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16. Abstract

Mass evacuations of the Texas Gulf Coast remain a difficult challenge. These events are massive in scale, highly complex, and entail an intricate, ever-changing conglomeration of technical and jurisdictional issues. This project focused primarily on the specific issue of developing a new technical tool to help TxDOT and other key operating agencies/stakeholders better predict when major elements of evacuation operations should be implemented. In particular, a variety of technical analyses were employed to develop a new, prototype decision support system that provides additional insights to more effectively decide when evaculane shoulder operations versus full contraflow operations are needed to manage evacuation demand. This new tool has a predictive mechanism designed to provide lead time for implementing these two prospective operational scenarios. The work conducted during this research involved a large-scale application of the DynusT model, and integrates several different factors into the evacuation operation decision-making process—namely real-time traffic conditions, hurricane characteristics (strength and size) and human behavior.

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PROTOTYPE DESIGN FOR A PREDICTIVE MODEL TO IMPROVE EVACUATION OPERATIONS: TECHNICAL REPORT

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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CHAPTER 1: BACKGROUND AND INTRODUCTION

As has been illustrated numerous times over the past decade in the United States, major hurricanes—and in particular, the oftentimes massive evacuations associated with them—present a complex, recurring challenge. The evacuation dynamics associated with these events are getting increasingly difficult, as baby boomers and population growth in general are contributing to an ever increasing number of people and properties that are exposed to the threats delivered by these storms.

While noteworthy progress has been in made in Texas in recent years to improve planning and operations related to hurricane evacuations, additional challenges remain. One of the more notable challenges is the decision-making process related to calling for (or deciding not to call for) contraflow operations on strategic evacuation routes. Implementing contraflow operations is an expensive, resource-intensive undertaking. As such, key operating agencies (and decision makers) involved in such deliberations are understandably hesitant to call for contraflow operations unless there is strong evidence of the need to do so.

This research project takes an in-depth look at the various factors impacting the volume of evacuating traffic. Based on these factors, researchers would then examine options for developing a decision support tool to provide key stakeholders a (to date non-existent) integrated means for quantifying the need (or lack thereof) for implementing contraflow operations. Additional information regarding past research as well as the tasks performed by the research team is provided subsequently. The report concludes with a reflection on key findings of this effort and next steps to be considered to improve implementation applications of the prototype tool developed in this research.

CHAPTER 2: CONFIRM RESEARCH PRIORITIES AND REQUIREMENTS, AND ESTABLISH A PROJECT MONITORING COMMITTEE

Due to the complex nature of this research, the wide variety of potential users, as well as the impacts of related results, work began immediately on establishing a large, diverse Project Monitoring Committee (PMC) for this project. Organizations to whom outreach was made for participation included:

- Multiple Divisions, Districts and Departments of the Texas Department of Transportation (TxDOT).
- Texas Division of Emergency Management (DEM).
- Department of Public Safety (DPS).
- Army Corps of Engineers.
- Houston-Galveston Area Council (H-GAC).

The complete list of those participating as members of the PMC throughout the course of this project [not including research staff from Texas Transportation Institute (TTI) or University of Houston] is noted below:

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- Seth Jones – Army Corps of Engineers.
- Christie Willhite – H-GAC.
- Chandra Carrasco – H-GAC.

During the first meeting of the PMC (in February 2009), the research requirements and priorities of this project were reviewed and approved by this group. The following chapters describe the core technical tasks and outcomes of this project in further detail.

CHAPTER 3:
LITERATURE REVIEW

The deadliest natural disaster in U.S. history was the Galveston Hurricane of 1900, which claimed over 8,000 lives as the storm inundated the entire island. One of the most catastrophic natural disasters in recent world history occurred in Bangladesh in 1970; where more than 300,000 people were lost in storm surge flooding during a powerful cyclone. Recent developments in warnings and evacuations have significantly reduced the number of U.S. fatalities due to storm surge (*1, 2*).

Unfortunately, as illustrated during the 2005 hurricane season and the evacuations surrounding Hurricanes Katrina and Rita in particular, many improvements can still be made. While many improvements have been made in the technical tools developed to aid decision makers, the events of 2005 served to highlight the important role of cooperation between jurisdictions, timely relevant information, and consistent communication with the public (*3*). With populations in hurricane-prone regions projected to continue increasing, and the elderly—a significant portion of the "special needs" population—expected to triple by the year 2050, the challenge of mass evacuations of Texas coastal regions will only increase in complexity and magnitude as we move forward (*3, 4*).

PAST HURRICANE EVACUATION STUDIES

Since the 1970s, evacuation modeling techniques have improved significantly. Many of the early models were initially developed to plan for other civil defense emergencies, such as nuclear missile attacks and nuclear power plant accidents. Among these programs are NETVAC, TEDSS and DYNEV. When applied for hurricane evacuation purposes, the data that feed many of these programs have come from the inventory of Hurricane Evacuation Studies (HES), which Federal Emergency Management Agency (FEMA) had initiated in the late 1980s to integrate key aspects of hurricane evacuation planning and to assist in disaster preparedness (*2*). Several models have been developed for and/or include hurricane evacuation traffic flow analysis. Such tools include Evacuation Traffic Information System (ETIS) and the Evacuation Travel Demand Forecasting System (ETDFS). Today, simulation programs are used to model weather, flooding, traffic flow and evacuation travel behavior, among others. An effort is also under way to develop a computer-based incident management decision aid system (IMDAS).

More recent research describes a simple, rapid method for calculating evacuation time estimates (ETEs) that is compatible with research findings about evacuees' behavior from approaching hurricanes. The revised version of an earlier version of the empirically based large scale evacuation time estimate method (EMBLEM) uses empirical data derived from behavioral surveys and allows local managers to calculate ETEs by specifying route system, behavioral, and evacuation scope/timing parameters (*5*). Data used to estimate and test the models of evacuation travel demand were from a household survey conducted in southwest Louisiana, with information related to Hurricane Andrew (in 1992). A logistic regression model and a neural network model were used. In the logistic regression model, households living in mobile homes were estimated to be 10.1 times more likely to evacuate than those living in multiple-dwelling homes. An evacuation order was estimated as increasing the likelihood of evacuation by 4.2 times, and those living near water were 2.2 times more likely to evacuate than those living elsewhere (*6*).

Zhang and Prater conducted research to assess respondents' levels of risk area accuracy, identify the demographic characteristics of those who are most prone to error, determine if prior hazard education is associated with higher levels of risk area accuracy, and determine if risk area accuracy is significantly related to evacuation. The official risk area was computed using ArcGIS to geocode the mailing address of the respondents and then overlaying these points onto the official risk area boundary file. Of the 312 respondents, 277 could be located and their official risk area identified. More people overestimated their risk (24.2 percent) than underestimated it (9.4 percent), but this had no effect on evacuation (*7*).

A recent survey performed by the Harvard School of Public Health (*8*) focused on potential evacuees in high-risk areas in most southern Atlantic and Gulf states. Most likely destinations for evacuation were cited as friends/family (56 percent), hotel/motel (18 percent), or a shelter (12 percent). Evacuation trip lengths were estimated as 6 percent less than 10 miles, 11 percent between 10 and 40 miles, 15 percent between 50 and 100 miles, 21 percent between 100 and 200 miles, and 36 percent greater than 200 miles. Evacuation mode was almost exclusively personal automobile (91 percent would use their vehicle and 3 percent would ride with a friend), though 4 percent of evacuees suggested they would use transit. In response to questions directed to those who would opt not to evacuate, 54 percent indicated roadway overcrowding as a reason, while 36 percent felt evacuation could be dangerous and 12 percent reported not having access to a personal auto (self or friend).

An additional Harvard survey performed in 2007 (*9*) found that 31 percent of residents would not leave if government officials told them to do so (up from 23 percent in 2006) and when asked why they would not evacuate, 75 percent of respondents felt that they would be safe in their homes. Respondents had concerns about shelter sanitation, water availability, crowding, illness exposure, and medical care. It was also revealed that 34 percent of respondents did not know if their home was located in an evacuation zone. Specific focus on residents of New Orleans revealed that only 14 percent would not evacuate, compared to 32 percent in other high-risk areas of the United States.

To determine what the latest policies and strategies are, how they differ from one location to another, and to increase knowledge and awareness of these new evacuation practices, a national review of evacuation plans and practices was undertaken by researchers from Louisiana State University's Hurricane Center. Some of the key issues were:

- Limited involvement from and awareness within the professional transportation community in the field of evacuation.
- Limited interagency coordination for regional and cross-state evacuations.
- Limited planning for the evacuation of low-mobility groups.
- Less than adequate use of the available transportation infrastructure during evacuation.
- A need to better coordinate construction work zone activities on hurricane evacuation routes (*10*).

More recently, FEMA HES for Hurricanes Katrina and Rita revealed the need to focus on storm surge as the deadliest element of these storms and identified the following general evacuation concerns:

- Counties are not issuing evacuation orders according to evacuation zones.
- Clearance times do not account for shut down and staging time needs.
- Typically found that many citizens never hear a specific evacuation warning order.
- Emergency managers may focus too much on the forecast track and not consider the error cone sufficiently (*11*).

Issues were also raised regarding the public's interpretation of evacuation orders (i.e., the differences between mandatory, voluntary, recommended, partial, full, etc.), in that National Hurricane Center watches and warnings were somewhat or very important to 95 percent of evacuating households, but their knowledge of these terms is limited.

EVACUATION PLANNING PROCESS

Baker (*12*) described the task of planning evacuations as the process that comprises the following components:

- Hazard analysis—to identify the area that would need to be evacuated for a particular hazard condition.
- Vulnerability analysis—to estimate the number of households and people who are susceptible to the threat condition.
- Behavioral analysis—to project how people will respond to the threat.
- Transportation analysis—to assess roadway capacities within the transportation network and identify conditions such as bottlenecks or links vulnerable to the hazard. One objective of this analysis is to develop clearance times within an evacuation area.
- Shelter analysis—to evaluate the capability of buildings to withstand the threat conditions and their sustainability to be used as refuges for evacuees.
- Decision making—to develop procedures to assess whether a hazard presents a level threat to warrant an evacuation and, if so, when to initiate an evacuation order.
- Development management—to regulate the growth of population and land development that could make evacuation more difficult.

TRAFFIC CONTROL DURING HURRICANE EVACUATION

Several transportation agencies have developed tools and strategies to convey information to travelers during evacuations. The three most common are signs, pavement markings, and traffic signals (*13*). This section also describes the hurricane evacuation tools that will be analyzed as part of this study.

Signs

The Manual of Uniform Traffic Control Devices (MUTCD) contains a section pertaining to signing for emergency management (*14*). Chapter 21 in the MUTCD provides guidance on the design, size, and placement of these devices. In addition to the formal signs designated in the MUTCD, local transportation agencies also develop their own signs for local use in emergencies and evacuations. These include signs for use on contraflow operations to convey radio frequencies for evacuation travel and to provide evacuation information that would be conveyed on variable message signs (VMS) (*13*).

Pavement Markings

Some pavement markings for evacuations are not designated by the MUTCD. The Texas Department of Transportation (TxDOT) developed markings to designate shoulders for use as an additional travel lane during evacuation. These lanes are referred to as *Evaculanes*. A recent TTI study developed guidelines for various hurricane evacuation signs and markings, including route signs, contraflow signs, emergency shoulder lane signs, and pavement markings (*15*).

Figure 1. Evaculane Pavement Markings (*15*).

Traffic Signals

The use of traffic signals to facilitate evacuations has begun to receive more attention, particularly for evacuation of urbanized areas under no-notice conditions (*13*). Currently there are no standardized or recommended rules of operation for traffic signal control during evacuation emergencies. Chen et al. (*16*) recommended a flashing yellow to give a virtual continuous green to the evacuation traffic. The same study also found that the usual non-emergency timing plans could be most effective if approach volumes are closer to those of routine peak periods.

Contraflow

Contraflow is a form of reversible traffic operation in which one or more travel lanes of a divided highway are used for the movement of traffic in the opposing direction. Contraflow is one of the hurricane evacuation tools that will be extensively modeled and evaluated in the current research effort.

Contraflow is more practical on freeway facilities because they do not have at-grade intersections, which can interrupt flow or permit unrestricted access into the reversed segment. Several recent studies have examined the characteristics of contraflow operations. The highest flow rates that the South Carolina Department of Transportation (SCDOT) measured during the Hurricane Floyd evacuation were between 1,500 and 1,600 vehicles per hour per lane (vphpl) (*17*). Traffic flows measured during the evacuations for Hurricane Ivan and Katrina on I-55 in

Louisiana were somewhat lower at 1,230 vphpl and 820 vphpl on normal and contraflow lanes, respectively, on average over the peak 10 hours of the evacuation (*18*).

Preparation of contraflow can take at least six hours in addition to the time to plan and acquire equipment for traffic control. Inadequate designs at the upstream and downstream ends can further limit the effectiveness of the contraflow operation. In addition, traffic incidents and work zones on evacuation routes can affect pre-planned operations. Therefore, these characteristics must be appropriately captured in the modeling process in order to realistically simulate and analyze evacuation strategies.

MODELING AND ANALYSIS TOOLS AS PART OF THE SOLUTION

Recent advances in both the affordability and computing power of personal computers have resulted in major advances in the development and application of computer-based evacuation modeling, simulation, and visualization. Hardy and Wunderlich (*19*) compared 30 of the most commonly used simulation systems for evacuation modeling. Among the significant contributions of this work was a characterization of the trade-offs between the scope of the scenario and complexity of the system. The study described three general classes of modeling scales—macro, meso, and micro—and how each system could be or has been used for modeling evacuation events. The review also included the analysis of the capability of each to model varying scopes and complexities as well as the tradeoff between handling suitable system detail, development effort and computational speed.

Macroscale models typically represent the traffic flow as fluid flows through a pipe. The level of abstraction is limited to the functional level of the roadways and the characteristics and movement of individual vehicles and people are aggregated to group averages. High-level decision makers have typically favored these macromodels since they can provide an overall perspective of how certain transportation management strategies are likely to impact evacuation operations.

