZ locations for the underlying region. Each origin household population was based on representative census and planning data for the model region. All road links that provide access from each TAZ to designated evacuation routes were identified and included.

Signal locations were identified and incorporated into the network. While signal timings were available, they weren’t implemented in the evacuation scenarios.

OD Matrix

The process utilized to create the OD files for the pilot network was implemented here for the case network. The matrices in this case were 84x12 (origins by period) and 84x84 (origins by destinations) respectively. The first matrix utilized the departure rate values shown in Table 4. The second matrix used equal percentages for destinations D14, D16, and D17 as shown in Figure 23.

Computer Simulation

Using previously stated assumptions, five replications were run for the same trip values as for the generic network. Since the case network density was not homogeneous, the trips had to be scaled in a different manner. The case network was divided into three similar zones. The first zone consisted of the core population, and most resembled an urban grid network. The second zone resembled a transition region, with some urban and some rural characteristics. The third zone was the remainder of the network, and reflected more rural characteristics. Figure 24 shows these zones.

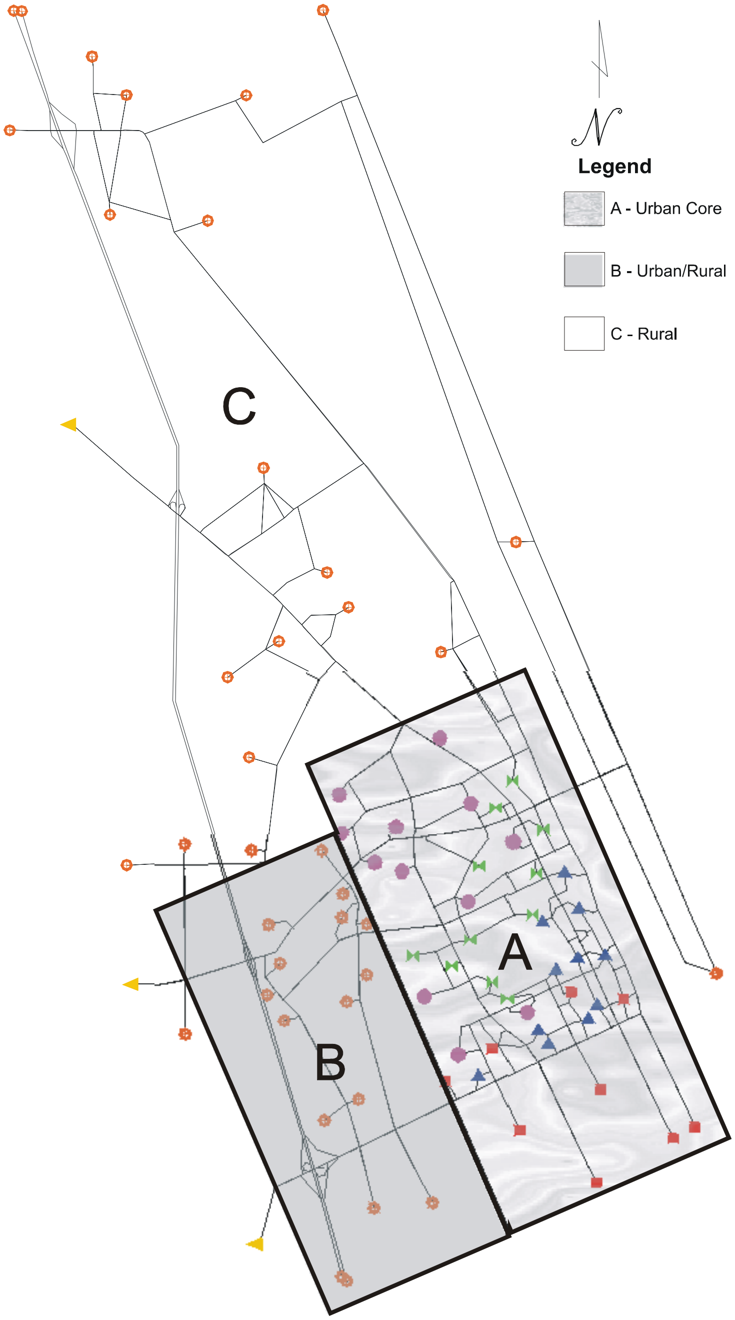

Figure 24 – Trip Scaling Zones

Trips were scaled by zone until the regional total was at the appropriate level. Table 21 lists the scaling factors and trip totals for each level.

Table 21 – Case Network *Total Trips* Scaling Factors

	Initial	40k	45k	50k	55k	60k
			Factor			
A	1.0	1.68	1.95	2.24	2.52	2.77
B	1.0	1.0	1.0	1.0	1.0	1.0
C	1.0	1.0	1.0	1.0	1.0	1.0
			Total Trips			
A	18257	30673	35602	40895	46008	50571
B	4715	4715	4715	4715	4715	4715
C	4885	4885	4885	4885	4885	4885
Sum	27857	40273	45202	50495	55608	60171

Table 22 lists the CTE (in seconds) and completed trips for the DO NOTHING scenario. Also shown are the mean and standard deviation values. CTE by intersection was defined as the time at which the last vehicle passed through the intersection and exited the network. It did not include vehicles passing through the intersection on the way to their final departure intersection.

Table 22 – Case Network DO NOTHING Results

Total Trips	40k		45k		50k		55k		60k	
Replication	CTE	Trips	CTE	Trips	CTE	Trips	CTE	Trips	CTE	Trips
1	46200	40077	52200	45042	57900	50316	61500	55455	73800	60015
2	49800	40082	53400	45043	59100	50309	63600	55452	72600	60011
3	47400	40083	53400	45041	59400	50311	65700	55457	74400	60014
4	47400	40084	52500	45040	63900	50308	66900	55452	72900	60012
5	47100	40085	50700	45038	59700	50309	66000	55457	74100	60015
Mean	47580	40082	52440	45041	60000	50311	64740	55455	73560	60013
StDev	1334.9	3.1	1110.4	1.9	2284.7	3.2	2177.8	2.5	776.5	1.8
C.I. (α=.05)	[46410, 48750]	[40079, 40085]	[51467, 53413]	[45039, 45043]	[57997, 62003]	[50308, 50314]	[62831, 66649]	[55453, 55457]	[72879, 74241]	[60011, 60015]

Replications were stopped at five, using an accepted rule of thumb that states that if the half-width of the confidence interval is within 10% of the mean, then no further replications are necessary. The variation in trips is due to the vehicle generation algorithm and origin-destination matrix in INTEGRATION. Each simulation was within 99.97% of the overall mean, and had negligible impacts on the overall results.

Regression Analysis

Figure 25 illustrates the simulated CTE (in seconds) for the case study network. It also shows the predicted CTE for the network using the overall regression model from Table 20 with the case study *ITDA* (903 km) as an input.

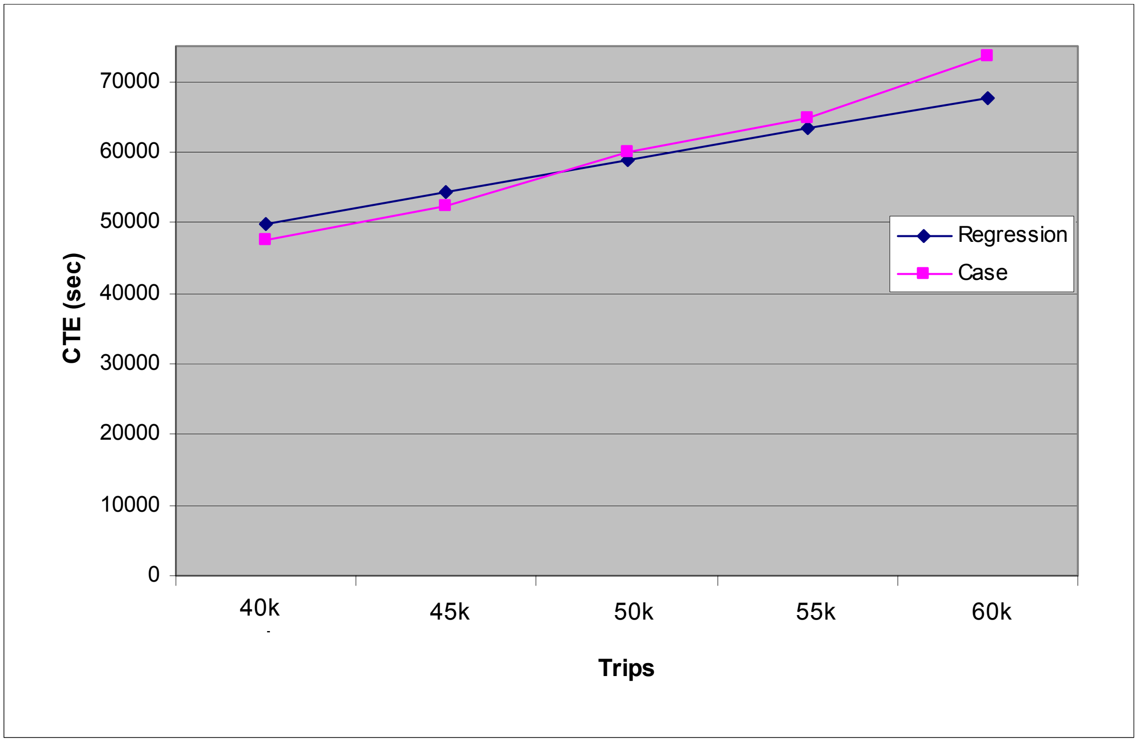

Figure 25 – Case Study Regression Comparison

As can be seen, over the given range of *Total Trips*, the pilot network regression model provided a reasonably close approximation for the case network CTE. One concern is the imbalance in the regression, whereas the underestimate at the lower trip totals is less than (in absolute terms) the overestimate at the higher trip totals. This is observed in the divergence at the higher trip count, and the calculated delta range of -4.7 % to 8.6 %. Further simulations to expand this regression model at both lower and higher trip totals would be required.