Mesoscale models are typically used to represent larger geographic areas than microscale models while permitting the computation at more disaggregate levels than macroscale models. One example of mesoscale techniques is to subdivide a corridor into sub-segments where the movement of vehicles is aggregated to represent average flow rates and speeds. The cell transmission model is one example of such an approach.

Microscale models provide the ability to model individual vehicles and specific geometric conditions in the network. The level of effort and the quantity of input data required to model such networks becomes a major limitation when using microscale techniques to simulate large networks. These issues have limited the applicability of microscale modeling for the simulation of large-scale evacuation scenarios.

Modeling Tools Currently in Use

Modeling and analysis tools can provide emergency managers, engineers and planners with a means to apply different disaster-related scenarios and make informed decisions about strategies to best accommodate evacuation demand. After evaluating different alternative scenarios, emergency managers have the opportunity to develop alternative means to evacuate based on prevailing conditions associated with a particular evacuation event. Although there are a number of modeling and analysis tools available, none are currently robust enough to integrate real time information so as to provide reliable decision support information during an event (*1*). The two dynamic traffic assignment models that come closest (but still fall short of this goal) are described in detail later in this report section. The following are transportation, weather and assessment monitoring and prediction tools that can support some form or aspect of evacuation—adapted from (*1, 2, 20*) and other sources as cited:

- Clarus—The U.S. Department of Transportation and the National Oceanic and Atmospheric Administration (NOAA) worked together to provide high-quality road and weather information. Clarus collects weather observations from weather and transportation sources and turns them into road weather information. Weather sources provide real-time travel conditions, and travelers can plan in advance if bad weather affects their route (*21*).
- Consequence Assessment Tool Set/Joint Assessment of Catastrophic Events (CATS/JACE)—This model was developed under the guidance of the U.S. Defense Threat Reduction Agency (DTRA) and the U. S. Federal Emergency Management Agency (FEMA). CATS helps assess the consequences of disasters to population, resources and infrastructure. The tool can estimate hazards from natural disasters to technological disasters and provides significant assistance to emergency managers in training, exercises, contingency planning, logistic planning and calculation requirements for humanitarian aid (*22*).
- Dynamic Network Assignment-Simulation Model for Advanced Road Telematics − Planning version (DynaSmart-P)—The Federal Highway Administration (FHWA) supported the development of this model, which provides the capability to model traffic flow in a roadway network based on the decisions of individual travelers seeking the best travel path over a given planning horizon. DynaSmart-P, which is a mesoscale model, considers the dynamic nature of traffic flow; therefore, it is expected to produce more useful estimates of speeds, queue lengths, delays and congestion effects than would be available from traditional transportation planning models. The FHWA is examining the application of this model for transportation management analysis during emergencies (*23*).
- Evacuation Traffic Information System (ETIS)—ETIS is an FHWA-supported geographic information system (GIS) web-based tool to help collect and disseminate transportation information during an evacuation. Transportation officials in each threatened state are responsible for inputting information on evacuation status, tourist occupancy, evacuation participation rate, and traffic information. The ETIS provides a platform for states and the FEMA Regional Operations Center to monitor the evacuation process. The ETIS-generated reports include shelter capacity by state, traffic count by state, traffic volume by corridor, destination percentage by city, and estimated state-to-state traffic (*24*).
- Evacuation Travel Demand Forecasting System—This web-based travel demand forecast system is a macro-level evacuation modeling and analysis system that was developed in the aftermath of Hurricane Floyd. Emergency management officials can access this model online and use it to input data and view results.
- Hazard US Multi-hazard (HAZUSMH MR2)—Developed by FEMA, this model is a nationally standardized methodology and software program that estimates potential

losses from earthquakes, hurricanes, and floods. The HAZUS-MH uses GIS software to map and display hazard data. The newest version, HAZUS-MH MR3, was released in September 2007 (*25*).

- Hurricane and Evacuation (HURREVAC)—First developed for FEMA in 1988, a new version was developed for the Windows 95/98/NT platform. This program uses GIS data to correlate demographic data with shelter locations and their proximity to evacuation routes to estimate the effect of strategic-level evacuation decisions. The model draws information from the National Hurricane Center (NHC) and SLOSH, and estimates the time required to evacuate an area. Using information from the NHC, HURREVAC tracks hurricanes on computer plots to aid emergency managers in making evacuation decisions. This program is currently undergoing major revisions in response to recent shortcomings identified by users (*26*).
- MASS eVACuation (MASSVAC)—MASSVAC was developed for modeling nuclear power plant evacuations. This is a mass evacuation computer program that models the evacuation process. This model was applied to test operational strategies for hurricane evacuations in Virginia.
- Network Emergency Evacuation (NETVAC)—NETVAC was developed at the Massachusetts Institute of Technology (MIT) in 1982 as a part of the reaction to the aftermath of the Three Mile Island accident. It is limited in application to hurricane evacuation because this model is limited to Point-A-to-Point-B situation. Emergency managers may be able to use this model to analyze route choice, intersection controls, and lane management.
- Oak Ridge Evacuation Modeling System (OREMS)—OREMS was developed by the Center for Transportation Analysis at the Oak Ridge National Laboratory. This model is a Windows-based software program designed to analyze and evaluate large scale vehicular emergency evacuations and develop evacuation plans. The development of OREMS was intended to produce a software system that uses the latest traffic simulation software from the U.S. Department of Transportation that would run faster than other models and simplify the data input and modeling processes. OREMS uses an adaptation of the FHWA's microscopic CORSIM simulator for traffic simulation and can be used to estimate clearance times and experiment with evacuation routes (evacuation rates, management strategies, etc.) (*27*).
- Sea, Lake, and Overland Surges from Hurricanes (SLOSH)—SLOSH is a computerized model developed by the National Weather Service (NWS). Storm surge heights and winds can be estimated resulting from historical, hypothetical, or predicted hurricanes. SLOSH is the primary model that FEMA, NOAA and U.S. Army Corps of Engineers (USACE) use. The accuracy of the SLOSH model is ±20 percent (*28*). It is also used to help plan evacuation routes and locate emergency shelters based on estimated geographic area flooding under certain storm scenarios.

Table 1 shows a summary of these tools. Again, these models help emergency managers and planners in making evacuation decisions, but only a few of these models can be used to estimate hazards due to the disaster or event necessitating evacuation.

Table 1. Models Used for Emergency Evacuation and Planning.

Model	Primary Purpose	Potential Users	Developer/ Funding	Released Date
Clarus	Weather information	Transportation managers, weather providers, and travelers	USDOT and NOAA	2005/2006 (testing)
CATS/ JACE	Estimate hazards from disaster	Emergency managers	DTRA and FEMA	2005 (version 6.0 for use with ArcView 9)
DYNASMART-P	Model traffic flow	Transportation managers	FHWA	2007 (version 1.3)
ETIS	Collect and disseminate transportation information	Emergency managers	FHWA	2002 (tested); online tool
ETDFS	Evacuation modeling and analysis	Emergency managers	FEMA, USACE, DOT	2002; online tool
HAZUS – MR3	Estimate potential losses from disaster	Emergency personnel and planners	FEMA	2007 (version 1.3)
HURREVAC	Evacuation decisions	Emergency managers	FEMA	May 2008 (current version 5.0.10 will be updated)
MASSVAC	Nuclear power plant evacuation/ used for hurricane evacuation	Emergency planners	Hobeika and Kim	1985 (original)
NETVAC	Nuclear power plant evacuation/ analyze route choice	Emergency managers and planners	MIT	1982 (original)
OREMS	Evaluate large scale vehicular evacuation, develop evacuation plan	Emergency personnel and planners	CTA/ORNL	2003 (version 2.6)
SLOSH	Estimate storm surge height and wind due to hurricane	FEMA, NOAA, USACE	NWS	2002 (version 1.31)

Modeling Tools under Development

A state-of-the-art, dynamic traffic management system uses simulation models combined with real-time traffic and origin-destination information to predict the effects of various management strategies, thus allowing more effective management and providing better traffic information than is currently possible. Route choice, travel time, and departure time data are collected from several sources of real-time information, such as loop detectors, roadside sensors, and GPS-equipped vehicle probes. This travel information is then used, along with simulation models, to predict network flow patterns and travel times given various combinations of management strategies such as incident management, ramp metering, signal control and traveler information. Based on these predictions, optimal strategies are selected and travel time predictions and route recommendations are made available to travelers. These systems—referred to as dynamic traffic assignment (DTA) models—are still under development and require more traffic data than is generally available, particularly information on origins and destinations.

Two DTA traffic estimation and prediction system prototypes, DynaMIT and Dynamic Network Assignment Simulation Model for Advanced Road Telematics (DynaSmart), were developed by MIT and the University of Texas at Austin, respectively. The development of both models was sponsored by Federal Highway Administration (FHWA) with Oak Ridge National Laboratory (ORNL) acting as the project manager.

There are two versions of DynaSmart being developed for real-time applications: DynaSmart-X and DynusT (the latter at the University of Arizona by the DynaSmart suite's original programmer, Yi-Chang Chiu). DynaSmart-X has the developmental goal of serving as a real-time computer system for traffic estimation and prediction that supports both transportation management systems, and advanced traveler information system (ATIS). Attempts are being made for DynaSmart-X to interact continuously with multiple sources of real-time information, such as loop detectors, roadside sensors, and vehicle probes, with the following goals as output:

- Reliable estimates of network traffic conditions.
- Predictions of network flow patterns and travel times in response to various contemplated traffic control measures and information dissemination strategies.
- Routing information to guide trip-makers in their travel.

Similarly, DynaMIT is being developed as a real-time computer system for traffic estimation, prediction, and generation of traveler information and route guidance to support the operation of traffic management systems and advanced traveler information systems (ATIS) at traffic management centers (TMC). DynaMIT is being designed to provide:

- Real-time estimation of network conditions.
- Rolling-horizon predictions of network conditions in response to traffic control measures and information dissemination strategies.
- Traffic information and route guidance for roadway users.

The performance of DynaSmart-X will be described in some detail in the next section; DynusT is being developed with similar goals.

In the last few years, traffic simulation and assignment models have been widely adopted by various (state) departments of transportation metropolitan planning organizations for operational planning. Mesoscopic and microscopic models are complementary to each other, and with proper integration, both tools can deliver desirable modeling performance and capabilities. The difficulty in integrating these two models is associated with the process of translating the mesoscopic model results into the microscopic model counterpart. Recently the researchers at the Texas Transportation Institute (TTI) and the University of Arizona have developed the DynusT-VISSIM Converter (DVC) tool, which takes user-defined sub-areas from the more regional DynusT mesoscale modeling tool and generates corresponding VISSIM, microscale network datasets (*29*).

VISSIM is a microscopic, time step and behavior based simulation model developed to model urban traffic and public transit operations. The program can analyze traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, etc., thus making it a useful tool for evaluating various alternatives based on transportation engineering and planning measures of effectiveness (*30*).

With the DVC tool, VISSIM simulation can utilize dependent paths and flows generated from tools with DTA logic, such as DynusT. This capability allows for detailed intersection-level analysis based on regional traffic assignment results and can be applied to a variety of applications where both microscopic and mesoscopic analyses are needed. In a very real sense, the ability of more regional models to capture overall travel behavior and the features of detailed, realistic traffic flow in microscale models are combined together to create a powerful testing platform for a range of traffic operations scenarios, including hurricane evacuations.

Modeling Efforts Using Real-Time Data

Most emergency evacuation studies have been conducted in a planning context using applications such as DynaSmart-P (*31, 32*). Houston's Claire-DynaSmart-Rhodes and Los Angeles' DynaMIT-R are two major recent efforts in applying DTA models with real-time data. These examples were examined for their potential application to hurricane evacuation studies, though the inability of operating real-time DTA tools at a sufficiently short time horizon for evacuation prediction has effectively limited their use in the current research.

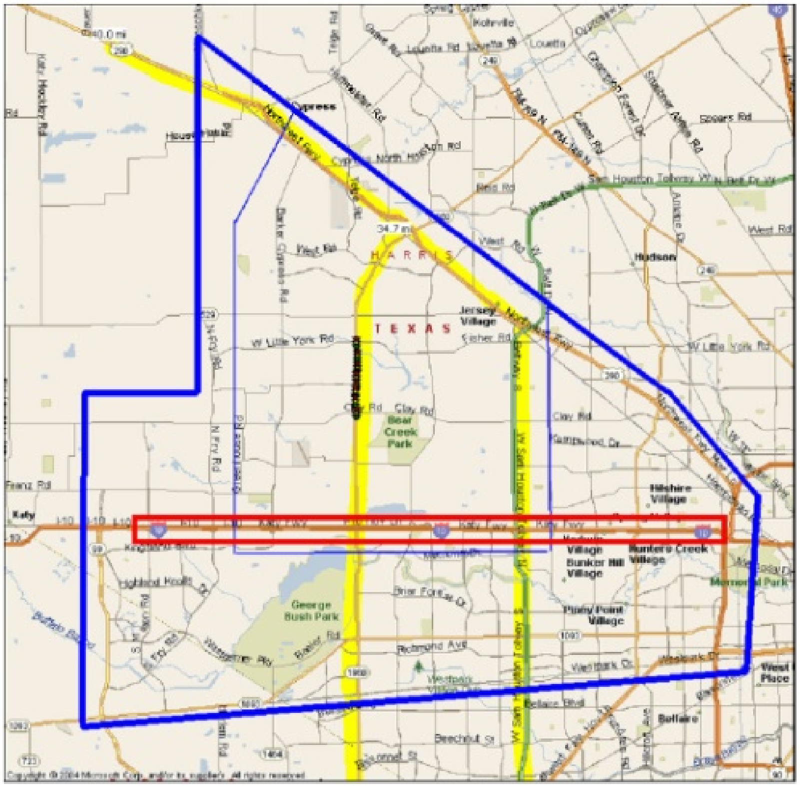
Houston Claire-DynaSmart-Rhodes Project

This ongoing project seeks to integrate and implement Claire, DynaSmart-X, and RHODES at the TxDOT/City of Houston's TranStar traffic management center to perform dynamic traffic management and control for the proposed I-10 west traffic corridor in Houston to alleviate traffic congestion, particularly congestion caused by freeway reconstruction and flooding. Figure 2 shows the boundaries of the study area and the corresponding simulation network.