HEURISTIC STAGING

Main Entry: 1heu·ris·tic

Pronunciation: hyu-'ris-tik

Function: adjective

Etymology: German heuristisch, from New Latin heuristicus, from Greek heuriskein to discover; akin to Old Irish fo-fúair he found

: involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods <heuristic techniques> <a heuristic assumption>; also : of or relating to exploratory problem-solving techniques that utilize self-educating techniques (as the evaluation of feedback) to improve performance <a heuristic computer program>

- heu·ris·ti·cal·ly /-ti-k(&-)lE/ adverb

In order to reduce the threat levels of at-risk populations in the event of a hazardous situation, regional and local agencies implement procedures developed based upon the various elements discussed in the previous section. These procedures, however, require that personnel be able to evaluate risk level within a region. In 1994 the National Hurricane Program Task Force was established to assist the Federal Emergency Management Agency (FEMA) with planning an enhanced Hurricane Program.[8]

The Federal Emergency Management Agency (FEMA), through its Chemical Stockpile Emergency Preparedness Program (CSEPP), has developed a system of evacuation based on Emergency Planning Zones (EPZ). According to FEMA[9], most CSEPP communities have established two planning zones for emergency planning purposes. The Immediate Response Zone (IRZ) is

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[8] http://www.saw.usace.army.mil/floodplain/Hurricane%20Evacuation.htm

[9] CSEPP: Protective Actions, http://www.fema.gov/rrr/csepp4.shtm

> *"the area closest to the site where chemical munitions and agents are being stored until they can be destroyed. This zone, usually within a six to nine mile radius of the stockpile, would require the quickest warning and response. People living or working in this zone may need to take protective measures quickly."*

The Protective Action Zone (PAZ) is

> *"the area immediately beyond the Immediate Response Zone. This zone extends to a radius of six to 31 miles from the stockpile. Protective measures may be necessary in this zone, but there would be more time for warning and response."*

A third zone, the Precautionary Zone (PZ), is the outermost EPZ and extends from the PAZ outer boundary to a distance where the risk of adverse impacts to humans is negligible. This zone represents a general destination for evacuees.

Within the transportation management realm, planners subdivide study regions (typically non-rural) into Traffic Analysis Zones (TAZ). The metadata definition for a TAZ is "*a statistical entity delineated by state and/or local transportation officials for tabulating traffic-related census data*." According to the US Census definition, this data focuses particularly on journey-to-work and place-of-work statistics. In addition, a TAZ usually consists of one or more census blocks, groups, or census tracts.[10]

Whereas EPZ boundaries are determined based upon risk analyses that take into consideration the specific types of agents and munitions stored, as well as local weather

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[10] http://www.census.gov

and geographic conditions, TAZ boundaries consider none of these, and to a certain extent are the antithesis of the EPZ. However, most urbanized areas are divided into TAZs, while only regions subject to known chemical or nuclear hazards are required to have defined EPZs.

Given the variability of many evacuation events, the use of EPZ is too limited to provide guidance in evaluating regional evacuation needs. It is here that the use of TAZs could prove beneficial. It should be noted that each of these optimization techniques described earlier utilizes the concept of the EPZ when developing evacuation strategies.

The objective in this project is to reduce the risks to a population in the event of an emergency situation. In order for emergency management personnel to better identify an effective staging scheme, evacuation zones must be defined in terms of parameters applicable to evacuation. Subsequent strategies would utilize these parameters in relation to the hazard and network configuration to reduce CTE relative to standard evacuation procedures.

In order to identify an effective evacuation staging scheme, parameters that define risk and other characteristics must be determined. This essentially parallels the standard decision analysis process (Church and Cova 2000).

The concept under consideration is a strategy to identify an improved order of evacuation for a region. Following is a preliminary list of zonal parameters that might influence the level of risk of a zone in an evacuation event:

- Population density
- Roadway exit capacity
- Distance to safety/shelter
- Distance to major evacuation route
- Number of other regions / level of population density to transit

In addition to these, the various hazard types also have an impact on the risk of zones. Such factors are not all necessarily applicable to a zone; that is a function of zone location. Specific to hurricanes these factors include:

- Flooding susceptibility
- Storm surge levels/risk

Furthermore, a global factor is event warning time. This can influence which procedures are put into place for an effective evacuation strategy.

Pilot Study Network

The generic grid network was used as a testbed for staging strategies. The purpose of this was twofold: first, to determine the validity of the various strategies; and, second, to understand the relationship between trip density and the staging strategies.

Scenario Development

One assumption for this network was a primary east-to-west evacuation direction, analogous to a coastal-to-inland evacuation under hurricane conditions. For all scenarios, three primary evacuation destinations were used, representing northwest, west, and southwest destination routes.

The staging strategy considered here was based on origin-destination distance. The network origins were divided into quartiles based on composite distance for each origin node to all designated evacuation destinations. This division is shown in Figure 26.

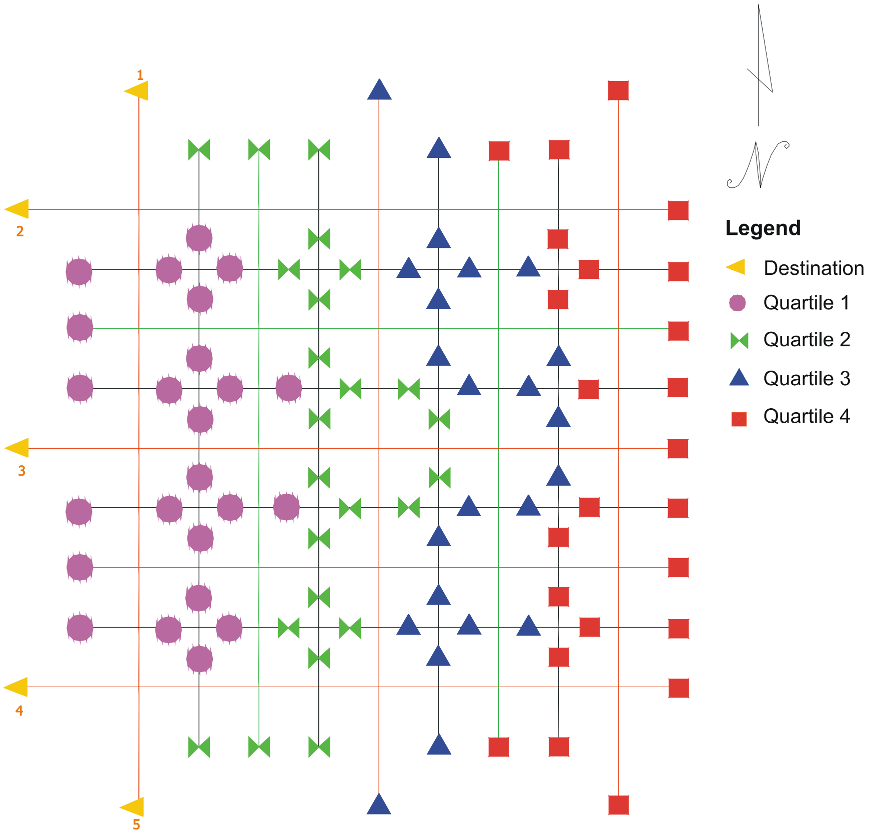


Figure 26 – Generic Origin-Destination Network

DO NOTHING Scenario

The baseline scenario assumed that all origins began their evacuations at the same time, i.e. Time 0. This established a target CTE (in seconds) for determining the success or failure of each staging scenario.

Staging Scenarios

Three different staging strategies were identified, each with two variations; therefore six total scenarios were evaluated. Stage timing was based on the network quartile division. The following combinations were used:

- HALF – Departures are grouped into the two quarters of the network nearest and the two quarters farthest from three destinations.
- QUARTER – Each quarter is its own departure group.
- SPLIT – The nearest (or farthest) quarter is a group, with the remaining three quarters being a second group.

Furthermore, the two variations for these combinations were NEAR and FAR; these were referenced to the destinations, and determined the order of departure for each group. The total scenarios were as follows:

- HALF NEAR (HN) – The half of the network nearest departs first; the rest are shifted.
- HALF FAR (HF) – The half of the network farthest departs first; the rest are shifted.

- QUARTER NEAR (QN) – The quarter of the network nearest departs first; the remaining three quarters are shifted in sequence (to farthest).

- QUARTER FAR (QF) – The quarter of the network farthest departs first; the remaining three quarters are shifted in sequence (to nearest).

- SPLIT NEAR (SN) – The quarter of the network nearest departs first; the rest (remaining three) are shifted together.

- SPLIT FAR (SF) – The quarter of the network farthest departs first; the rest (remaining three) are shifted together.

Figure 27, Figure 28, and Figure 29 illustrate the various staging orders for each of the above scenarios.

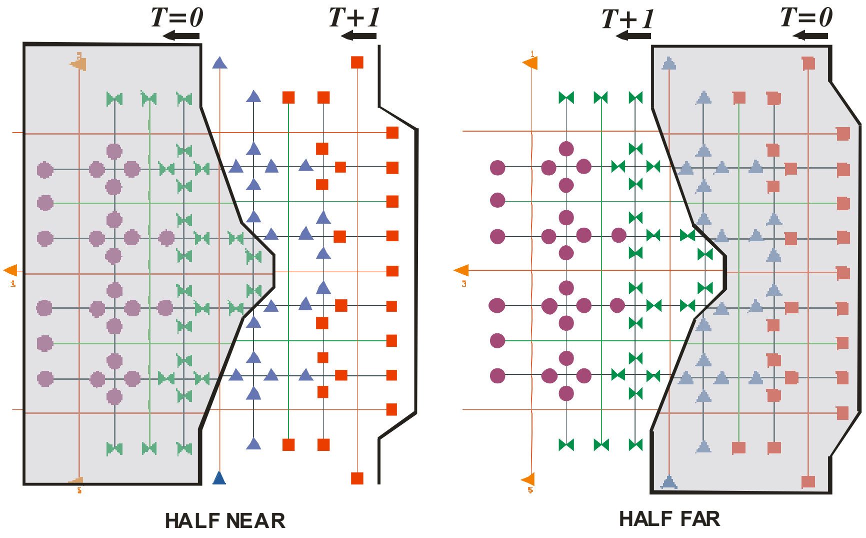
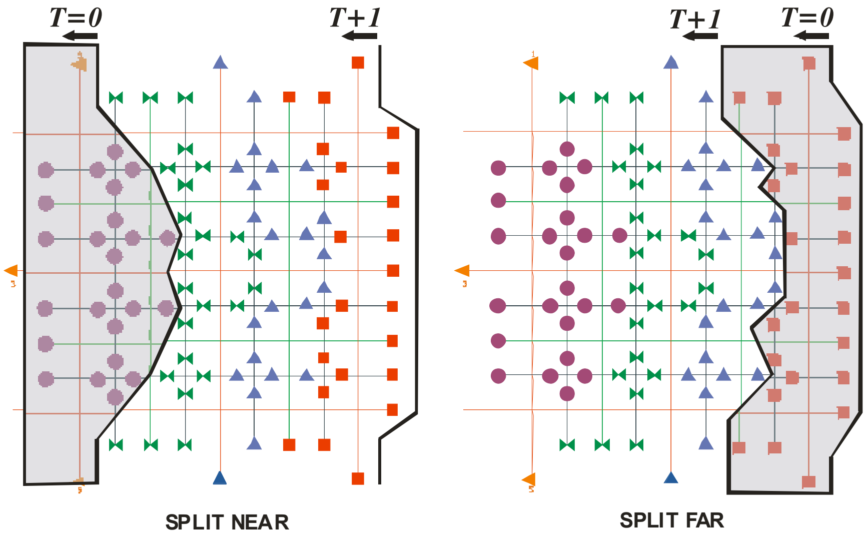