Claire is a rule-based decision-making system dedicated for congestion management. Using historical and real-time data, Claire can detect the onset of traffic congestion, predict its development, and make suggestions for its relief. Claire has been implemented in many European cities and operated as an automated system in Paris since 1990.

DynaSmart-X can be used to evaluate the traffic management scenarios Claire recommended to mitigate traffic congestion. Figure 3 shows a schematic view of DynaSmart-X. The DynaSmart-X system currently implemented in Houston allows the simultaneous evaluation of two scenarios in module P-DYNA while running the real-time simulation in module RT-DYNA. Based on the evaluation results, the operator can choose the traffic management scenario to implement.

Houston Claire-DynaSmart-Rhodes Project Location



Legend

- Small blue line outlines H-CDR "control area" network
- Heavy [wide] blue line outlines complete H-CDR network
- Red outlines IH-10 Katy freeway managed lane project
- Highlighted lines are hurricane evacuation routes in corridor
- ACS Lite locations identified along SH 6 [Clay Road to W. Little York] with traffic signal icons

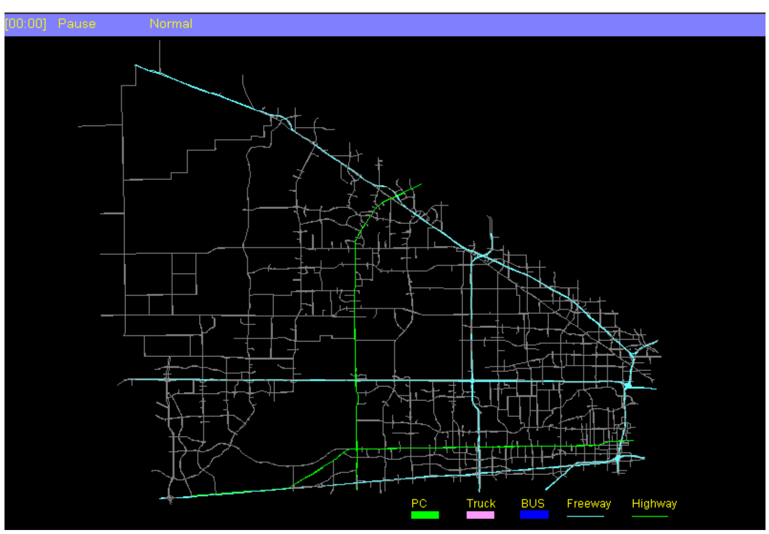


Figure 2. Houston Claire DynaSmart-RHODES Study Area and Network.

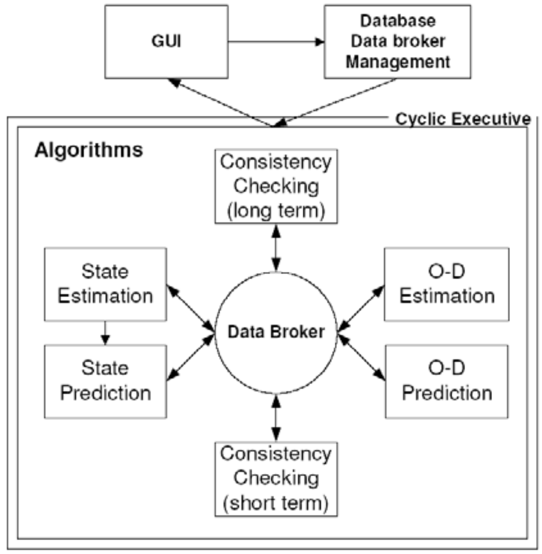


Figure 3. DynaSmart-X Schematic View (*33*).

DynaSmart-X uses real-time data to perform two types of consistency checks: short-term and long-term. The short-term consistency check compares estimated and observed densities, and adjusts the simulated link speeds to minimize the discrepances. The long-term consistency check adjusts the estimated OD values based on observed link densities.

RHODES is a distributed real-time traffic-adaptive signal control system developed by the University of Arizona. It is based on short-term prediction of vehicle arrivals between peer intersections on a network. RHODES can be integrated, in a hierarchical fashion, with real-time DTA models such as Dynasmart-X.

The Claire-DynaSmart-RHODES system is intended to be integrated into the advanced transportation management system (ATMS) that resides in TranStar. The predicted traffic information based on the surveillance data collected in real-time will allow TMC operators to examine evolving traffic conditions and to implement proactive traffic control strategies.

The FHWA selected Houston for the implementation of the Claire-DynaSmart-RHODES system due to the high degree of congestion and dependency on central control of traffic on freeways and surface streets. The other motivation was to partner with innovative and forward thinking jurisdictions that have sufficient existing infrastructure to reduce implementation costs. TTI was selected to evaluate and help facilitate the implementation of this project. Analyses to date indicate that this integration has not been successful and that DynaSmart-X has some noteworthy limitations, including:

- The model requires a massive amount of computing power (e.g., several computers running in tandem with excessive amounts of memory required).
- Projections of future system operations are limited to 30-minute estimates.

DynaMIT Project in Los Angeles

DynaMIT has been deployed in the South Park area of Los Angeles as part of a FHWA-funded project to improve the incident detection and prediction-based traffic management capabilities of the city (*34*). The online implementation of DynaMIT (DynaMIT-R) had two main purposes:

- To determine baseline traffic conditions for other systems to automatically detect non-recurring congestion and incidents.
- To make short-term predictions for the location and severity of maximum impact zones due to confirmed incidents.

The system is also expected to be applicable to emergency/evacuation management and route guidance to support an advanced traveler information system. Figure 4 shows the framework of the DynaMIT-R system deployed in Los Angeles. Various types of off-line and real-time data were used in the implementation. The real-time information DynaMIT-R used is very similar to what DynaSmart-X used. The minimum required real-time data include dependent link flows, incident characteristics (location, duration, severity), and traffic control data and strategy.

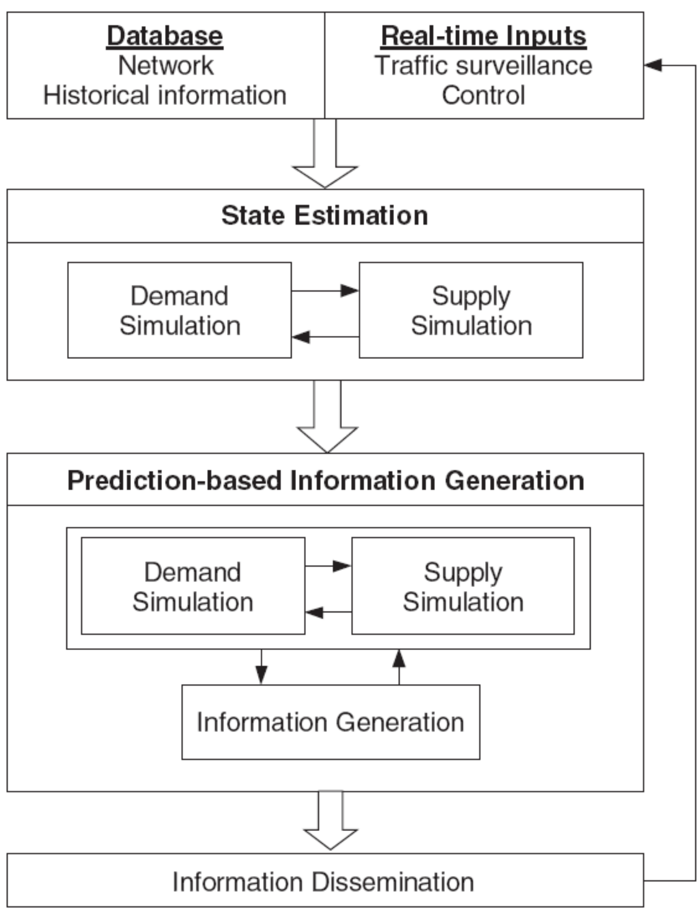


Figure 4. DynaMIT-R Framework (*32*).

Preliminary evaluation results of the DynaMIT-R implementation were promising in terms of both computational efficiency and prediction accuracy. Future studies will focus on on line calibration, which allows the fine-tuning of model parameters in real time to adapt to changes in traffic control, weather and roadway conditions, and other factors.

DECISION SUPPORT TOOLS FOR EVACUATION

Overview of Decision Support Tools

A hurricane evacuation is an area-wide evacuation event that has a high probability of occurrence with sufficient lead time. Most emergency management agencies determine alternate evacuation routes a priori. Modeling a large-scale evacuation such as a hurricane event is a complex and difficult task requiring efficient utilization of available roadway capacities and advanced traveler information systems as well as effective and coordinated evacuation schemes. Current challenges for accurate modeling of hurricane evacuation include (*31*):

- Constructing an optimization model that properly incorporates the objectives for optimal evacuation schedules and evacuation routes (e.g., minimizes casualties, exposure or other relevant measures).
- Accurate estimations of traffic conditions based on traffic loadings resulting from varying evacuation time and route scenarios.

There are four major components that need to be considered in the process of developing a decision support tool for evaluating hurricane evacuation strategies:

- Infrastructure modification—infrastructure changes as part of hurricane evacuation strategies, such as capacity addition(s), ramp access control, and contraflow.
- Information provision—this involves procedures to model the impacts of various information provision strategies and advisory compliance behavior of evacuees.
- Real-time data—identifying critical real-time traffic data elements and the predicted and evolving intensity and track of hurricanes and then incorporating them into the decision-making process.
- Hurricane evacuation operations—representing various hurricane evacuation strategies to be tested, such as departure scheduling and deployment timing of hurricane evacuation tools.

A decision support tool to be developed as part of this study will utilize simulation models combined with real-time traffic and origin-destination information to predict the effects of various management strategies, thus allowing more effective management and providing better traffic information than is currently possible. Route choice, travel time, and departure time data can be collected from several sources of real-time information, such as probe-vehicle systems, loop detectors, and roadside sensors. This travel information is then used, along with simulation models, to predict network flow patterns and travel times given various combinations of hurricane forecast and evacuation management strategies such as incident management, ramp metering, signal control, and traveler information. Based on these predictions, optimal strategies can be determined and travel time predictions and route recommendations can be made available to decision makers and evacuees.

Researchers will evaluate the pros and cons of commercially available transportation system analysis tools to be used in this study. In general, the tools with dynamic traffic assignment algorithms will be able to provide more realistic simulation of hurricane evacuation. The next section describes the traffic analysis tools that are currently being used to support the analysis, evaluation, and development of hurricane evacuation decision support tools.

Transportation System Analysis Tools

This section describes available analytical tools currently being used to support the evaluation and analysis of large-scale evacuation plans ranging from no-notice to planned events. A recent FHWA-sponsored study produced a guide for decision makers to develop a successful evacuation modeling analysis (*35*). Literature review has indicated that mesoscopic analysis tools are the most commonly used type of tool for the analysis and evaluation of large-scale evacuations.

DYNASMART-P

DYNASMART-P supports transportation network planning and traffic operations decisions, including evaluation of ITS deployment options, through the use of simulation-based dynamic traffic assignment. This tool combines

- Dynamic network assignment models, used primarily in conjunction with demand forecasting procedures for planning applications.
- Traffic simulation models, used primarily for traffic operational studies (*36*).

DYNASMART-P requires input data commonly used by traditional traffic assignment and simulation models, particularly with regard to network representation and spatial demand loading patterns. The input data vary with the network being analyzed and the level of detail the user requires. Complexity of the network can range from a linear freeway network to an integrated network with high-occupancy vehicle (HOV) lanes, high-occupancy toll (HOT) lanes, ramp metering, transit services, incidents and signal-controlled intersections on surface streets. DYNASMART-P produces a wide array of output information to assist users in performing detailed traffic analysis. The output report contains measures of effectiveness (MOEs) commonly used by traffic engineers, such as volumes, speeds, travel times, delays, etc. (*36*).

Cube Voyager and Cube Avenue

Cube is a transportation analysis package Citilab had developed and that integrates geographic information system technologies from prominent industry developers into its products. Cube Voyager is capable of modeling and analyzing passenger transportation systems containing any transportation mode. This package has a modular script-based structure that allows users to apply any modeling methodology, including standard four-step models, discrete-choice models, and activity-based models (*37*).

Cube Avenue is an extension to Cube Voyager in providing dynamic traffic assignment. Cube Avenue enhances Cube Voyager’s traffic assignment model by explicitly modeling time. With Cube Avenue, analysts can study problems for which traditional models do not provide enough data and for which microscopic models provide too much data (*37*).

TransModeler

TransModeler is Caliper Corporation's integrated traffic simulation package applicable to a wide array of traffic planning and modeling tasks (*38*). TransModeler incorporates dynamic routing of trips based on historical or simulated time-dependent travel times, and also models trips based on origin-destination trip tables or turning movement volumes at intersections. It simulates public transit as well as car and truck traffic, and handles a wide variety of ITS features such as electronic toll collection, route guidance, and traffic detection and surveillance.

TransModeler can simulate wide area networks at varying levels of fidelity and with different simulation methods. It includes mesoscopic and macroscopic simulators in addition to its microscopic simulator. In the mesoscopic simulator, vehicles are collected into traffic cells and streams and their movements are based on predefined capacities and speed-density functions. Individual vehicles are represented, but their movements are based on aggregated speed-density functions rather than car-following and lane-changing logic. In the macroscopic simulator, vehicle movements are based on volume delay functions that depend on the functional class of the road system.

TRANSIMS

The Transportation Analysis and Simulation System, or TRANSIMS, is an integrated system of travel forecasting models designed to give transportation planners accurate and complete information on traffic impacts, congestion, and pollution. The Los Alamos National Laboratory developed TRANSIMS to address new transportation and air quality forecasting procedures that the Clean Air Act, the Intermodal Surface Transportation Efficiency Act, and other regulations, require. TRANSIMS is part of the Travel Model Improvement Program (TMIP) sponsored by the U.S. Department of Transportation, the Environmental Protection Agency (EPA), and the Department of Energy (*39*).

Individuals and their activity-travel pattern are required to run a microsimulation in TRANSIMS. To generate synthetic households and people in these households, TRANSIMS uses census data and land use data. TRANSIMS tracks individuals, households, and vehicles, not zonal aggregation of households and employment. It also creates the transportation network and trip routes that satisfy all individual activities. The model also forecasts how changes in transportation policy or infrastructure might affect those activities and trips. The modules developed for TRANSIMS contain many significant advances beyond four-step models. For example, TRANSIMS simulation observes the movement of individuals and vehicles second by second throughout the entire day rather than the total travel for various periods. The regional microsimulation uses vehicle interactions to produce operating speeds, intersection operations, and vehicle operating conditions for each vehicle in the system rather than the deterministic equations of meso- or macroscopic tools. The TRANSIMS microsimulation permits very detailed analysis of traffic operations on the transportation network. This capability could be used to evaluate improvements such as traffic signal plans and ramp metering (*39*).

Factors Influencing the Selection of the Tool

Hardy et al. (*35*) classified factors influencing the selection of modeling tools into five categories:

- Modeling context.
- Geographic scale.
- Data.
- Agency resources.
- Development and analysis time.

Modeling context provides guidance on the nature of the event (event notification), amount of time available for decision making (timeframe), and the type of strategies that need to be investigated (evacuation strategies). Event notification can range from a planned event to a no-notice event. Planned events are typically easier to make informed decisions about evacuation plans since there is a longer lead time to better understand the impact of the event. The timeframe for decision making is generally one of the three categories: long-term planning, operational planning, and real-time operations. The evacuation strategies are typically a combination of travel demand management (TDM) and control strategies. TDM aims to manage the overall demand placed on the transportation network in the event of an evacuation. Control strategies aim to control the movement of people and vehicles once an evacuation order has been given.

Geographic scale defines the spatial scope of the analysis. The larger the scale, the less detail associated with the model and vice versa. Hardy et al. (*35*) provides the definitions for the following geographic scales: geographic region, metropolitan region, sub-region, corridor, facility, multiple intersections, and intersection.

Evacuation modeling generally involves two types of data: transportation supply and travel demand characteristics. The supply side describes the transportation network infrastructure such as physical attributes (e.g., lane configuration, signal locations, etc.), policy attributes (roadway capacity, signal timing plans), and service attributes (transit schedules). The demand side explains how the users utilize the infrastructure. Examples of these include vehicle counts, vehicle occupancy, and origin-destination data. The tools chosen will determine what extent data are needed.

Agency resources available for transportation modeling are also critical to the selection of the tools. Institutional arrangements within the organization that promote or hinder the flow of information, the availability of technical staff, the funding to acquire the technical expertise or models, and scheduling requirements play an important role in deciding on the modeling approach. The agency must also budget sufficient development and analysis time to develop and apply an evacuation modeling tool as either part of long-term planning, operational planning, or real-time operations. In selecting the appropriate tools, an agency must recognize the limitations of available resources.

Applications

Hardy et al. (*35*) sums up several case studies using different tools to analyze and evaluate evacuation strategies. This section summarizes recent applications of the analysis tools and their findings from the case studies. Table 2 presents the study location, event type, and selected tool. Table 3 summarizes the applications of mesoscale analysis tools, and Table 4 sums up the applications of microscopic analysis tools.

Table 2. Summary of Analysis Tools and Study Locations—Adapted from (*35*).

Location	Tool	Event Type	References
Washington, D.C.	CORSIM	No Notice	(*16*)
Houston-Galveston, TX	DYNASMART-P	No Notice	(*40*)
Umatilla & Morrow Co., OR	OREMS	No Notice	(*35*)
Houston-Galveston, TX	Cube Avenue	Hurricane Evacuation	(*41, 42*)
Hampton Roads, VA	VISSIM	Hurricane Evacuation	(*43*)
Nags Head, NC	TransModeler	Hurricane Evacuation	(*35*)
New Orleans, LA	CORSIM	Hurricane Evacuation	(*44*)
New Orleans/Baton Rouge, LA	TRANSIMS	Hurricane Evacuation	(*45*)
Daytona Beach, FL	DYNASMART-P	Planned	(*35*)

Table 3. Applications of Mesoscale Decision Support Tools for Evacuation.

Tool	Applications	Findings
DYNASMART-P	• Evaluated contraflow and phased evacuation strategies for the Houston-Galveston area. • Evaluated and developed a new evacuation plan for the Daytona Speedway in Daytona Beach, Florida.	• The analysis identified the problematic locations resulting from the surge of evacuation traffic. • The simulation run time can be significant. For instance, the Houston-Galveston area simulation took 20 hours for an evacuation period of 24 hours. • The model can successfully evaluate the effects of lane closure, vehicle-pedestrian conflicts, additional one-ways, and added capacity.
OREMS	• Analyzed evacuation time estimates (ETEs) for chemical plant emergency evacuation plan in Oregon.	• The model was a useful tool in a quick analysis of different operational scenarios but the data input, error checking, and validation can be burdensome. • There was a known "bug" associated with the program which has been corrected in the current version.
Cube Avenue	• Identified bottlenecks in the transport system and policies that could more effectively move evacuees during the natural disaster in the Houston-Galveston area.	• A hybrid model process with aggregate zones and network was found to be too complex. Only a strategic-zone simplification was used in the final model approach. • Network coding and correct representation of operational features (signals) is crucial when using dynamic traffic assignment.
TransModeler	• Evaluated traffic operations under a hypothetical scenario of forced evacuation from Nags Head, North Carolina. The strategies examined were reverse lanes, shoulder lanes, and modified signal timing.	• Integrated transportation analysis packages such as TransModeler can provide useful simulation capabilities for evacuation operations planning. • TransModeler is a powerful tool for the before-and-after visualization and animation of traffic from a simulation.
TRANSIMS	• Developed multimodal evacuation plans for the New Orleans metropolitan region, including the assisted evacuation process for mobility-limited individuals.	• Comprehensive network coding with a significant level of effort to calibrate and validate the model is required. • TRANSIMS is less user-friendly than other comparable software packages. • Detailed parcel-level demographic representation required to produce realistic outbound corridor level flows.

Table 4. Applications of Microscale Decision Support Tools for Evacuation.

Tool	Applications	Findings
VISSIM	• Evaluated the traffic control plan (TCP) and the performance of all the evacuation routes - interstate routes (I-64, I-264, and I-664) and arterial routes (Rt. 58, Rt. 460, Rt. 60, Rt. 17, and Rt. 10) within the Hampton Roads region (Virginia).	• Based on simulation results, a lane reversal should always be implemented for a Category 4 storm or higher. • Simulation results show that the reversed lanes have the potential to carry more vehicles than are currently assigned to them. • For a Category 3 storm, the throughput values for different evacuation routes are nearly the same with or without lane reversal.
CORSIM	• Evaluated the effectiveness of signal timing plans for evacuation and response in the event of no-notice disaster in an urban area. • Evaluated traffic conditions on contraflow freeway segments during an evacuation in New Orleans, Louisiana.	• Conventional microscopic simulation can be adapted and applied for modeling of evacuation contraflow. • Contraflow showed a 53% increase in roadway capacity based on simulation results. • Entry point and traffic control plan to load vehicles into the contraflow lanes play a critical role on the effectiveness of the operations.

CHAPTER 4: ASSEMBLE CATALOG OF AVAILABLE ARCHIVED AND REAL-TIME DATA

The purpose of this task was to gather relevant evacuation-related data for the Texas coastal regions. This includes historical traffic volume and flow data, as well as a catalog of real-time data sources that can serve as valuable information in the event of a major hurricane evacuation and in the critical phases of decision making leading to such events. Specific to this research project, the resources examined in this document concentrate on data available in the Houston region; this is based on the project direction as the Project Monitoring Committee agreed to develop the prototype design for the model for the I-45 freeway from Galveston Island to north of the Houston region. This freeway corridor was selected as I-45 is the primary evacuation route for the City of Galveston and the other communities within Galveston County located in the storm surge zone.

Beginning with the 2005 Atlantic Hurricane season, the Houston office of the Texas Transportation Institute has compiled an extensive catalog of hurricane event-related traffic data in the Houston region. This data not only include data during evacuations, but also base data for non-evacuation traffic conditions. The data include traffic volumes using traditional road tube-based traffic counters, automatic vehicle identification (AVI)-based travel time and speed information from the Texas Department of Transportation (TxDOT)/Houston TranStar real-time traffic information system, and spot speeds and volumes from TxDOT roadside radar sensors within the Houston region. The TxDOT Houston District provided funds to collect all of this data from 2005 through 2008.

EVACUATION DATA – TRADITIONAL ROAD TUBE BASED TRAFFIC COUNTS

Table 1 presents a summary of the road tube counts completed from 2005 through 2008 with respect to hurricane evacuations. During the summer months of 2005, traffic counts were completed at 27 locations throughout the Houston-Galveston-Beaumont regions to develop a set of base traffic data prior to any hurricane evacuation. The goal of this data collection effort was to complete initial capacity analysis on designated and secondary evacuation routes to estimate any reserve capacity that may be available for evacuation traffic on typical weekdays. This effort concentrated only on typical weekday traffic periods and also considered that while coastal areas may be involved in an evacuation, areas inland may be going about normal daily activities while being watchful of an approaching storm. As the threat of Hurricane Rita approached the Texas coastal regions in September 2005, TTI again deployed traffic counters at the same locations. The traffic data for the peak evacuation days of September 21–22, 2005, were recorded and summarized. It is believed that this is the only comprehensive set of traffic count data available in the region, which could measure the citizen response to the evacuation. In August 2007, Hurricane Dean again posed a threat for the Houston area. Traffic counters were deployed on August 17, and the threat to this region dissipated over the weekend. Although no evacuation was ordered, the weekend traffic data were summarized to serve as base non evacuation data for a Saturday and Sunday time period.

From June through August 2008, traffic counters were deployed at 28 locations in the region to update the base non-evacuation volume data. While 15 of these were the same as for the 2005 studies, the other 13 sites represented new locations. These new locations were identified as necessary collection points to provide for increased traffic data to monitor any localized evacuation impact within the immediate Houston region. This would provide for a more comprehensive coverage of areas on the west and southwest side of Houston to develop better screen-line documentation of evacuation outflows.

The first 2008 deployment to monitor evacuation behavior was for the Hurricane Gustav threat in August. The traffic counters monitored traffic volumes from August 29–31. Since the tropical system made landfall near Cocodrie, Louisiana, on September 1, there was essentially no evacuation impact of local residents leaving Houston. However, some of the traffic counters deployed on the east side of Houston did note volume increases attributive to the evacuation from the east. As the predictions of the National Hurricane Center (NHC) began to indicate likely landfall for Hurricane Ike along the Texas coast, the traffic counters were again deployed at the 28 locations on September 9, 2008. Hurricane Ike made landfall at Galveston on Saturday, September 13, 2008. Since the counters were deployed three days prior to landfall, TTI was able to again obtain a unique set of evacuation traffic data. Because of the direct impact of the tropical system on the Houston region, the traffic counters remained in place through September 17; therefore, traffic volumes were available to assess traffic flows before, during, and after the storm's landfall. Figure 5 presents a generalized location map of the traffic counts completed in 2008 to assess the hurricane evacuation traffic flows.

EVACUATION DATA – REAL-TIME TRAFFIC VOLUME AND SPOT SPEED DATA

In response to the lack of real-time traffic information available during the 2005 Hurricane Rita evacuation, TxDOT dedicated significant monetary and personnel resources to develop improved plans and increase traffic monitoring capabilities to facilitate future evacuations. Prior to the 2006 hurricane season, TxDOT began installing cameras and traffic data sensors at critical locations in the Houston-Galveston and Beaumont-Port Arthur regions. These new installations were mostly located in the rural regions where traffic congestion first began to develop during the Hurricane Rita evacuation in 2005. While the traffic monitoring systems of Houston TranStar provide for significant real-time information in the immediate urban area, these additional resources result in a more comprehensive region-wide traffic monitoring for evacuation events as well as for observing normal daily traffic operational events. Some of these additional traffic monitoring systems include data collection capabilities, but many only provide snapshot image views of the roadway either from cameras with pan-zoom-tilt capabilities or from traffic signal intersection video detection camera systems. The addition of these real-time visual and traffic information resources were vital to TxDOT monitoring the evacuation of the Houston area during the Hurricane Ike evacuation in September 2008. Figure 6 shows the general locations and device type equipment TxDOT has permanently deployed. As these devices are located outside of the Houston TranStar fiber optic communication network, connection to each of these devices is via the cellular telephone network.

In a manner similar to that practiced regarding the road-tube based traffic counters, TTI compiled traffic data for 29 of the TxDOT radar sensors within the region. Base non-evacuation data observed during June 2008 were compiled as well as summaries for the Hurricane Gustav and Hurricane Ike evacuations. The data for the Gustav event were summarized for August 29 through September 3; in addition to evacuation data, data for evacuees returning to regions east of Houston were documented. Data for the Hurricane Ike evacuation were summarized from Wednesday, September 10 through Saturday, September 13; Table 6 presents the locations included. As the storm made landfall and the power outages in the region became widespread, the real-time data from the remote sensors were no longer available at TranStar. However, this was beyond the time period of evacuation and traffic volumes had significantly decreased at that time. Although this represents a very good set of evacuation data, there were lapses in the cellular communication network during critical time periods that may have prevented delivery of the radar data for some of the 30-second data transmit interval as the system is designed. Therefore, the traffic volumes the devices reported may be less than the actual volumes because of the periods of communication loss. The radar sensor monitoring system does provide information on the percentage of time the data were successfully transmitted. As a part of the data review, the date and time when each of the radar sites returned to normal operation after the tropical storm were also logged. This was done in part such that an inventory of properly working radar sites was readily available should another tropical system threaten the region in 2008 while the recovery from the impact of Hurricane Ike was still underway.