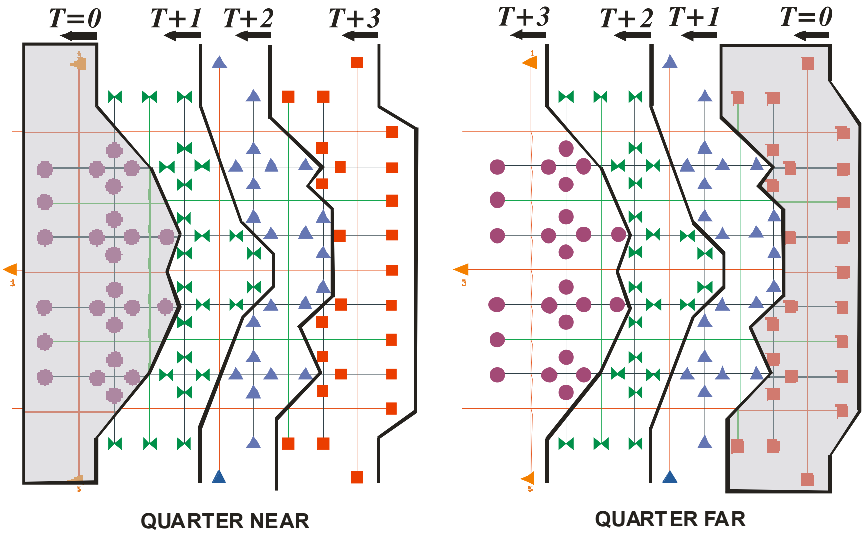
Figure 27 – Half Near/Far Staging Scenario Departure Sequencing



SPLIT NEAR

SPLIT FAR

Figure 28 – Split Near/Far Staging Scenario Departure Sequencing



QUARTER NEAR

QUARTER FAR

Figure 29 – Quarter Near/Far Staging Scenario Departure Sequencing

(1) Timing

In order to determine the amount of time shift necessary for effective staging, upper and lower bounds must first be established. This shift window is derived by defining staging goals in terms of target reduction in CTE. This target reduction is a percentage improvement in the CTE over doing nothing (i.e. no shift). For example, if the CTE equals 43200 seconds, a 10% reduction would equate to a target CTE of 38800 seconds (43200 * 0.9).

Using this framework, the upper and lower bounds can be determined using the following relationships:

$$CTE_{Target} = (1\text{-}Reduction) * CTE_{DoNothing} \tag{7}$$

$$S_{Max} = CTE_{Target} - (DW + TT) \tag{8}$$

where

CTE_{Target} : target CTE (seconds)

$CTE_{DoNothing}$: CTE for simultaneous departure (seconds)

Reduction : fraction

S_{Max} : maximum shift in departure time

DW : departure window (10 hours)

TT : max free flow travel time for the network

Since CTE is defined as the time it takes for the last vehicle to reach a safe destination (i.e. exit the network), the minimum CTE is the time of the final vehicle's departure from its origin plus the maximum free flow travel time for the network, or *DW + TT*. Figurex illustrates this relationship graphically.

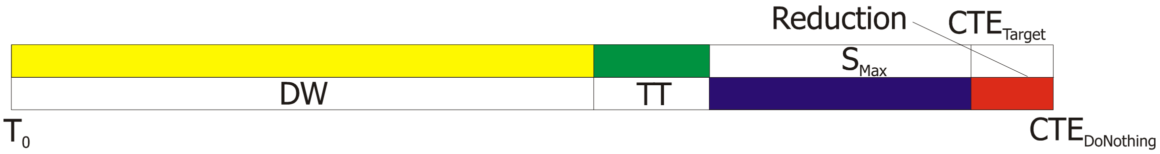


Figure 30 – Departure Shift Calculation

Furthermore, the DO NOTHING is equivalent to $S_{max} = 0$; therefore, the minimum target CTE is

$$CTE_{Target}\,(\mathrm{min}) = DW + TT \qquad (9)$$

From this the maximum *Reduction* (fraction) is calculated by

$$Reduction\ (max) = 1 - (DW + TT\,)\,/\,CTE_{DoNothing} \qquad (10)$$

thus setting the upper bound. The upper bound is equivalent to a simultaneous departure; consequently CTE_{Target} cannot be shifted beyond this value.

(2) OD trip statistics

The range of *Total Trips* previously simulated (40k, 45k, 50k, 55k, 60k) was simulated here.

Methodology

Due to the internal programming structure of INTEGRATION, not all replications complete successfully. The vehicle routing algorithms and buffers limit path choices such that some vehicles would not complete their trips.

Given this, a pool of ten random seeds was chosen, and from these, five were selected as the base seeds for simulation. If a replication encountered errors, an additional replication was run using the next seed from the pool, and if successful was used in place of the defective run. Should the five pool seeds encounter errors, additional seeds were utilized until a successful run was achieved.

Due to simulation time and resource constraints, a single replication was run for every scenario within each identified *Total Trips*. Also due to these constraints, target CTEs were calculated in 10% increments using the CTE_{Target} across departure shift range. Smaller increments could be used, though 10% provides a reasonable representation. Using the previously discussed *CreateOD* macro, a specific origin-destination matrix file was generated for each of these departure shifts.

Given the total number of possible scenarios for each trip set, and taking into consideration both the computational requirements and likelihood for success of each scenario, it was necessary to narrow the scenarios to those showing the greatest probability of reduction in CTE. For this it was necessary to establish a statistical testing protocol and criteria for reduction. A number of techniques were considered. Scenario results could be ranked in order of value, and then selecting the five with the lowest values, or selecting the scenarios that were lower than some aspect of the DO NOTHING scenario (e.g. the average CTE). However, these techniques did not provide any indication of statistical success; for example a single result that fell outside the top five might still be part of a potentially successful scenario.

The goal of this test is to determine if one population is shifted with respect to another; therefore the Wilcoxin Two Sample Rank-Sum Test, also known as the Mann-Whitney Test, was chosen. This test also provided some statistical indication of all scenario results.

The Mann-Whitney Test is a nonparametric alternative to the two-sample t-test, and is based solely on the order of the observations from the two samples. Consequently, it provides a technique for quickly evaluating populations based on very few data points.

Inspection of the Mann-Whitney Critical value table reveals a minimum rank total value defined for the number of data points n_1 and n_2 for the two samples. Using this value, ranking criteria for the single scenario value in relation to the $CTE_{DoNothing}$ values can be established, without knowing the remaining scenario data points. Specifically, the best-case for the remaining scenario runs (four total) is ranks 1 through 4, or a rank sum of 10. Therefore, the known scenario value rank must be

$$R_{KSV} \leq MWCV_{n_1,n_2} - 10 \tag{11}$$

where

R_{KSV}: Rank of known scenario value

$MWCV_{n_1,n_2}$: Mann-Whitney Critical Value for n_1, n_2

From this, the known values can be ordered, and if the scenario value exceeds a certain position in the order, this value would exceed the R_{KSV}. Consequently, the scenario would be discarded. Those that do not fail would be fully simulated and reevaluated using the Mann-Whitney Test. This is illustrated in the following section.

Data Analysis

Table 23 shows the *Reduction*, CTE_{Target}, and S_{max} for each trip total.

Table 23 – Target CTE by Trip Total

Trip Total	Reduction (%)	CTE_{Target} (sec)	S_{max} (sec)
40k	10	46035	8595
	20	40920	3480
45k	10	49707	12267
	20	44184	6744
50k	10	54184	16744
	20	48163	10723
	30	42143	4703
55k	10	58628	21188
	20	52114	14674
	30	45599	8159
60k	10	62867	25427
	20	55882	18442
	30	48896	11456

For $n_1 = 5$ and $n_2 = 5$, the $MWCV_{n_1,n_2}$ (α=0.05) is 17.[11] Using the above methodology, $R_{KSV} = 7$. This means that the known scenario value can rank no higher than 7 out of 10

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[11] Table IX (page 702), Probability and Statistics in Engineering and Management Science by William Hines and Douglas Montgomery, 3rd Edition (1990).

data points. Therefore, using the existing set of $CTE_{DoNothing}$ data points, the scenario value must be exceeded by at least three of the DN values (e.g. less than or equal to the rank 3 $CTE_{DoNothing}$). The selection criteria were determined from Table 15 values and this scenario CTE value. Table 24 lists the five replications for the ranked $CTE_{DoNothing}$ values and the selection criteria, by trip total.

Table 24 – Ranked $CTE_{DoNothing}$ by Trip Total

			Trip Total		
Rank	40k	45k	50k	55k	60k
1	50580	54690	59430	64110	69150
2	51300	54840	59580	65190	69510
3	51300	54840	60240	65370	70050
4	51120	55800	60360	65370	70140
5	51450	55980	61410	65670	70410

Table 25 shows the results for a single replication for all shift scenarios at each given trip total. Scenarios meeting the selection criteria are bolded.

Table 25 – CTE (in seconds) Results for Shift Scenarios

	Total Trips				
Scenario	40k	45k	50k	55k	60k
HN10	52680	56310	60960	66720	73080
HN20	51480	58740	61170	65550	71160
HN30	-	-	62460	67800	72300
HF10	**50580**	55650	**59970**	**64110**	**69510**
HF20	52650	55620	60600	**64650**	**70050**
HF30	-	-	62310	**65310**	**69060**
QN10	53850	60060	64020	70890	76470
QN20	52680	59500	64590	69300	74490
QN30	-	-	63390	68250	75990
QF10	52710	56160	61230	66810	**69870**
QF20	52500	57240	61380	66600	71850
QF30	-	-	63090	66810	72480
SN10	56910	63540	71040	80640	90870
SN20	55020	59070	66630	72390	81930
SN30	-	-	63210	70230	76710
SF10	53640	58350	64650	71310	80490
SF20	53760	59910	63900	70500	76170
SF30	-	-	63300	68730	75990
CTE Criteria	51300	54840	60240	65370	70050

Figure 31 shows the CTE values (in seconds) in graphic form. The $CTE_{DoNothing}$ criteria value is also indicated.