Evacuation Data – Survey of Evacuation Behaviors

To gauge the evacuation response of Houston area residents, TTI completed surveys for both the 2005 Hurricane Rita threat and the Hurricane Ike evacuation in 2008. Both of these surveys were completed using the Houston TranStar website within a few months after the tropical storms' impacts on the region. While the 2005 survey provided results from 6,570 responses, the 2008 survey yielded information from only 1,788 respondents. The *Houston Chronicle* also conducted a survey in the aftermath of Hurricane Ike; they received 4,075 survey responses. Rice University also completed random telephone surveys of Harris County adults in 2005 and 2008; 405 samples were gathered in 2005 compared to 1,503 in 2008. The results of these surveys may provide background information in terms of how citizens have reacted in the past when personal decisions regarding hurricane evacuation are necessary.

Historical Freeway Travel Time and Speed Data

The focal point of freeway traffic operations for the Houston region is the Houston TranStar transportation and emergency management center. TranStar is a consortium of state, county, and city agencies that has been operating since 1996. One of the most visible features of the facility is the real-time traffic map as available on the Internet and mobile smart phones. While the traffic map provides commuters with current traffic, incident, and construction information on Houston area freeways, there is a large database of historical travel time and speed data available for each of the monitored roadways. The staff of the Houston TTI office routinely completes the detailed analyses and archiving of this data. The data were an excellent resource for determining average historical travel conditions because it can be used to verify the calibration of traffic models. An extensive review of the traffic map data was completed to provide documentation of freeway operations during the Hurricane Rita-related evacuation, thus somewhat validating the travel times and speeds the general public and the news media reported about the 2005 event. One important aspect of this data review was to provide a visual tracking of the progression of the limits of the queued evacuating traffic over several days as citizens opted to leave the immediate Houston area. Considering the September 2008 evacuation for Hurricane Ike, a review of the TranStar data indicated that there was limited impact on the freeway system during the actual evacuation; this was expected as the number of citizens who chose to evacuate was less when compared to that for Hurricane Rita. However, subsequent studies determined that there was significant impact on the freeway travel times and speeds in the weeks after the impact of the tropical system since many commuters used the freeways instead of the arterial street system which were plagued by inoperable traffic signals due to storm damage and long-term regional electrical power outages. The lack of electrical power also impacted the availability of data for various TranStar systems throughout the region. As the power was restored for each part of Houston, resources that the impact of the storm did not damage returned to normal operation, allowing for improved traffic monitoring capabilities.

Freeway Mainlane and Ramp Volumes

In addition to traffic volume information related to hurricane evacuation scenarios, TTI has current and historical data for freeway entrance and exit ramps as well as the adjacent frontage roads. Freeway mainlane volume counts and, in some instances, detailed vehicle classification data, is available for selected freeway locations as well. In addition, road tube count data may be available for selected surface streets including major arterials, collectors, and local streets. All of this data, which were collected for other traffic studies and research projects, is available for developing any simulation models used for this project. A brief review of the data available for the I-45 corridor shows that much of the data have been collected since 2006, with a significant portion of the data collected in 2007 and 2008. Data from these time periods should be recent enough for constructing the simulation models for this research project.

Table 5. Houston Region Evacuation Counts, 2005–2008.

Sheet #	Location	Sept 2005 {1}	Data Summary Period Dean {2}	2008 {3}	Gustav {4}	Ike {5}
Loc 1	SH 36 NB -- North of FM 1301 [823-U in West Columbia]	x				
Loc 2	SH 36 NB -- South of US 59 [604-Y in Rosenberg]	x	x	x	x	x
Loc 3	SH 36 NB -- North of US 90A [604-K in Rosenberg]	x				
Loc 4	SH 288 NB @ SH 35 [827-Q in Angleton]	x	x	x	x	x
Loc 5	SH 288 NB @ SH 6 [652-V in Manvel]	x	x	x	x	x
Loc 5R	SH 288 NB SH 6 Entry [652-V in Manvel]	x	x	x	x	x
Loc 6	SH 6 WB -- West of FM 2004 [736-S in Hitchockl]	x				
Loc 7	SH 6 WB -- East of SH 288 [652-V in Manvel]	x	x	x	x	x
Loc 8	SH 6 WB -- West of SH 288 [652-V in Manvel]	x	x	x	x	x
Loc 9	SH 6 NB -- South of US 59 [568-X in Sugar Land]	x	x	x	x	x
Loc 10	SH 6 NB -- North of US 59 [568-X in Sugar Land]	x	x	x	x	x
Loc 11	SH 6 NB -- North of Memorial [488-A in Houston]	x	x	x	x	x
Loc 12	SH 6 NB -- South of Patterson [488-N in Houston]	x		x		
Loc 13	SH 6 NB @ Hempstead Road [408-C]	x	x	x	x	x
Loc 14	US 290 Northwest Freeway WB @ Mueschke [336-C]	x				
Loc 15	I-45 North Freeway NB @ Hardy Toll Road [292-B]	x				
Loc 15R	Hardy Toll Road Entry to I-45 North Freeway NB [292-B]	x				
Loc 16	SH 146 NB -- North of FM 519 [737-V in La Marque]	x				
Loc 17	SH 146 NB @ Fred Hartman Bridge [540-L]	x		x	x	x
Loc 18S	SH 146 NB -- South of I-10 East [463-N in Baytown]	x		x	x	x
Loc 18N	SH 146 NB -- North of I-10 East [463-N in Mt. Belvieu]	x		x	x	x
Loc 19	SH 146 NB -- South of US 90 [Dayton]	x		x	x	x
Loc 20	SH 321 NB -- North of FM 1960					
Loc 21	SH 146 NB -- South of FM 1011	x				
Loc 22	US 90 WB -- West of SH 61	x				
Loc 23	FM 365 / FM 1406 NB -- South of US 90	x				
Loc 24	FM 1406 NB -- North of I-10	x				
Loc 25	SH 124 NB -- North of SH 65	x				
Loc 26	SH 124 NB -- North of FM 1985					
Loc 27	US 290 WB @ SH 6 [Hempstead]		x			x
Loc 28	US 290 WB SH 6 Exit to College Station [Hempstead]		x	x	x	x
Loc 29	US 290 EB @ SH 6 [Hempstead]		x	x	x	x
Loc 30	US 290 EB SH 6 Entrance Ramp [Hempstead]		x	x	x	x
Loc 31	SH 6 EB to US 290 EB Ramp from College Station [Hempstead]		x	x	x	x
Loc 32	Spur 10 NB -- North of US 59 in Rosenberg]			x	x	x
Loc 33	Beltway 8 North Belt WB M/L entry @ Old Humble Rd [375-T]			x	x	x
Loc 33F	Beltway 8 North Belt WB Frontage Road @ Old Humble Rd [375-T]			x	x	x
Loc 34	FM 1093 [Westheimer Rd] WB -- west of Richmond [487-Z]			x	x	x
Loc 35	FM 529 WB -- west of Sommerall [407-R]			x	x	x
Loc 36	SH 249 NB -- north of Spring Cypress [329-J]			x	x	x
Loc 36F	SH 249 NB Frontage Road -- north of Spring Cypress [329-J]			x	x	x
Loc 37	US 90 EB -- west of Sheldon [458-B]			x	x	x
Loc 38	US 90 WB -- west of Sheldon [458-B]			x	x	x

{1} Data collected durring Hurricane Rita evacuation and base non-evacaution data -- September 2005
{2} Data collected during Hurricane Dean, no evacuation ordered, no landfall near Houston area -- August 2007
{3} Data collected as base non-evacuation data -- June to August 2008
{4} Counters deployed at indicated locations for Gustav impact analysis
-- counters out for part of 8/29-31,2008 [Landfall near Cocodrie, LA on Sept 1, 2008 approx 1100am]
{5} Counters deployed at indicated locations for Ike impact analysis
-- counters out for part of 9/9-17,2008 [Landfall at Galveston, TX on Sept 13 @ 2:10am]

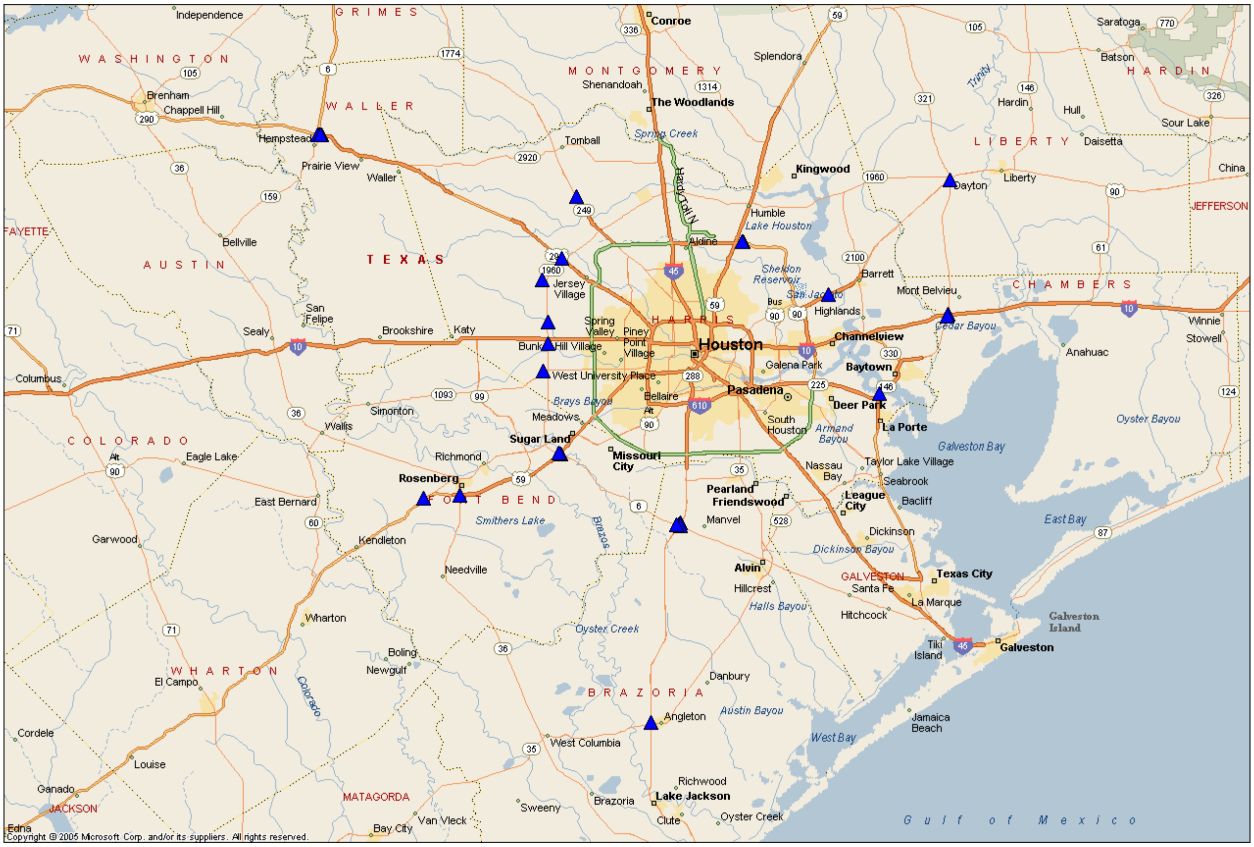


Figure 5. Road Tube Counter Locations, 2008 Hurricane Season.

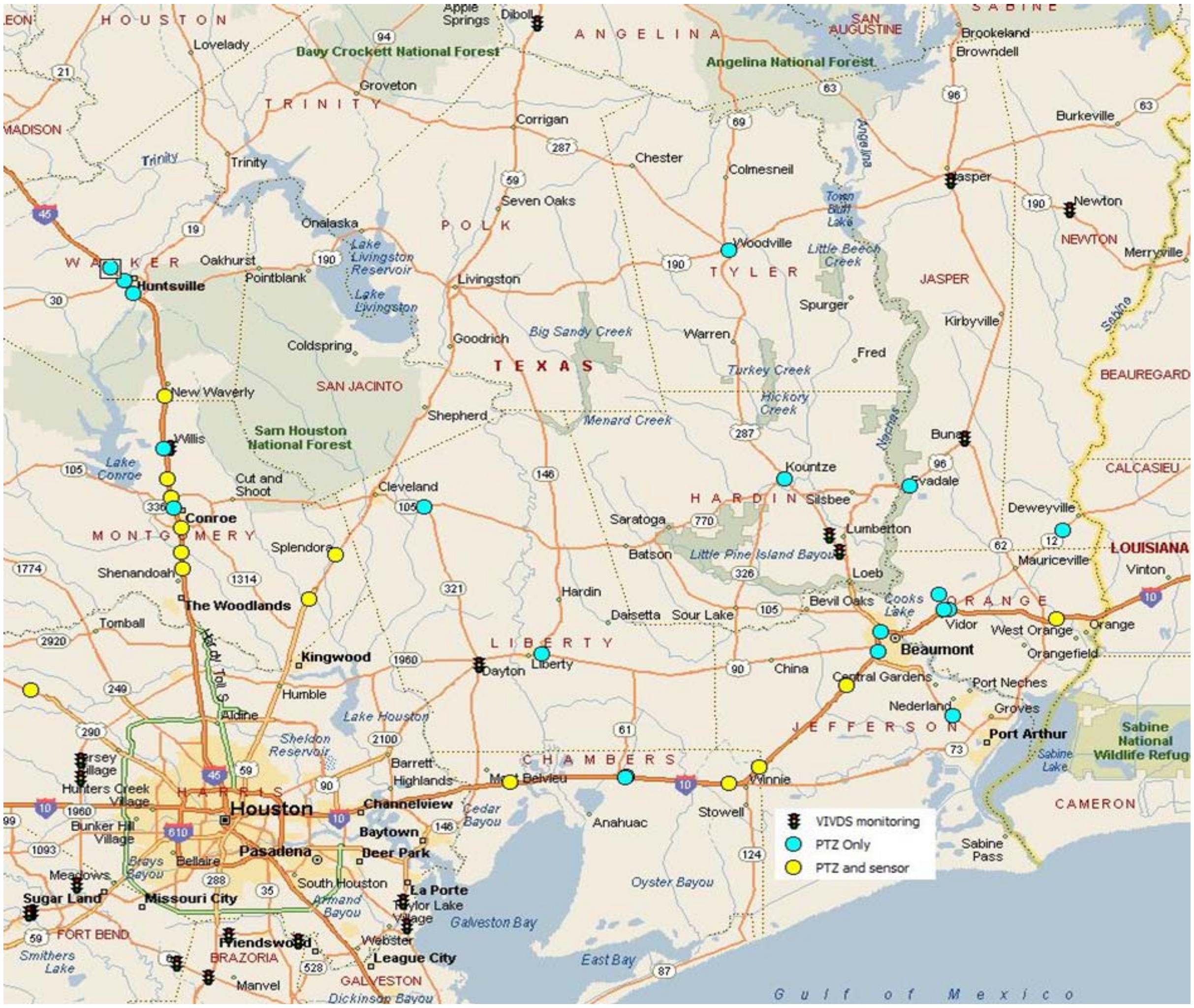


Figure 6. Location of TxDOT Hurricane Evacuation Cameras and Sensors, Houston-Galveston and Beaumont-Port Author Regions.