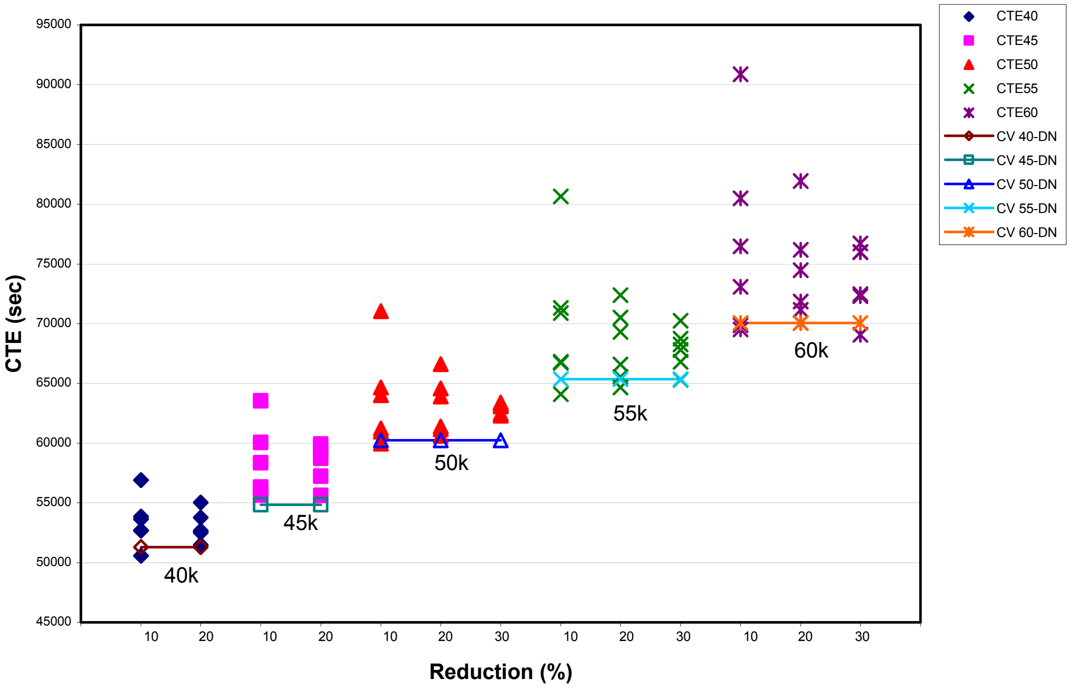

Figure 31 – Scenario Results (single run)

The scenarios identified in Table 25 were fully simulated. Table 26 shows the results for the replications. Also shown is the mean and standard deviation for each set.

Table 26 – Scenario Replications

Total Trips	Scen	Run 1	2	3	4	5	Mean	StDev
40	HF-10	50580	50970	50790	52590	51450	51276	801.7
50	HF-10	59970	59790	60330	61410	60150	60330	636.4
55	HF-10	64110	65550	65550	65010	64650	64974	615.7
55	HF-20	64650	65550	65010	65550	64650	65082	451.8
55	HF-30	66210	65100	65490	66000	64950	65550	548.7
60	HF-10	69510	69330	68970	71130	69150	69618	868.9
60	HF-20	70050	70770	70590	71850	68790	70410	1116.9
60	HF-30	69060	68730	71460	71970	70530	70350	1429.8
60	QF-10	69870	71850	72570	71850	72030	71634	1029.3

A Mann-Whitney Test was conducted using the values from Table 15. Table 27 shows the rank sum totals for each scenario.

Table 27 – Scenario Rank Sums

Total Trips	Scen	Run					Rank Total
		1	2	3	4	5	
40	DN	5	6.5	6.5	1.5	8.5	28
40	HF-10	1.5	4	3	10	8.5	27
50	DN	8	6	9.5	2	1	26.5
50	HF-10	4	3	7	9.5	5	28.5
55	DN	5	6.5	1.5	10	6.5	29.5
55	HF-10	1.5	8.5	8.5	4	3	25.5
55	DN	5	6.5	1	10	6.5	29
55	HF-20	2.5	8.5	4	8.5	2.5	26
55	DN	4	5.5	1	8	5.5	24
55	HF-30	10	3	7	9	2	31
60	DN	7	5.5	2.5	8	9	32
60	HF-10	5.5	4	1	10	2.5	23
60	DN	4.5	3	2	6	7	22.5
60	HF-20	4.5	9	8	10	1	32.5
60	DN	5	4	3	6	7	25
60	HF-30	2	1	9	10	8	30
60	DN	4	2	1	5	6	18
60	QF-10	3	7.5	10	7.5	9	37

Based on $MWCV_{5,5}$ = 17, none of the scenarios appears to indicate a shift in CTE. However, inspection of the values for the HF-10 scenario for 60k trips reveals a potential outlier value of 71130. Outliers lessen the ability of the sample to represent the population of interest. Therefore, a conventional technique[12] for identifying values that are “extreme” was utilized on this dataset.

1. Order values

depth:	1	2	3	2	1
value:	68970	69150	69330	69510	71130

2. Find median depth
   $(n+1) / 2 = (5+1) / 2 = 3$
   median = 69330
3. Find depth of fourths
   $(\text{median depth} + 1) / 2 = (3 + 1) / 2 = 2$
4. Find values of fourths
   lower fourth: 69150
   upper fourth: 69510
5. Find fourth spread
   fourth spread = upper fourth – lower fourth = 69510 – 69150 = 360
6. Calculate the upper and lower outlier bounds
   LOB = lower fourth – 1.5 (fourth spread) = 69150 – 1.5(360) = 68610
   UOB = upper fourth + 1.5(fourth spread) = 69510 + 1.5(360) = 70050

An outlier is defined as any score which is outside the upper and lower outlier bounds. Based on the above analysis, there are no lower value outliers; however, the value of 71130 is greater than the upper bound of 70050, and can be considered an outlier. Since the replication did not show any unusual computational performance or other cause for the result, the value was kept in the analysis. However, five additional replications were made to provide a larger set of data. Table 28 shows ranked CTE values (in seconds) for the added runs.

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[12] Hoaglin, D.C., Mosteller, F., & Tukey, J.W. (1983). Understanding Robust and Exploratory Data Analysis. New York: Wiley.

Table 28 – Scenario Rank Sum with Extended Data

Run	DN	Rank	HF-10	Rank
1	70050	12	69510	9.5
2	69510	9.5	69330	7.5
3	69150	5.5	68970	3.5
4	70140	13	71130	15
5	70410	14	69150	5.5
6	-	-	69870	11
7	-	-	69330	7.5
8	-	-	68610	2
9	-	-	68430	1
10	-	-	68970	3.5

The *MWCV* criteria for n_1=5, n_2=10, and α=0.05 is 54.0. A Mann-Whitney analysis from Minitab v13 shows that, using the null hypothesis of DN = HF-10, versus the alternative hypothesis that DN > HF-10, the test is significant at 0.0485 (adjusted for ties). Based on this analysis the HF-10 scenario for *Total Trips* of 60k shows a potential reduction in CTE.

Case Study Network

Given that staging strategies showed viability using the pilot network, these strategies were evaluated using the same case study network discussed previously. Many of the assumptions used for the pilot network had to be adjusted to account for physical network differences. Some of these assumptions were discussed in the previous section on the case study network.

Scenario Development

As with the pilot network, the staging strategy considered here was based on origin-destination distance. Based on the results of the pilot network, staging strategies were ineffective at lower trip densities. Therefore, the staging strategies were applied to the "urban" section of the case network (previously identified as Zone A). The urban section was comprised of the approximately grid-like portion of the network similar to the pilot network, and is illustrated in Figure 32. Everything outside this region was considered the rural section.

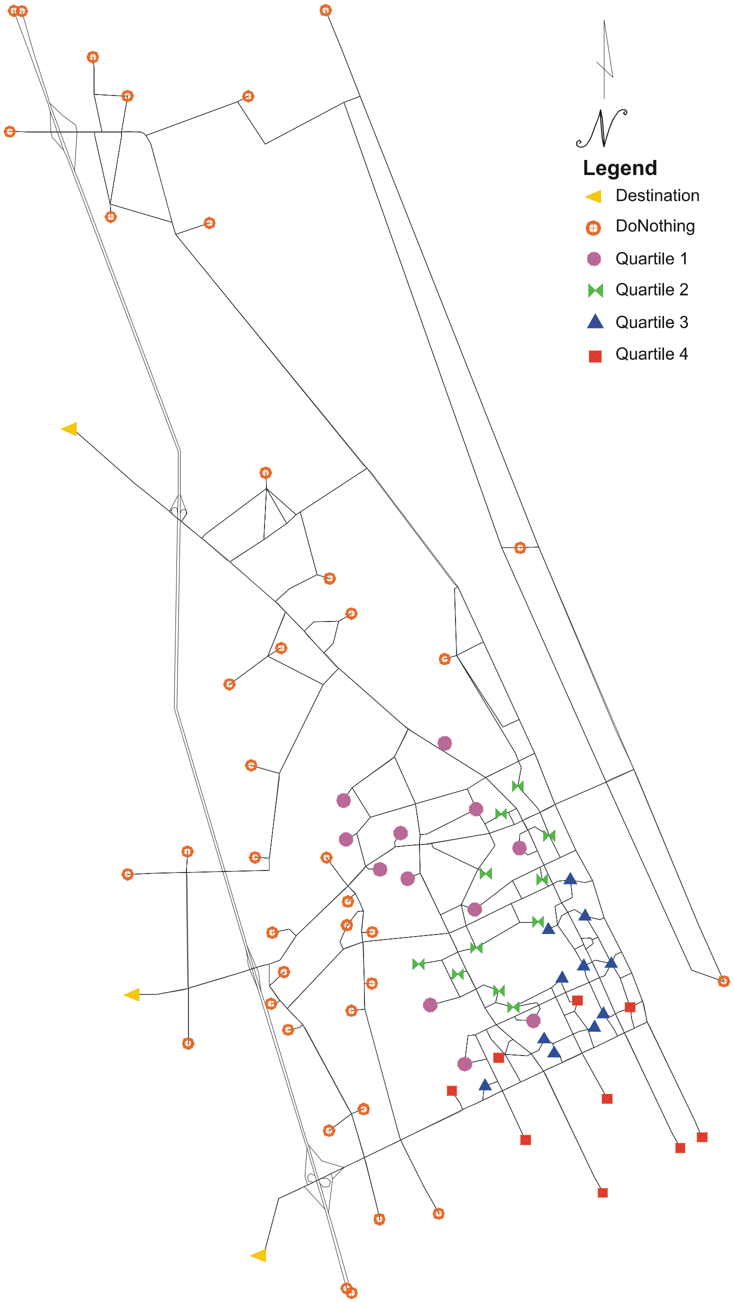

Figure 32 – Ormondsville Origin Groups

The east-west movement assumption for the pilot network was applied to the case study network as well. The destinations from the previous DO NOTHING analysis were utilized here.

DO NOTHING Scenario

The baseline scenario assumed that all origins began with evacuations at the same time, i.e. Time 0. This established a target CTE (in seconds) for determining the success or failure of each staging strategy.

Staging Scenarios

The same strategies tested on the pilot network were used for the case network. Figure 32 illustrates the origin groupings used in this network. Like the pilot network, the urban network origins were divided into quartiles, based on composite distance for each origin node to all designated evacuation destinations. This is further illustrated in Figure 33.