Table 6. Summarized Houston TranStar Radar Data, 2008.

		Data Summary Period		
Sheet #	Location	2008 {1}	Gustav {2}	Ike {3}
R_1-EB	SH 71 EB @ US 90 in Columbus	x	x	
R_1-WB	SH 71 WB @ US 90 in Columbus	x	x	
R_2-EB	I-10 East EB @ Weigh Station in Anahuac	x	x	x
R_2-WB	I-10 East WB @ Weigh Station in Anahuac	x	x	x
R_3-EB	I-10 East EB @ Business 90 in Orange	x	x	x
R_3-WB	I-10 East WB @ Business 90 in Orange	x	x	x
R_4-EB	I-10 Katy EB @ FM 1463 in Katy	x	x	x
R_4-WB	I-10 Katy WB @ FM 1463 in Katy	x	x	x
R_5-EB	I-10 West EB @ Luling DMS	x	x	x
R_5-WB	I-10 West WB @ Luling DMS	x	x	x
R_6-NB	I-45 North NB @ Airline	x	x	x
R_7-NB	I-45 North NB @ League Line Road	x	x	x
R_7-SB	I-45 North SB @ League Line Road	x	x	x
				x
R_8-NB	I-45 North NB @ New Waverly	x		
R_8-SB	I-45 North SB @ New Waverly	x		
R_9-NB	I-45 North NB @ FM 1488	x	x	x
R_9-SB	I-45 North SB @ FM 1488	x	x	x
R_10-NB	I-45 North NB @ SH 75 in Hunstville	x	x	x
R_10-SB	I-45 North SB @ SH 75 in Hunstville	x	x	x
R_11-EB	US 290 Northwest EB @ SH 6 DMS in Hempstead	x	x	x
R_11-WB	US 290 Northwest WB @ SH 6 DMS in Hempstead	x	x	x
R_12-EB	US 290 Northwest EB @ Katy-Hockley	x		
R_12-WB	US 290 Northwest WB @ Katy-Hockley	x		
R_13-EB	US 290 Northwest EB @ SH 6 Exit in Hempstead	x	x	x
R_13-WB	US 290 Northwest WB @ SH 6 Exit in Hempstead	x	x	x
R_14-EB	US 290 Northwest EB @ Mueschke	x	x	
R_14-WB	US 290 Northwest WB @ Mueschke	x	x	
R_15-EB	I-10 Katy EB @ US 90 east of Columbus		x	x
R_15-WB	I-10 Katy WB @ US 90 east of Columbus		x	x

{1} -- June 2008 data collected as base data, no evacuation
{2} -- Gustav data from Fri Aug 29 to Wed Sept 3 [will provide evac and return info]
{3} -- Ike data from Wed Sept 10 to Sat Sept 13
[storm impact in Southeast Texas caused damage/power loss to TranStar systems]

CHAPTER 5:
SELECT CASE STUDY LOCATION

BACKGROUND

This task entailed the selection of the case study location for the development of the decision support system prototype. To provide the maximum amount of time possible over the course of the project, this issue was discussed thoroughly amongst the Project Monitoring Committee (PMC) membership and research team as part of the kick-off meeting in March 2009.

CASE STUDY LOCATION

Early on in the project, the research team developed a set of criteria that would be used to evaluate the selection of best case study location. These factors included:

- Availability of historical data.
- Availability of real-time data.
- At-risk population in the area (i.e., potential value captured from near-term application of a new decision support tool).
- Existing/prior analyses, tools, etc. (e.g., existing simulation models).
- Complexity of developing a new application for the region.

These factors were carried forward into the kick-off meeting as preliminary points of discussion for the PMC and research team to consider. The most populated (and, therefore, most at-risk to hurricane) areas are the Lower Rio Grande Valley, the Coastal Bend (Corpus Christi and surrounding area), and the Houston-Galveston region (see Figure 7). With regard to case study location selection, the PMC noted that while the Lower Rio Grande Valley had not experienced many tropical storms/hurricanes in the last 20 years or so, it would be helpful to include that region in consideration of project activities and applications.

Figure 7. Texas Coastal Areas.

It was clear early on in the group discussion that the most logical case study location would be either the Corpus Christi or the Houston-Galveston region. Both of these geographic areas offer a solid set of historical data and have been the focus of numerous studies over the past decade. It was agreed that using Corpus Christi as the case study location would offer the advantage of a less complex environment to develop new tools and applications, as compared to the highly complex and dynamic transportation system operations in the Houston-Galveston area. Two significant advantages that were pointed out for the latter, however, are the extremely robust sources of real-time data (some of the best in the entire United States, see Task 3 technical memorandum for further details) and the existing regional traffic simulation/network models that are already available as starting points for analysis in the Houston region. After a thorough weighing of the pros and cons, the PMC agreed that selection of the Houston-Galveston region made the most sense. As such, that region will now be the focus of detailed data gathering and analyses for all subsequent and related tasks.

CHAPTER 6:
ASSEMBLE DATA FOR HURRICANE EVACUATION MODELING AND CALIBRATION

The input data necessary for modeling large-scale hurricane evacuation with transportation analysis tools depend on the type of model selected. Three general types of transportation analysis models exist, and each is briefly described below. Specific past studies are identified where work has been done for Texas urban areas, as these regions may ultimately be covered by the evacuation support tools developed under this research effort.

MACROSCOPIC MODELS

Transportation modeling tools that represent traffic flows in aggregation are macroscopic models. Such tools can vary in scope of application from roadway intersections to region- or even state-wide models. Macroscopic models that could be applied for hurricane evacuation modeling are travel demand models; examples include Cube Voyager, TRANPLAN, and TransCAD. Unique origin-destination demand tables would be necessary for hurricane evacuation events, as the trip destination and purpose are not consistent with the daily travel patterns accounted for in-demand models that departments of transportation or planning organizations employ for typical demand projections and network analyses.

MESOSCOPIC MODELS

Mesoscopic models most often represent traffic flows as composed of unique vehicles, but not at a level of detail where interactions among those vehicles are explicitly modeled. These tools are typically used to model roadway corridors or sub-regional networks; examples include DynusT, DYNASMART-P, and Integration. Mesoscopic platforms are often linked with dynamic traffic assignment tools, which can enable analysts to specify the level of real-time traffic information available to the simulated vehicles within the modeled network. Vehicles able to receive this information can alter their route according to prevailing conditions. Mesoscopic tools have been successfully applied for hurricane evacuation modeling in Texas, including an analysis of the impacts of contraflow in the Houston-Galveston region and an analysis of the Hurricane Rita evacuation in the same region.

MICROSCOPIC MODELS

The most detailed traffic models are known as microscopic models. These tools directly represent the individual vehicles spatially and temporally within the simulation network. Microscopic models are often constrained in coverage area due to computational requirements, with a corridor-level or small area subnetwork model being a practical upper boundary. Common examples of these tools include AIMSUN, CORSIM, Paramics, TransModeler, and VISSIM. Some microscopic models feature dynamic traffic routing and/or assignment functions that allow the model to internally determine optimal vehicle routing for the network. The most likely application of microscopic models for hurricane evacuation would be to determine the impact of evacuation-level volume (demand) on specific roadway corridors or interchanges, or to determine the impacts of allowing contraflow on a limited segment of a given roadway corridor. Microscopic tools have been used in Texas to simulate the impacts of contraflow on Interstate 37 departing the Corpus Christi region and more recently as a means of identifying bottlenecks within contraflow plans established for coastal urban areas.

In earlier project stages, the Houston-Galveston region was selected as a case study for the development of the decision support tool designed to assist local agencies with assessing the need for implementing contraflow in support of a large-scale hurricane evacuation. The modeling necessary to compare cases involving and not involving contraflow are very broad in coverage area, extending not only throughout the Houston-Galveston region in southeast Texas, but also along evacuation routes to San Antonio, Austin, and Dallas/Fort Worth. Such representational scale in the model precludes the use of microsimulation, leaving either mesoscopic or macroscopic tools in contention to fulfill the project's modeling requirements. However, because macroscopic tools do not represent individual vehicles within the network, they do not accurately model congestion in a sufficiently finite time scale and spatial distribution to realistically represent roadway operations that would exist under heavily loaded evacuation demand conditions. Mesoscopic models have demonstrated their capabilities in simulating hurricane evacuation conditions, and past research into contraflow system-wide benefits for the Houston-Galveston region is being leveraged to expedite the modeling analyses necessary to support this project's contraflow decision support prototype.

MODEL INPUT REQUIREMENTS

Consistent with previous efforts of modeling contraflow within the Houston-Galveston region and its evacuation routes, analysts selected the DynusT mesoscopic tool for hurricane evacuation modeling. As with all transportation analysis tools, input to the model is required in terms of geometric data, traffic control data, and demand (or volume) data. Compared with other modeling tools, the data necessary to populate the DynusT mesoscopic analysis model are neither as detailed as the data necessary for microscopic modeling nor as generalized as the aggregated, link-capacity representation of the roadway network found in a macroscopic model.

Geometric Data

DynusT uses a link-node structure to represent roadways and intersections. However, unlike many models, it does not use nodes directly as centroids or as driveway/minor street junctions with higher-volumes roadways that are included in the modeled network. Vehicles are loaded onto the network along links designated to be the "generation links" for vehicles outbound from a zone (or zones) that they pass through. Destinations are strategically located nodes in the network along designated roadways within or bound by each zone.

When coding roadways, analysts specify the geometry of the link with feature points (i.e., roadways are "drawn" in the DynusT user interface) and then enter the number of lanes, the lane capacity, number of turn bays, grades, and a traffic flow model. Flow model choice is dependent on the type of roadway being modeled (i.e., freeway, arterial, user specified, etc.). Zone boundaries, roadway locations, and node locations are located in a spatially scaled user interface (see Figure 8), so details such as link length and the overlaps between roadway links and zones are either automatically or semi-automatically accounted for in model coding. Both zone (network sub area) and roadway (link) data are typically imported from other tools or models, including geographic information systems or travel demand models.

Traffic Control Data

Analysts specify traffic control for the at-grade intersections within the modeled network. Options are available for yield control, two-way stop control, all-way stop control, pretimed signalization or actuated signalization. Each control type has the expected impact on vehicles using the link (i.e., yield signs result in minor traffic yielding to major roadway traffic, vehicles stop at signals during the red phase, etc.), though the fact that the model is mesoscopic in nature affects the level of precision in representing real-world intersections operations.

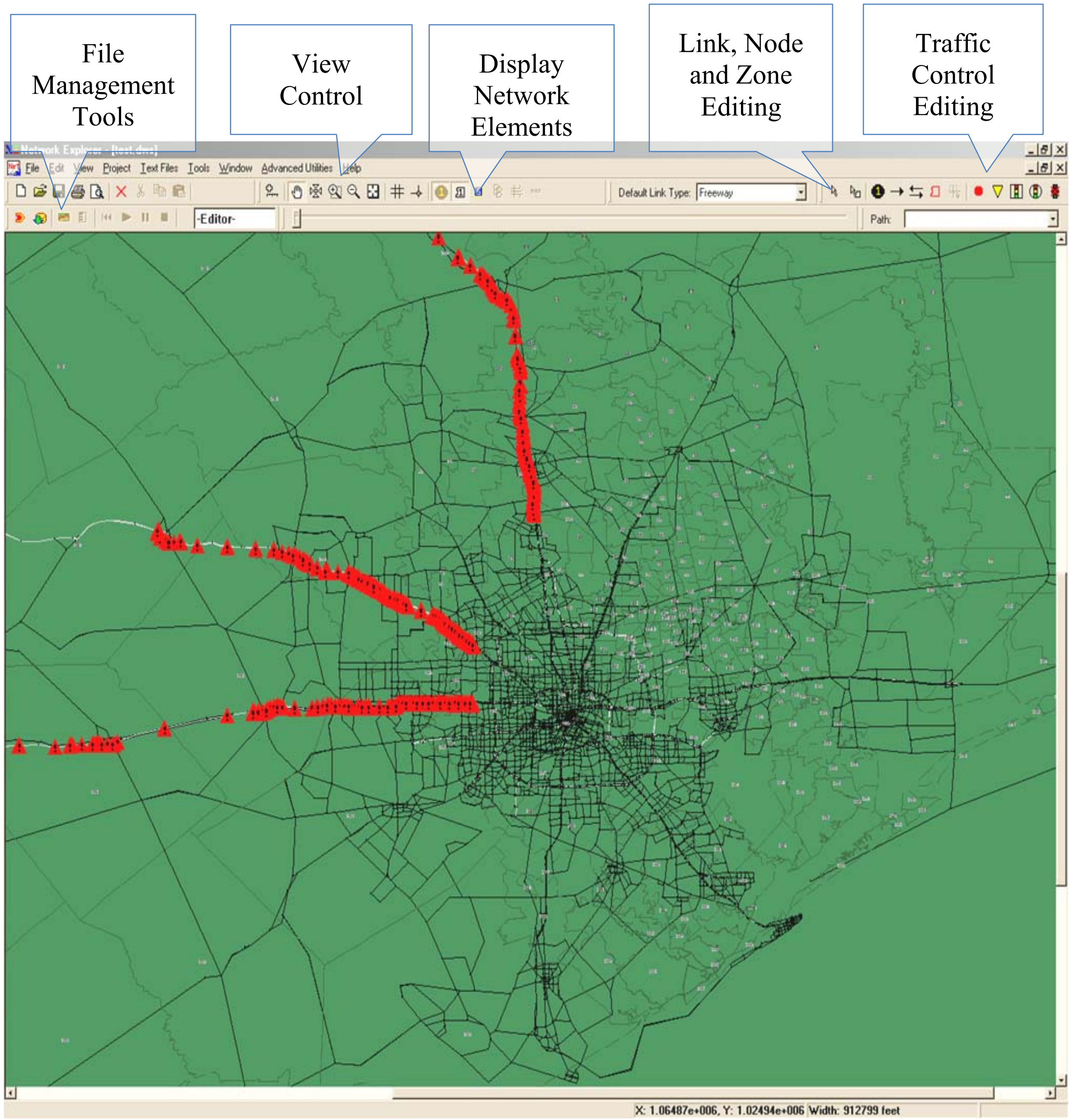


Figure 8. DynusT Evacuation Model (Houston Region).

Variable message signs can be coded into the model to influence driver behavior consistent with the purpose of the sign display. Options exist to model speed advisory, detour, and congestion warning messages.

Demand Data

Traffic demand is specified in DynusT through the use of origin-destination demand tables that specify the number of trips between the origin zone and destination node for a given unit of time (Figure 9). Options exist within the program to import these data, and the source of origin-destination tables is often a travel demand model. Multiple demand tables can be used, and options exist to specify separate demand tables for trucks and high-occupancy vehicles (HOV). The analyst can control when individual demand tables of each type begin and end, and whether any demand modification factors are used, both at the system level and for each table used in the model. An option also exists to create “superzones,” a form of zone aggregation that simplifies calculations when DynusT is modeling large networks for evacuation.

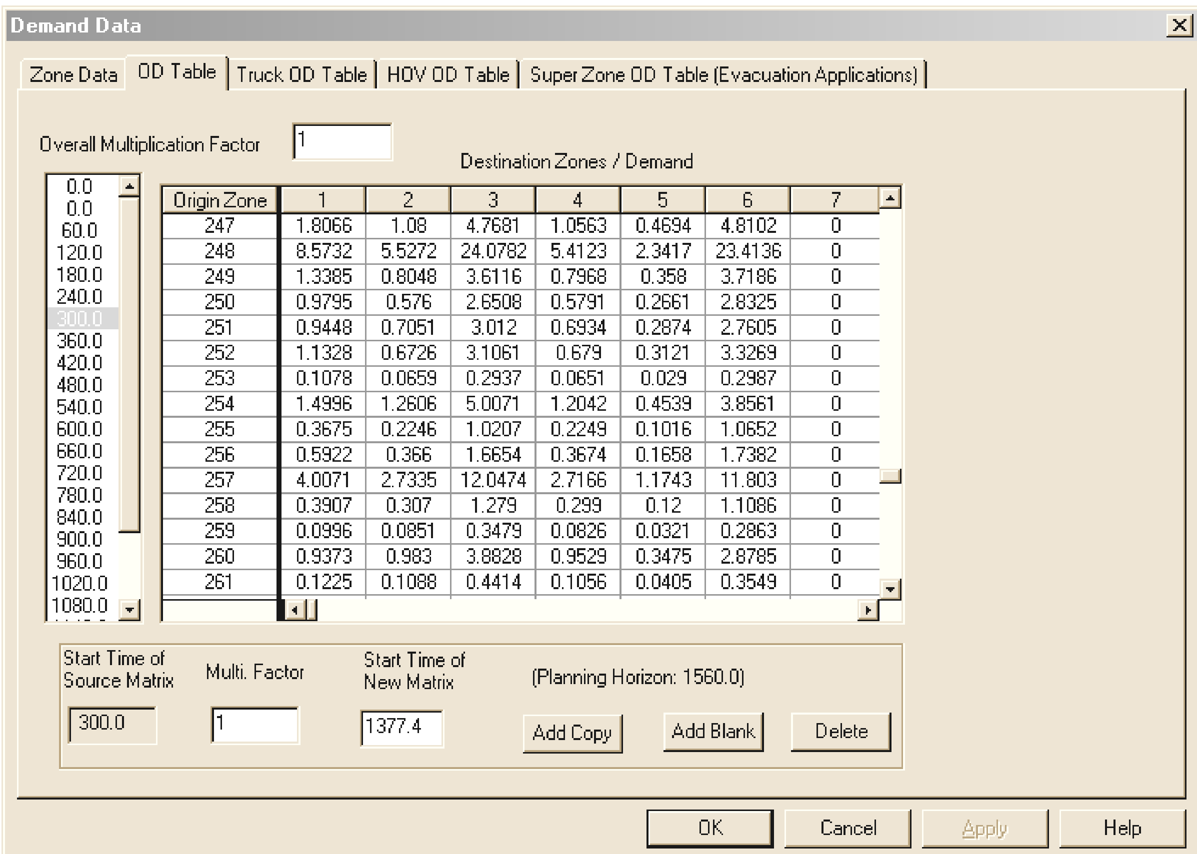


Figure 9. DynusT Origin-Destination Demand Data.

Additional Features

DynusT has additional features that allow the analyst to specify incidents, work zones, and ramp metering. For hurricane evacuation modeling, the incident features will be used to create a simulation data set that determines the impacts of an incident on a major Houston evacuation route (i.e., I-10, US 290, or I-45) under both contraflow and non-contraflow operations. The potential also exists for analysts to use the ramp metering function as a method for controlling access to evacuation corridor through lanes during time periods when evacuation plans favor traffic departing from zones closer to the coastline (i.e., experimentation with “staged” evacuation).

DYNUST MODEL OF THE HURRICANE RITA EVACUATION

Previous DynusT modeling efforts have already produced a network for the Hurricane Rita evacuation in 2005. Modelers for that study began their effort with the Houston-Galveston Area Council of Government's (HGAC) TransCAD travel demand model (TDM) and the Texas Department of Transportation's TransCAD Statewide Analysis Model (SAM). Both networks were simplified by removing all roadways below the arterial class, and then the SAM was "cut" to leave only the southeast Texas region, including the I-10 corridor to San Antonio, the I-45 corridor to Dallas, and the US 290 corridor to Austin. Additional modification to the SAM removed the HGAC modeling boundary, which was replaced with the HGAC TDM (see Figure 10). Detailed coding was then performed along all freeway corridors to provide directional freeway links, ramps, contraflow links, and to increase the level of accuracy in representing major arterial roadway intersections.

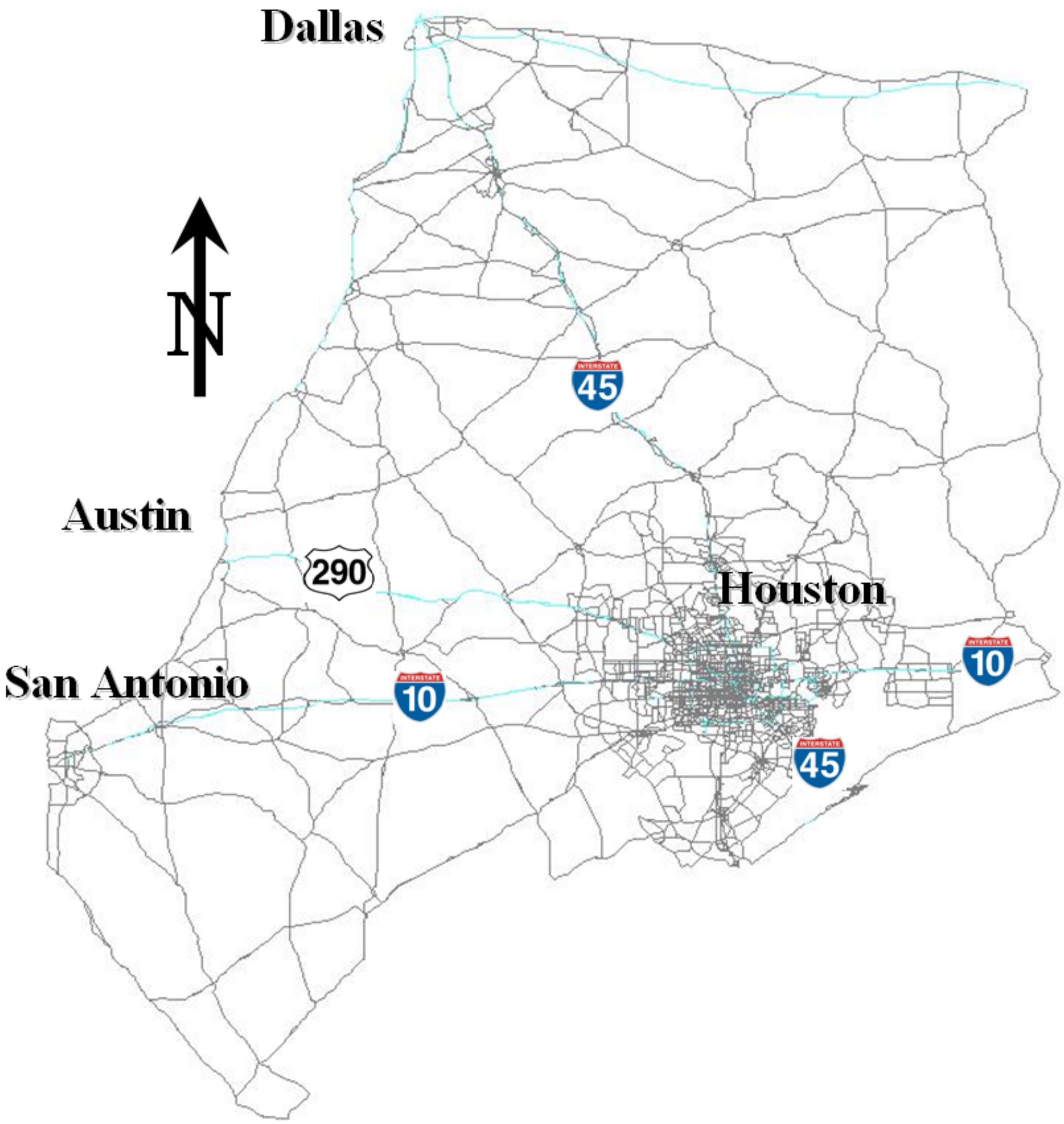


Figure 10. Hurricane Rita Evacuation Modeling Network.

Figure 11 provides detail as to the link/node structure of the evacuation model in DynusT as well as the frontage road, freeway, and arterial network components found in the model. Red icons in the figure mark the contraflow links along US 290 outside of SH 6.

Interchange and intersection signal timing was estimated based on setup runs of the evacuation network. Queue management and equal queue distribution were used to guide signal timing settings for intersections mostly serving background traffic, while increased green time was given on approaches to intersections serving greater proportions of evacuating traffic.