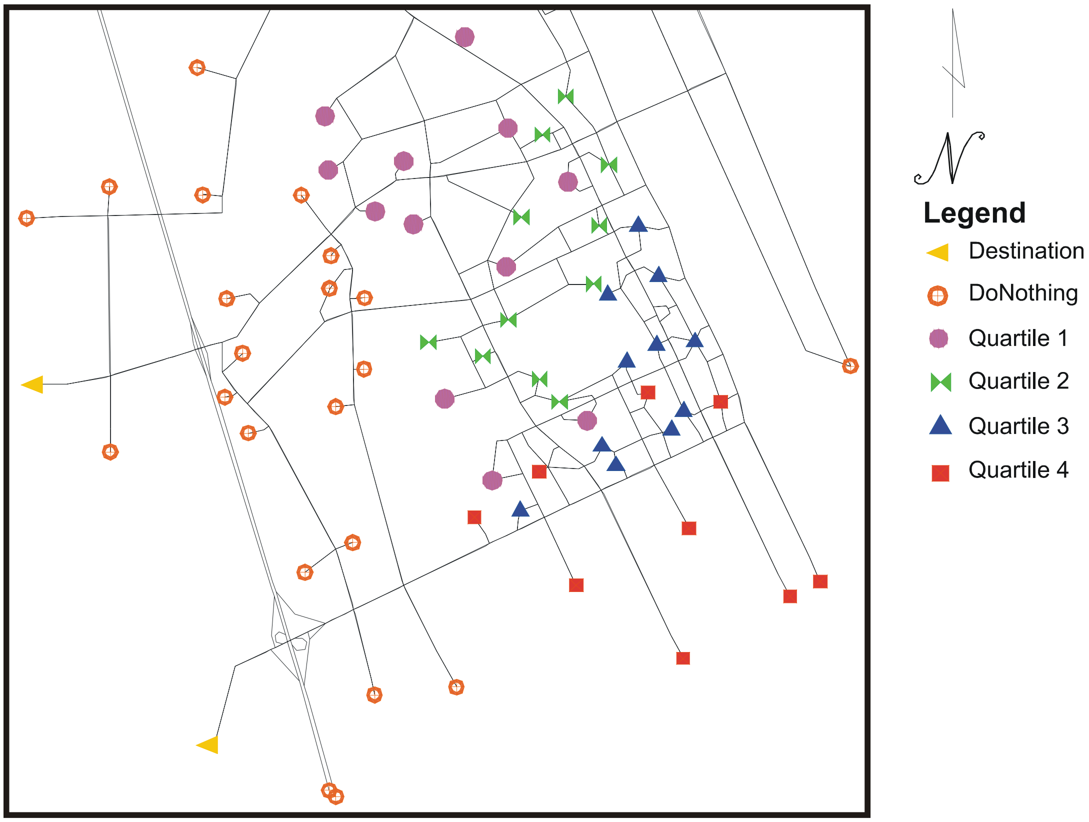

Figure 33 – Case Study Core Region

(3) Timing

The process utilized previously to determine time shift for each strategy was utilized here as well.

(4) OD trip statistics

The *Total Trips* matched that of the pilot network for the scenarios tested.

Methodology

As with the previous simulations, ten seeds were randomly pre-selected, and every scenario used the same seed set. Five replications were run for the DO NOTHING scenario. The mean $CTE_{DoNothing}$ was calculated from these replications, establishing the value by which each scenario was evaluated for success or failure.

Based on the results of the generic network analysis, five replications were run for each scenario shift within the successful shift type (i.e. HF/HN, QF/QN, SF/SN) for the appropriate *Total Trips*. Target CTEs were calculated in 10% increments using the $CTE_{DoNothing}$ across departure shift range. A specific origin-destination matrix file was generated for each of these departure shifts.

The results were analyzed in Minitab v13 using a one-way ANOVA, with the Dunnett's option. This provided a two-sided confidence interval for the difference between each scenario (treatment) and a control mean (DO NOTHING scenario). The family error rate was set at 0.10 for an individual error rate of 0.045. The resulting confidence intervals allow for the practical significance of differences among means, in addition to statistical significance. The implicit null hypothesis of no difference between means is rejected if and only if zero is not contained in the confidence interval.

Data Analysis

From the generic network simulations, the HF-10 scenario for 60k total trips indicated potential reduction in CTE. Table 29 shows the Reduction, CTE_{Target}, and S_{max} for each

HF-x scenario for the 60k total trips for the case network. These values were calculated from the CTE values in Table 22.

Table 29 – Case Network Target CTE

Trip Total	Reduction (%)	CTE_{Target} (sec)	S_{max} (sec)
60k	10	66204	28299
	20	58848	20943
	30	51492	13587

Table 30 shows the CTE results for the HF-x scenarios. Listed are the trips and CTE (in seconds) for each of five runs, as well as the mean and standard deviations.

Table 30 – Case Study Scenario Results

Run	Trips	HF-10	HF-20	HF-30
1	60020	73800	71700	67500
2	60015	73800	68400	70500
3	60014	74700	75000	73800
4	60018	75000	69600	66600
5	60015	74400	69900	76200
Mean	60016	74340	70920	70920
StDev	2.5	536.7	2568.5	4083.7

Inspection of the above values reveals a number of potential outliers. The previously utilized conventional technique for identifying “extreme” values was utilized on this dataset. Table 31 shows the analysis; columns are median, lower fourth value (LFV), upper fourth value (UFV), spread, lower outlier bound (LOB), and upper outlier bound (UOB).

Table 31 – Outlier Analysis

Scenario	Median	LFV	UFV	Spread	LOB	UOB
HF-10	74400	73800	74700	900	72450	76050
HF-20	69900	69600	71700	2100	66450	74850
HF-30	70500	67500	73800	6300	58050	83250

From this analysis, an outlier is indicated in the HF-20 dataset (75000). Since the replication did not show any unusual computational performance or other cause for the result, the value was kept in the analysis. However, five additional replications for each scenario were made to provide a larger set of data. Table 24 shows trips and CTE values (in seconds) for the additional runs.

Table 32 – Scenario Additional Runs

Run	Trips	HF-10	HF-20	HF-30
6	60015	74100	68700	68400
7	60010	73500	70200	71100
8	60015	73200	69000	66000
9	60007	76800	75600	66900
10	60021	73500	69300	69900

Figure 34 shows the results of the one-way ANOVA analysis in Minitab v13.

```
One-way ANOVA: CTE versus Scenario
Analysis of Variance for CTE
Source     DF        SS          MS           F          P
Scenario   3     132645857   44215268       8.00       0.00
Error      31    171441000    5530355
Total      34    304086857
                                          Individual 95% CIs For Mean
                                          Based on Pooled StDev
Level      N        Mean       StDev      --------+---------+---------+--------
1          5        73560       777                     (-------*--------)
2          10       74280       1051                         (-----*-----)
3          10       70740       2576           (-----*-----)
4          10       69690       3323       (-----*-----)
                                          --------+---------+---------+--------
Pooled StDev = 2352                           70000     72500     75000
```

Figure 34 – One-way ANOVA: CTE versus Scenario

Figure 35 shows the boxplot for the analysis.

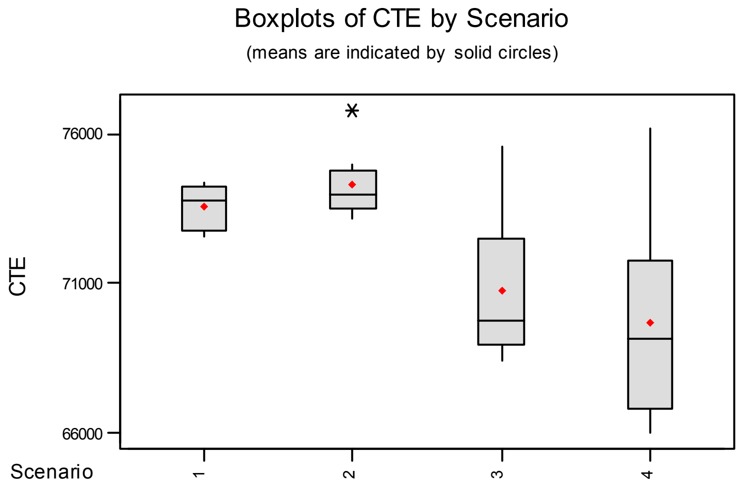

Figure 35 – Scenario Boxplot

Figure 36 shows the results of Dunnett’s comparison.

```
Dunnett's comparisons with a control
          Family error rate = 0.100
      Individual error rate = 0.0449
Critical value = 2.09
Control = level (1) of Scenario
Intervals for treatment mean minus control mean
Level    Lower    Center    Upper   --+---------+---------+---------+-----
2        -1972      720     3412                    (--------*--------)
3        -5512    -2820     -128         (--------*--------)
4        -6562    -3870    -1178    (--------*--------)
                                    --+---------+---------+---------+-----
                                    -6000     -3000       0      3000
```

Figure 36 – Dunnett’s comparisons with a control

Summary

A number of shift strategies showed the potential to reduce CTE; however, only one at the highest trip total proved successful both on a generic grid network and the case study network. An examination of smaller incremental shifts (e.g. 5%) might have revealed a greater sensitivity to this factor, and perhaps additional successful strategies. It should be noted that because the *Reduction* variable is a function of the $CTE_{DoNothing}$, and because this CTE is a function of the specific network, similar *Reduction* values correspond only in relative terms.

One area to investigate regarding total trips for the case network is the shifting of trip densities. Given the case study configuration, a larger density within the grid portion of the network (Zone A of Figure 24) would likely influence the results of the shift strategies.

CONCLUSIONS

Hazardous events, both natural and man-made, present tremendous risks to communities throughout the world. These events typically necessitate the evacuation of local or regional populations to safe destinations or shelters, and have warning times ranging from minutes to hours or even days. Some events are predictable in either location or potential impacts, while others are quite random, varying in size and duration.

The size and scope of these events present a challenge to the emergency management or agency personnel who must see to the health and safety of those living or working in their jurisdiction. They must make many decisions regarding the best methods and actions to take to evacuate at-risk populations in an effective and timely manner. This dissertation examined three different aspects of evacuation of an at-risk region from an analysis standpoint.

The first portion of this work looked at the determination of clearance time using the Input/Output analysis method, and compared the results with the output of a simulated network. Analysis showed that the I/O analysis method (based on HCM techniques) underestimated the simulated CTE as a function of network size, with a correction factor range of 1.09 to 1.19. This correction factor can be used by regions for planning purposes; knowing total trips and size, they can roughly estimate clearance time.

Furthermore, the I/O analysis results were highly sensitive to assumptions made concerning approach volumes and rates. These values are typically not known at the time of the evacuation, and therefore I/O analysis results can vary substantially, and do not have a high degree of confidence. Departure intersection approach percentages and vehicle routings must be assumed when multiple approaches are possible. Estimated percentages may not accurately reflect those observed in the field, or within a simulation. Since clearance times are a function of arrival rates versus approach capacities, a highly skewed approach distribution can indicate extensive queues, whereas a more even distribution may indicate no queues.

The I/O method did not provide an accurate estimation for a network clearance time due to the many assumptions that must be made. The I/O method does not take into account thru traffic at departure intersections; i.e. it does not accommodate vehicles that are passing through the destination intersection on paths to their final destinations. Since these volumes are not known, and can vary over time, no accurate assumption can be made.

The I/O method also assumes unconstrained arrival rates, i.e. all vehicles arrive at the departure intersection without accounting for deferred trips (vehicles delayed when entering the network), and travel time variations from all origins. In addition, traffic congestion upstream of the approach, or elsewhere in the network, cannot be estimated. This homogeneous arrival rate estimation does not accurately reflect real arrival rates and times.

The second portion examined the technique of using a generic traffic network model to reasonably estimate the CTE of a case study network. A regression model was developed that incorporated total network trips, and an estimator of network size *ITDA*, or average internal travel distance. This regression model was then compared with the results of the simulated case study. Nine regression analyses were conducted for the generic network, using CTE as the response variable, and size (*ITDA*) and trips (*Trips*) as predictors. Four of the analyses held size constant while varying *Total Trips*. Four more analyses held trips constant while varying size. The final included both size and trips in the regression analysis. Regression results indicated a strong relationship between the predictor variables (either *Trips* or *ITDA*) and CTE. The overall equation also indicated that the two predictors, *Trips* and *ITDA*, account for virtually all of the variation in the response variable CTE.

Over the given range of *Total Trips*, the generic network regression model provided a reasonably close approximation for the case network CTE, though they began to diverge at the highest trip count. Calculated deltas ranged from -4.7% to 8.6%. From this it was concluded that a generic network of similar dimensions can serve as a surrogate for a user-specific network under these conditions. This will enable regions to quickly estimate clearance time based on total anticipated trips, and distances determined from available data or field data collection. Further simulation is necessary to expand the size and trip range regression model.

The last portion of this work examined the technique of staging departure times within a region to reduce the CTE. It looked at six different geographic grouping strategies, HF/HN, QF/QN, and SF/SN, each with varying shifts in departure times. An initial evaluation was conducted using the generic network as a testbed, and strategies that showed potential CTE reduction were implemented on the case study network.

Given the total number of scenarios to test, and the length of time required for simulation, a Mann-Whitney test was used to quickly identify potentially viable scenarios. A single replication was run for each scenario, and viable scenarios were fully simulated. From this, the HF geographic grouping showed potential across virtually all trip totals, with the QF grouping showing potential at the highest trip total. In addition, some staging strategies can actually exacerbate the situation, increasing CTE by upwards of 30%. Since scenarios that increased CTE were not of interest, this increase was based on a single replication, and thus is a gross estimate. It does, however, indicate that a situation can be made worse if the incorrect staging strategy is selected.

Since only a shift in CTE was of interest, a Mann-Whitney was conducted on the fully simulated scenarios. Based on this analysis only one scenario, the HF-10 for 60k total trips, showed potential reduction. From this it was deduced that staging is dependent upon *Total Trips*, and that lower *Total Trips* would not benefit from implementation of any staging strategy.

Given the inherent differences between the generic and case study networks, it was determined that all HF strategies for 60k trips should be evaluated using the case network. A complete simulation was conducted, and an ANOVA analysis was run using Dunnett's comparison. The results indicated that the HF grouping with 20% and 30% departure shifts showed potential for CTE reduction. From this it was concluded that the generic network could be used as a testbed for strategies that would show success on a case network.

The framework and methodologies developed in this dissertation can serve as a prototype for future evacuation research and studies. Using this work as a foundation, further research should examine sensitivity of the generic network to signal timings, total number of destinations, departure window length, assumed loading curve, destination weighting, and greater number of *Total Trips*. This research could also examine how these sensitivities apply to non-grid network configurations. Larger networks and greater trips would be impractical to model microscopically. Given this, other simulation packages, such as INTEGRATION v1.5 and Dynasmart-P, should be evaluated for use given the total CPU requirements of microscopic simulation.

APPENDIX A
SAMPLE INTEGRATION INPUT

```
INTEGRATION Node File
442   1     1
1     1108.1      6032.5      1     -1    00000.00
2     114         5039.4      1     -2    00000.00
3     114.7       3039.9      1     -3    00000.00
4     113.7       1040.4      1     -4    00000.00
5     1108.1      46.7        1     -5    00000.00
6     3107.6      6031.6      1     -6    00000.00
7     3107.6      47.6        1     -7    00000.00
8     5107.1      6033.9      1     -8    00000.00
9     5107.1      43.8        1     -9    00000.00
10    1608.2      5539.2      1     -10   00000.00
11    2107.8      5539.3      1     -11   00000.00
12    2608.1      5539.3      1     -12   00000.00
13    3607.8      5539.3      1     -13   00000.00
14    4107.3      5539.3      1     -14   00000.00
15    4607.6      5539.3      1     -15   00000.00
16    5606.9      5039.4      1     -16   00000.00
17    5607.3      4539.5      1     -17   00000.00
18    5606.9      4039.7      1     -18   00000.00
19    5607.3      3539.8      1     -19   00000.00
20    5606.9      3039.9      1     -20   00000.00
21    5607.3      2540        1     -21   00000.00

<snip>

567   2145.9      1540.5      4     0     00000.00
568   2607.5      1078.5      4     0     00000.00
569   2683.9      1040.6      4     0     00000.00
570   3031.3      1040.2      4     0     00000.00
571   2107.6      1116.6      4     0     00000.00
572   2108        1464.1      4     0     00000.00
573   2184        1040.6      4     0     00000.00
574   2531.5      1040.2      4     0     00000.00
575   1608.3      1540.3      4     0     00000.00
577   1608.3      2002        4     0     00000.00
579   2070.4      1539.8      4     0     00000.00
582   1107.8      1616.4      4     0     00000.00
583   1108.3      1963.9      4     0     00000.00
584   1146.2      1540.5      4     0     00000.00
585   1607.7      1078.5      4     0     00000.00
586   1684.1      1040.6      4     0     00000.00
587   2031.6      1040.2      4     0     00000.00
588   1107.8      1116.6      4     0     00000.00
589   1108.3      1464.1      4     0     00000.00
590   1184.3      1040.6      4     0     00000.00
591   1531.8      1040.2      4     0     00000.00
```

```
INTEGRATION Link File
ID     From   To     Len     Spd   Flow   Lan    SVar   SCap   Den    Proh   PStrt  PStp   Opp1   Opp2   Sig    Ph1    DP1    Ph2    DP2    Ph3    DP3    Ph4    DP4    VProh  Surv  Desc
-748   1      1      1       1     1
1      150    2      0.994   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AB3
2      152    150    0.076   72    1900   -3     0.2    62     81     0      0      0      114    0      -1     2      111    0      0      0      0      0      0      0      11111 36AB1
3      2      152    0.918   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AB0
4      36     154    0.462   16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AAD
5      154    155    0.037   16    1900   1      0.2    14     249    0      0      0      300    0      10001 0      0      0      0      0      0      0      0      0      11111 36AAC
6      155    36     0.5     16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AAB
7      156    35     0.5     56    1900   1      0.2    48     105    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AAA
8      158    156    0.076   56    1900   -1     0.2    48     105    0      0      0      314    0      -6     2      111    0      0      0      0      0      0      0      11111 36AA8
9      35     158    0.424   56    1900   1      0.2    48     105    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AA7
10     34     160    0.462   16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AA4
11     160    161    0.037   16    1900   1      0.2    14     249    0      0      0      444    0      10001 0      0      0      0      0      0      0      0      0      11111 36AA3
12     161    34     0.5     16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AA2
13     162    3      0.993   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36AA1
14     164    162    0.076   72    1900   -3     0.2    62     81     0      0      0      458    0      -9     2      111    0      0      0      0      0      0      0      11111 36A9F
15     3      164    0.917   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36A9E
16     33     166    0.462   16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36A9B
17     166    167    0.037   16    1900   -2     0.2    14     249    0      0      0      588    0      10001 0      0      0      0      0      0      0      0      0      11111 36A9A
18     167    33     0.5     16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36A99
19     168    32     0.5     56    1900   1      0.2    48     105    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36A98
20     170    168    0.076   56    1900   -1     0.2    48     105    0      0      0      602    0      -14    2      111    0      0      0      0      0      0      0      11111 36A96
21     32     170    0.424   56    1900   1      0.2    48     105    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36A95

<snip>

728    582    173    0.076   72    1900   -3     0.2    62     81     0      0      0      743    0      0      0      0      0      0      0      0      0      0      0      11111 3667D
729    583    168    0.076   72    1900   -3     0.2    62     81     0      0      0      598    0      -14    1      111    0      0      0      0      0      0      0      11111 3667C
730    173    583    0.954   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 3667B
731    88     584    0.208   16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 3667A
732    584    173    0.038   16    1900   -2     0.2    14     249    0      0      0      23     0      10001 0      0      0      0      0      0      0      0      0      11111 36679
733    173    88     0.246   16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36678
734    87     585    0.209   16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36677
735    585    200    0.038   16    1900   -2     0.2    14     249    0      0      0      50     0      10001 0      0      0      0      0      0      0      0      0      11111 36676
736    200    87     0.247   16    1900   1      0.2    14     249    0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36674
737    195    586    0.954   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36673
738    586    200    0.076   72    1900   -3     0.2    62     81     0      0      0      747    0      0      0      0      0      0      0      0      0      0      0      11111 36672
739    587    195    0.076   72    1900   -3     0.2    62     81     0      0      0      710    0      -18    2      111    0      0      0      0      0      0      0      11111 36671
740    200    587    0.954   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 36670
741    173    588    0.954   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 3666F
742    588    174    0.076   72    1900   -3     0.2    62     81     0      0      0      53     0      -17    1      111    0      0      0      0      0      0      0      11111 3666E
743    589    173    0.076   72    1900   -3     0.2    62     81     0      0      0      728    0      0      0      0      0      0      0      0      0      0      0      11111 3666D
744    174    589    0.954   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 3666C
745    200    590    0.954   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 35864
746    590    174    0.076   72    1900   -3     0.2    62     81     0      0      0      26     0      -17    2      111    0      0      0      0      0      0      0      11111 35863
747    591    200    0.076   72    1900   -3     0.2    62     81     0      0      0      738    0      0      0      0      0      0      0      0      0      0      0      11111 35862
748    174    591    0.954   72    1900   2      0.2    62     81     0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      11111 35861
```

```
INTEGRATION Signal File
21     1      3600
1
1      180    150    210    0      2      85     5      85     5     0
2      180    150    210    0      2      85     5      85     5     0
3      180    150    210    0      2      85     5      85     5     0
4      180    150    210    0      2      85     5      85     5     0
5      180    150    210    0      2      85     5      85     5     0
6      180    150    210    0      2      85     5      85     5     0
7      180    150    210    0      2      85     5      85     5     0
8      180    150    210    0      2      85     5      85     5     0
9      180    150    210    0      2      85     5      85     5     0
10     180    150    210    0      2      85     5      85     5     0
11     180    150    210    0      2      85     5      85     5     0
12     180    150    210    0      2      85     5      85     5     0
13     180    150    210    0      2      85     5      85     5     0
14     180    150    210    0      2      85     5      85     5     0
15     180    150    210    0      2      85     5      85     5     0
16     180    150    210    0      2      85     5      85     5     0
17     180    150    210    0      2      85     5      85     5     0
18     180    150    210    0      2      85     5      85     5     0
19     180    150    210    0      2      85     5      85     5     0
20     180    150    210    0      2      85     5      85     5     0
21     180    150    210    0      2      85     5      85     5     0
```

```
INTEGRATION Lanestripe File
132
1     2     3     100   010   011   00000 00000 00000
2     14    3     100   010   011   00000 00000 00000
3     17    2     100   011   00000 00000
4     23    2     100   011   00000 00000
5     26    3     100   010   011   00000 00000 00000
6     29    3     100   010   011   00000 00000 00000
7     32    2     100   011   00000 00000
8     38    2     100   011   00000 00000
9     41    3     100   010   011   00000 00000 00000
10    44    2     100   011   00000 00000
11    50    2     100   011   00000 00000
12    53    3     100   010   011   00000 00000 00000
13    56    3     100   010   011   00000 00000 00000
14    59    3     100   010   011   00000 00000 00000
15    62    2     100   011   00000 00000
16    65    3     100   010   011   00000 00000 00000
17    66    3     100   010   011   00000 00000 00000
18    72    3     100   010   011   00000 00000 00000
19    73    3     100   010   011   00000 00000 00000
20    76    2     100   011   00000 00000
21    79    3     100   010   011   00000 00000 00000

<snip>

113   667   3     100   010   011   00000 00000 00000
114   670   3     100   010   011   00000 00000 00000
115   671   3     100   010   011   00000 00000 00000
116   674   3     100   010   011   00000 00000 00000
117   675   3     100   010   011   00000 00000 00000
118   699   2     100   011   00000 00000
119   702   3     100   010   011   00000 00000 00000
120   703   3     100   010   011   00000 00000 00000
121   710   3     100   010   011   00000 00000 00000
122   711   3     100   010   011   00000 00000 00000
123   728   3     100   010   011   00000 00000 00000
124   729   3     100   010   011   00000 00000 00000
125   732   2     100   011   00000 00000
126   735   2     100   011   00000 00000
127   738   3     100   010   011   00000 00000 00000
128   739   3     100   010   011   00000 00000 00000
129   742   3     100   010   011   00000 00000 00000
130   743   3     100   010   011   00000 00000 00000
131   746   3     100   010   011   00000 00000 00000
132   747   3     100   010   011   00000 00000 00000
```

```
INTEGRATION Detector Input File
16    0           2
1     1     112   0.1   0.005 300   369F3
2     1     1     0.1   0.005 300   36AB3
3     1     13    0.1   0.005 300   36AA1
4     1     27    0.1   0.005 300   36A8F
5     1     52    0.1   0.005 300   36A67
6     10    114   0.070 0.005 30    A-E
7     10    116   0.001 0.005 30    A-EB
8     10    297   0.070 0.005 30    A-N
9     10    454   0.070 0.005 30    B-N
10    10    456   0.001 0.005 30    B-NB
11    10    458   0.070 0.005 30    B-E
12    10    460   0.001 0.005 30    B-EB
13    10    585   0.070 0.005 30    B-S
14    10    583   0.001 0.005 30    B-SB
15    10    742   0.070 0.005 30    C-S
16    10    746   0.070 0.005 30    C-E
```

APPENDIX B
SAMPLE INTEGRATION OUTPUT

```
INTEGRATION Runerr File
=================================================================
    INTEGRATION Release 2.30g: TRAFFIC NETWORK SIMULATION MODEL

              Copyright 1984-2005  M. Van Aerde & Assoc., Ltd.

                    Medium     Version - Jan.  2005
=================================================================

 A. Array dimensions :

    - max number of od pairs           =       50000
    - max number of vehicles           =      125000
    - max number of vehicle types      =           5
    - max number of links              =        1250
    - max node number                  =        1250
    - max links into/out of node       =          12
    - max number of vehicles on network=      500000
    - max zone number                  =         150
    - max number of future time steps  =          20
    - max signal number                =         125
    - max number of phases per signal  =           8
    - max incident number              =          12
    - max number of files              =          50
    - max number random number seeds   =           6
    - max number equilibrium paths vt1 =          25
    - max number of forward tree nodes =           1
    - max number of forward minutes    =          60
    - max number of macro zone clusters=         150
    - max number of network lanes      =        8750
    - max veh concurrent on network    =       50000
    - max detector station number      =        1250

     - Opening Master file: gm-69-1800-f16.int

     - Master file title: Medium Generic Rt5-2 10hr S=69 3-dest 12/6/05

     - Simulation Time (sec):    96000
     - Output Rate 1 (sec)  :      900
     - Output Rate 2 (sec)  :      900
     - Output Rate 3 (sec)  :        0
     - Output Rate 4 (sec)  :        0

     - Master File Format   :            3

     - Input  Subdirectory  : Generic\

     - Output Subdirectory  : Generic\Output\GM-69-eq3-1800-f16-

     - Summary output   : summary.out

---------------------------------------------
 11. Error check flag settings
     - No error check values set
-----------------------------
     - Reading file:   1  NODES.dat
     - Reading file:   2  LINKS-med.dat
 - Reading link=         100 of     748 pass 1
 - Reading link=         200 of     748 pass 1
```

```
 - Reading link=         300 of     748 pass 1
 - Reading link=         400 of     748 pass 1
 - Reading link=         500 of     748 pass 1
 - Reading link=         600 of     748 pass 1
 - Reading link=         700 of     748 pass 1
 - Reading link=         748 of     748 pass 1
     - Reading link=         500 of     748 pass 2
     - Reading file:   3  SIGNALS.dat
     - Reading file:   4  OD-GM-3dm.dat
  - Reading od  =         500 of         2565
  - Reading od  =        1000 of         2565
  - Reading od  =        1500 of         2565
  - Reading od  =        2000 of         2565
  - Reading od  =        2500 of         2565
     - Reading file:   5  INCIDENT.dat
     - Reading file:   6  none
     - Reading file:   7  none
 ------------------------------------------------
    - Building trees - distance only - pass:            1
           - tree number =            1
           - tree number =            3
           - tree number =            5
 ------------------------------------------------
    - Building trees - distance only - pass:            2
---------------------------------------------


     - Decomposing O-Ds into individual vehicles
     - First and last od pair :           1        2850
     - First/last od override :           0      999999
    - Vehicle Generation o-d pair:      1000      7089
    - Vehicle Generation o-d pair:      2000     42028
       - Total vehicles to generate:     45402
   - vehicle      100 generated at time=     1491 secs.
   - vehicle      200 generated at time=     2145 secs.
   - vehicle      300 generated at time=     4032 secs.
   - vehicle      400 generated at time=     4394 secs.

<snip>

   - vehicle    45100 generated at time=    31807 secs.
   - vehicle    45200 generated at time=    33940 secs.
   - vehicle    45300 generated at time=    34556 secs.
   - vehicle    45400 generated at time=    35091 secs.

    - Completed data input phase

    - Initiating minimum path calculations
       - Minimum path vehicle type           1
   - Tree Build:           0           1        2200
       - Minimum path vehicle type           2
   - Tree Build:           0           2        2200
   - Tree Build:           0           3        2200
   - Tree Build:           0           4        2200
   - Tree Build:           0           5        2200

    - Initiating simulation logic
```

```
 B. Simulation speed :

 Calling Read 8 - First Time
 Return  Read 8/9 - First Time:           8           1           0
 Calling Read 8 - First Time
 Return  Read 8/9 - First Time:           9           1           0
    - sim time:     0.00  after      0.39 real mins.
   - Tree Build:         360           1           2        1000
   - Tree Build:         360           2           7        2200
    - sim time:    10.00  after      0.47 real mins.
   - Tree Build:         720           1           3        1000
   - Tree Build:         720           2           8        2200

<snip>

    - sim time:  1590.00  after    389.83 real mins.
   - Tree Build:       95400           1           1        1000
   - Tree Build:       95400           2           6        2200
   - Tree Build:       95760           1           2        1000
   - Tree Build:       95760           2           7        2200
    - sim time:  1600.00  after    389.92 real mins.

 C. Activity distribution :

    - activity   110 percent =    0.0    - total:     0.1
    - activity   120 percent =    0.0    - total:     0.1
    - activity   130 percent =    0.0    - total:     0.5

<snip>

    - activity   710 percent =    0.0    - total:     1.1
    - activity   720 percent =    0.0    - total:     0.6
    - activity   730 percent =    0.0    - total:     0.4
---------------------------------------------
 D. Simulation summary statistics:

    - Simulation clock time       :        96000
    - Total simulation horizon    :        96000
    - Real world time elapsed     :        23395
    - Number of errors found      :            0
    - Scheduled departures        :        45402
    - Deferred departures         :            0
    - Current vehicles en-route   :            0
    - Total trips completed       :        45402
```

```
INTEGRATION Summary File
Total Statistics:
  1      36415.00       8987.00      0.00      0.00      0.00      45402.00     - vehicle trips
  2      36415.00       8987.00      0.00      0.00      0.00      45402.00     - person trips
  3     336902.03      98030.09      0.00      0.00      0.00     434932.13     - vehicle-km
  4     336902.03      98030.09      0.00      0.00      0.00     434932.13     - person-km
  5     408307.78      97023.97      0.00      0.00      0.00     505331.75     - vehicle-stops
  6  351645824.00   87005088.00      0.00      0.00      0.00  438650912.00     - vehicle-secs
  7  351645824.00   87005088.00      0.00      0.00      0.00  438650912.00     - person-secs
  8  233561568.00   54253868.00      0.00      0.00      0.00  287815424.00     - total delay
  9  152787920.00   47768636.00      0.00      0.00      0.00  200556560.00     - stopped delay
 10   80773792.00    6485082.00      0.00      0.00      0.00   87258872.00     - accel/decel delay
 11 4027812610.00 1127149700.00      0.00      0.00      0.00 5154962430.00     - accel-noise
 12     105888.08      26856.79      0.00      0.00      0.00     132744.86     - fuel (l)
 13      17102.34       4459.16      0.00      0.00      0.00      21561.50     - HC (g)
 14     390994.41     101978.26      0.00      0.00      0.00     492972.66     - CO (g)
 15      46199.05      12749.34      0.00      0.00      0.00      58948.39     - NOx (g)
 16  247212144.00   62684908.00      0.00      0.00      0.00  309897056.00     - CO2 (g)
 17          0.00          0.00      0.00      0.00      0.00          0.00     - PM (g)
 18   11344373.00    4126653.50      0.00      0.00      0.00   15471026.00     - crashes*10e-6
 19    4538581.50    1649614.13      0.00      0.00      0.00    6188195.50     - injury crashes
 20       2775.77        781.58      0.00      0.00      0.00       3557.35     - fatal crashes
 21      41117.78      12129.72      0.00      0.00      0.00      53247.50     - no damage
 22   10880598.00    3983484.25      0.00      0.00      0.00   14864082.00     - minor damage
 23     250532.36      78158.05      0.00      0.00      0.00     328690.41     - moderate damage
 24          0.00          0.00      0.00      0.00      0.00          0.00     - dollars of toll
```

```
Average Statistics:
 1       1.0000       1.0000      0.0000    0.0000    0.0000       1.0000     - vehicle trips
 2       1.0000       1.0000      0.0000    0.0000    0.0000       1.0000     - person trips
 3       9.2517      10.9080      0.0000    0.0000    0.0000       9.5796     - vehicle-km
 4       9.2517      10.9080      0.0000    0.0000    0.0000       9.5796     - person-km
 5      11.2126      10.7960      0.0000    0.0000    0.0000      11.1302     - vehicle-stops
 6    9656.6201    9681.2158      0.0000    0.0000    0.0000    9661.4883     - vehicle-secs
 7    9656.6201    9681.2158      0.0000    0.0000    0.0000    9661.4883     - person-secs
 8    6413.8833    6036.9277      0.0000    0.0000    0.0000    6339.2676     - total delay
 9    4195.7412    5315.3037      0.0000    0.0000    0.0000    4417.3506     - stopped delay
10    2218.1462     721.6070      0.0000    0.0000    0.0000    1921.9169     - accel/decel delay
11  110608.6090  125420.0160      0.0000    0.0000    0.0000  113540.4300     - accel-noise
12       2.9078       2.9884      0.0000    0.0000    0.0000       2.9238     - fuel (l)
13       0.4697       0.4962      0.0000    0.0000    0.0000       0.4749     - HC (g)
14      10.7372      11.3473      0.0000    0.0000    0.0000      10.8580     - CO (g)
15       1.2687       1.4186      0.0000    0.0000    0.0000       1.2984     - NOx (g)
16    6788.7446    6975.0649      0.0000    0.0000    0.0000    6825.6255     - CO2 (g)
17       0.0000       0.0000      0.0000    0.0000    0.0000       0.0000     - PM (g)
18     311.5302     459.1803      0.0000    0.0000    0.0000     340.7565     - crashes*10e-6
19     124.6349     183.5556      0.0000    0.0000    0.0000     136.2979     - injury crashes
20       0.0762       0.0870      0.0000    0.0000    0.0000       0.0784     - fatal crashes
21       1.1291       1.3497      0.0000    0.0000    0.0000       1.1728     - no damage
22     298.7944     443.2496      0.0000    0.0000    0.0000     327.3883     - minor damage
23       6.8799       8.6968      0.0000    0.0000    0.0000       7.2396     - moderate damage
24       0.0000       0.0000      0.0000    0.0000    0.0000       0.0000     - dollars of toll
```

```
INTEGRATION Detector Output File
    0    0    0
    30     1     1    0.00     0     0     0.0     0
    30     2     1    0.00     0     0     0.0     0
    30     3     1    0.00     0     0     0.0     0
    30     4     1    0.00     0     0     0.0     0
    30     5     1    0.00     0     0     0.0     0
    60     1     1    0.00     0     0     0.0     0
    60     2     1    0.00     0     0     0.0     0
    60     3     1    0.00     0     0     0.0     0
    60     4     1    0.00     0     0     0.0     0
    60     5     1    0.00     0     0     0.0     0
    90     1     1    0.00     0     0     0.0     0
    90     2     1    0.00     0     0     0.0     0
    90     3     1    0.00     0     0     0.0     0
    90     4     1    0.00     0     0     0.0     0
    90     5     1    0.00     0     0     0.0     0
   120     1     1    0.00     0     0     0.0     0
   120     2     1    0.00     0     0     0.0     0
   120     3     1    0.00     0     0     0.0     0
   120     4     1    0.00     0     0     0.0     0
   120     5     1    0.00     0     0     0.0     0
   150     1     1    0.00     0     0     0.0     0
   150     2     1    0.00     0     0     0.0     0
   150     3     1    0.00     0     0     0.0     0
   150     4     1    0.00     0     0     0.0     0
   150     5     1    0.00     0     0     0.0     0

<snip>

 56280     1     1    0.00     0     0     0.0     0
 56280     2     1    0.00     0     0     0.0     0
 56280     3     1    0.00     0     0     0.0     0
 56280     4     1    0.00     0     0     0.0     0
 56280     5     1   68.65  1200   600    43.7     1
 56310     1     1    0.00     0     0     0.0     0
 56310     2     1    0.00     0     0     0.0     0
 56310     3     1    0.00     0     0     0.0     0
 56310     4     1    0.00     0     0     0.0     0
 56310     5     1    0.00     0     0     0.0     0
 56340     1     1    0.00     0     0     0.0     0
 56340     2     1    0.00     0     0     0.0     0
 56340     3     1    0.00     0     0     0.0     0
 56340     4     1    0.00     0     0     0.0     0
 56340     5     1    0.00     0     0     0.0     0
 56370     1     1    0.00     0     0     0.0     0
 56370     2     1    0.00     0     0     0.0     0
 56370     3     1   86.08   120    60     3.5     1
 56370     4     1    0.00     0     0     0.0     0
 56370     5     1    0.00     0     0     0.0     0
 56400     1     1    0.00     0     0     0.0     0
 56400     2     1    0.00     0     0     0.0     0
 56400     3     1    0.00     0     0     0.0     0
 56400     4     1    0.00     0     0     0.0     0
 56400     5     1    0.00     0     0     0.0     0
```

REFERENCES

1. Alsnih, Rahaf, and Stopher, Peter (2004) “A Review of the Procedures Associated With Devising Emergency Evacuation Plans”, *Transportation Research Board*
2. Bateman, Julie, and Edwards, Bob (2002), “Gender and Evacuation: A Closer Look at Why Women Are More Likely to Evacuate for Hurricanes”, *Natural Hazards Review*, August 2002, pp 107-117
3. Boxill, Sharon, and Yu, Lei (2000), “An Evaluation of Traffic Simulation Models for Supporting ITS Development”, *Center for Transportation Training and Research*
4. Chen, Xuwei (2004), “Agent-Based Simulation of Evacuation Strategies Under Different Road Network Structures”, *Transportation Research Board*
5. Church, Richard, and Cova, Thomas (2000), “Mapping Evacuation Risk on Transportation Networks Using a Spatial Optimization Model”, *Transportation Research Part C*, 2000, pp 321-336
6. Church, Richard, and Sexton, Ryan (2002), “Modeling Small Area Evacuation: Can Existing Transportation Infrastructure Impede Public Safety?”, *California Department of Transportation Final Report*, April 2002
7. Farahmand, Kambiz (1997), “Application of Simulation Modeling to Emergency Population Evacuation”, *Proceedings of the 1997 Winter Simulation Conference*
8. Franzese, Oscar, and Han, Lee (2000), “A Methodology for the Assessment of Traffic Management Strategies for Large-Scale Emergency Evacuation”, *Oak Ridge National Labs*
9. Franzese, Oscar, and Han, Lee (2000), “Modeling Mass-Evacuation Traffic Operations Due to Hurricanes”, *Oak Ridge National Labs*
10. Fu, Haoqiang (2004), “A Sequential Logit Dynamic Travel Demand Model For Hurricane Evacuation”, *Transportation Research Board*
11. Hobeika, Antoine (1985), “MASSVAC: A Computer Simulation Model for Evaluating Evacuation Plans”, *Virginia Polytechnic Institute*
12. Hobeika, A (1987), “TEDSS – A Software for Evacuating People Around Nuclear Power Stations”, *Applications of Advanced Technology in Transportation*, pp 688-695
13. Keller, Gordon (2002), “Rural Roads Vulnerability Reduction Assessment, Mitigation Measures, and Training”, *Natural Hazards Review*, November 2002, pp 139-147
14. Lewis, Donald C., “Transportation Planning for Emergency Evacuation”, ITE Journal, August, 1985, pp 31-35.

15. Luo, Anna, Maguire, Stephen, and Chang, Edmond (2002), “Analysis of Traffic Modeling for Evacuation Systems”, *Office of Emergency Transportation*
16. Moeller, M, Urbanik, T, Desrosiers, A (1981), “CLEAR (Calculates Logical Evacuation And Response): A Generic Transportation Network Model for the Calculation of Evacuation Time Estimates”, *Texas Transportation Institute*
17. Ngo, Ehren (2001), “When Disasters and Age Collide: Reviewing Vulnerability of the Elderly”, *Natural Hazards Review*, May 2001, pp 80-89.
18. Perkins, Judy (2001), “Modeling Transit Issues Unique to Hurricane Evacuations: North Carolina’s Small Urban and Rural Areas”, *North Carolina A&T State University Transportation Institute*
19. Rakha, H., and Van Aerde, M. (2004), *INTEGRATION User’s Guide*, Volumes I and II, M. Van Aerde & Associates
20. Sattayhatewa, Phansak, and Ran, Bin (2000), “Developing a Dynamic Traffic Management Model for Nuclear Power Plant Evacuation”, *Transportation Research Board*
21. Sorenson, J.H., Vogt, B.M., and Mileti, D.S. (1987), “Evacuation: An Assessment of Planning and Research”, Oak Ridge National Laboratory, report prepared for the Federal Emergency Management Agency Washington D.C.
22. Southworth, Frank, Nanson, Bruce, and Venigalla, Mohan (1991), “DYMOD: Towards Real Time, Dynamic Traffic Routing During Mass Evacuations”, *Oak Ridge National Labs*
23. Tunasar, C., Bender, G., Young, H (1998), “Modeling Curbside Vehicular Traffic at Airports”, *Proceedings of the 1998 Winter Simulation Conference*, pp 1113-1117
24. Van Aerde, M, Hellinga, B, Baker, M, and Rakha, H (1996), “INTEGRATION: An Overview of Traffic Simulation Features”, *Transportation Research Board Annual Meeting*
25. Van Burgsteden, M. C., Joustra, P. E., Bouwman, M. R., Hullegie, M (2000), “Modeling Road Traffic on Airport Premises”, *Proceedings of the 2000 Winter Simulation Conference*, pp 1154-1163
26. Wolshon, B. (2001), “ ‘One-Way-Out’: Contraflow Freeway Operation for Hurricane Evacuation”, *Natural Hazards Review*, August 2001, pp 105-112
27. Wolshon, B., Hamilton, E., Levitan, M., Wilmot, C. (2005), “Review of Policies and Practices for Hurricane Evacuation. II: Traffic Operations, Management, and Control”, *Natural Hazards Review*, August 2005, pp 143-161