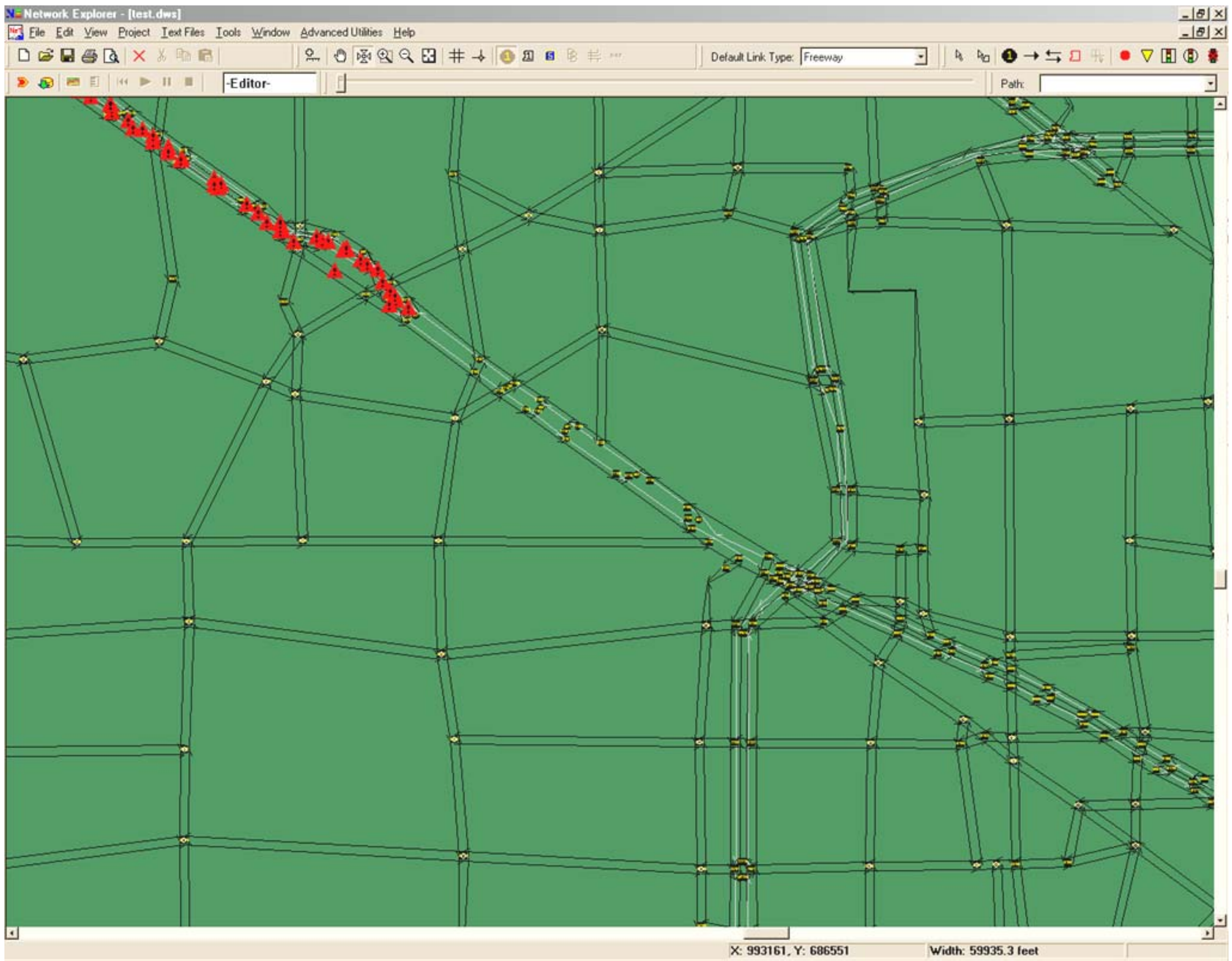


Figure 11. DynusT Representation of US 290 Corridor in Northwest Houston.

Gathering the demand data for hurricane evacuation proved to be one of the more complex tasks of the evacuation/contraflow simulation effort. Within the limits of the HGAC TDM, everyday demand in the network was geographically distributed in traffic analysis zones (TAZ), or zones of relatively common land use for which origin-destination data are estimated. However, most evacuation data traffic estimates were based on phone surveys conducted by zip code. To rectify this inconsistency, TAZ data for the TDM were reassigned to (larger) zip code zones rather than TAZs for the evacuation model. Outside of the HGAC modeling boundary, background traffic data were organized by county.

Estimation of traffic conditions during the evacuation involved not only estimating the number of vehicles departing zip code zones close to the coast (and throughout the HGAC urban area), it also involved estimating the amount of background traffic continuing to occur while evacuation was under way. Evacuation traffic was estimated based on the results of a comprehensive post-evacuation household survey. Evacuation behavior by county was extracted from survey responses, which ultimately identified approximately 124,000 evacuating vehicles from Brazoria County, 161,000 from Galveston County, 282,000 from within the storm surge zone portion of Harris County, and 696,000 from within the non-surge zone portions of Harris County. Evacuation traffic for each county was distributed by zip code zone based on the number of households per zone. Vehicle occupancy based on survey results was used to convert the number of evacuees to the number of evacuating vehicles by county. A gravity model was used to assign evacuation vehicle trips to destination zones in the network, including destination cities of Dallas/Ft. Worth, Austin, and San Antonio. Survey data were also used to develop an evacuation demand time profile, which was used to develop time-varying demand tables for the evacuation model. These tables essentially identified when traffic was departing each zip code zone for the evacuation trip purpose, and these data were kept in separate tables from background traffic demand.

Whereas survey data could be used for evacuating traffic, the level of background traffic—which included disaster preparation trips as well as the "normal" travel activity of roadway users able to pursue their daily schedule despite the oncoming hurricane—had to be experimentally derived. Analysts used basic assumptions to guide a first tier of decision making, accounting for the fact that everyday trips whose original destination was within a flood zone were extremely limited. Five percent of trips were allowed to/for Flood Zone 1, which included zip codes along the coast, 10 percent of trips were allowed to/within Flood Zone 2, and 25 percent of trips were allowed to Flood Zone 3 (see Figure 12 for Flood Zone definitions). In the remainder of the HGAC network, 50 percent of normal everyday trips were scheduled to occur. Trips were organized into hourly demand tables according to hourly volume profiles so they could be used alongside the evacuation demand tables.

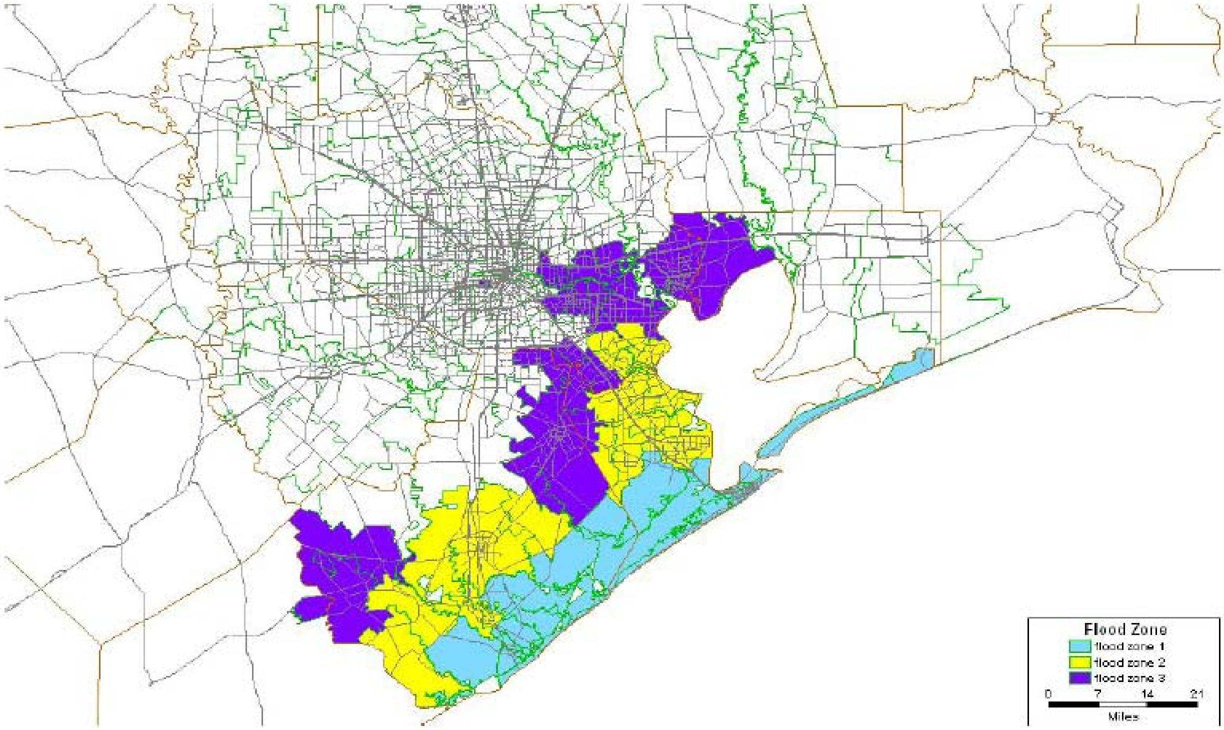


Figure 12. Flood Zone Boundaries Based on Zip Code (Adapted from Error! Bookmark not defined.**).**

Both evacuation and background traffic demand tables were loaded into the DynusT simulation network. A mathematical process was used to compare traffic counts from the model against traffic count data that TTI and TxDOT collected in the days preceding the landfall of Hurricane Rita. In an iterative procedure, background traffic demand tables were adjusted until discrepancies between counts from the DynusT model and the field data were minimized. Table 7 provides a list of traffic data used in the calibration effort.

Table 7. Evacuation Traffic Count Data.

Roadway, Direction, and Location	Daily Traffic Count (Normal)	Rita Evacuation (9/15/2005)
I-45 North Freeway NB @ Airline	106,864	94,693
I-45 North Freeway NB @ Cavalcade	95,535	89,705
I-45 North Freeway NB @ North Main	88,734	80,276
I-45 North Freeway NB @ Quitman	86,792	77,183
SH 288 NB @ Airport	57,891	65,405
SH 288 NB @ Holly Hall	93,220	84,662
SH 288 NB @ Fournace	97,005	89,582

US 59 Southwest NB @ Airport	59,038	49,094
US 59 Southwest SB @ Airport	76,956	68,301
US 59 Southwest NB @ SH 288	46,981	35,357
US 59 Southwest NB	24,241	15,791
SH 36 NB – North of FM 1301	4,779	13,025
SH 36 NB – South of US 59	7,722	20,287
SH 36 NB – North of US 90A	7,210	11,192
SH 288 NB @ SH 35	9,156	15,404
SH 288 NB @ SH 6	15,373	31,057
SH 288 NB SH 6 Entry	12,039	11,272
SH 6 WB – West of FM 2004	5,410	11,343
SH 6 WB – East of SH 288	11,719	28,982
SH 6 WB – West of SH 288	9,474	29,310
SH 6 NB – South of US 59	27,410	32,846
SH 6 NB – North of US 59	26,215	32,474
SH 6 NB – North of Memorial	32,389	32,324
SH 6 NB – South of Patterson	28,213	26,230
SH 6 NB @ Hempstead Road	26,959	31,738
US 290 Northwest Freeway WB @ Mueschke	31,149	49,222
I-45 North Freeway NB @ Hardy Toll Road	87,995	67,129
Hardy Toll Road Entry to I-45 North Freeway	14,431	27,451
I-45 North Freeway NB – North of Hardy Toll Road	102,426	94,580
SH 146 NB – North of FM 519	8,548	7,025
SH 146 NB @ Fred Hartman Bridge	33,910	51,111
SH 146 NB – South of I-10 East	15,615	35,144
SH 146 NB – North of I-10 East	13,468	21,134
SH 146 NB – South of US 90	6,382	18,805
SH 146 NB – South of FM 1011	5,103	12,352
US 90 WB – West of SH 61	4,360	6,668
FM 365/FM 1406 NB – South of US 90	1,149	5,330
FM 1406 NB – North of I-10	1,128	3,600
SH 124 NB – North of SH 65	5,966	11,178

Two different DynusT models were created; one did not include contraflow lanes and the other included contraflow lanes as indicated in TxDOT and Texas Department of Public Safety evacuation plans for the I-45 corridor to Corsicana (most of the way to Dallas), I-10 corridor to San Antonio, and US 290 corridor to Hempstead (part of the way to Austin). Results of this modeling effort showed a variety of corridor evacuation congestion improvements along I-10, I-45, and US 290 and an overall benefit to evacuation traffic of 10 percent improved travel time and 16 percent improved average speed. The model was further used to conduct a theoretical exercise on the impacts of phased evacuation.

NECESSARY UPDATES TO THE DYNUST EVACUATION MODEL

Since the Hurricane Rita evacuation, a number of institutional and background changes have taken place that affect future hurricane evacuation modeling for this region. On the roadway infrastructure side, several changes have taken place that will be incorporated into the DynusT model. Construction on a 20-mile Katy Freeway (I-10) improvement project has been completed from Loop 610 to the City of Katy. Table 8 presents details regarding the new I-10 cross-section, which will be coded in an updated version of the DynusT evacuation model.

Table 8. Lane Configuration on the Katy Freeway (I-10).

I-10 Freeway Section	Mainlanes (each direction)	Frontage (each direction)
Fort Bend County Line to SH 99	4	3
SH 99 to SH 6	4 + 1 HOV	3
SH 6 to Loop 610	4 + 2 HOV/HOT	3

Another important infrastructure change is the completion of an "Evaculane" along I-10 between SH 359 in Brookshire, TX and Loop 1604 in San Antonio, TX. With the outside, improved shoulder allowing evacuating traffic to use three westbound traffic lanes west of Brookshire, improved lane geometry will be coded for this corridor.

Recent modifications to Houston region evacuation plans have included a "mini" contraflow plan for Conroe while construction is underway along I-45. During construction, the existing four lanes of capacity are reduced to two near Loop 336 South in the Conroe area. The proposed "mini" contraflow plan includes using the southbound I-45 lanes as contraflow lanes from south of Loop 336-South in Conroe to the Walker/Madison county line using FM 2989 and Spur 67. This option to use the "mini" contraflow plan will occur when high Category 2 or low Category 3 hurricane events occur; for more intense storms, the full I-45 contraflow plan will be exercised.

In addition to roadway infrastructure changes, traffic demand in the City of Houston has also changed over the last few years. The project team has met directly with HGAC staff to discuss their travel demand model and the changes in traffic demand over the last four years. HGAC provided researchers with an updated travel demand model, and this model will be compared against the demand tables currently found in the background traffic tables of the DynusT evacuation model.

DATA RESOURCES IN THE HOUSTON REGION AVAILABLE FOR AN EVACUATION EVENT

During the evacuation from the Houston-Galveston area because of Hurricane Rita in 2005, there were limited resources available for monitoring traffic operations beyond the immediate urban areas. Traffic speeds and travel times were available within Houston TranStar from the toll-tag based traffic monitoring system. However, with traffic moving at speeds less than 5 mph, and with the traffic bottlenecks beyond the urban area, the resulting information was of limited use to traffic management personnel. CCTV camera views of the roadways were also limited essentially to the freeways within the toll-tag monitoring area. While there were a few radar sensors along the freeways to monitor traffic volumes and speeds in real-time, these were also located in the urban area and were not installed for evacuation traffic monitoring. TTI collected the vast majority of data collected during the Rita event using road-tube based traffic counters. While this information provided a valuable resource to measure roadway performance during the after action review of the evacuation, the data were not available on a real-time basis during the event.

The Rita evacuation from the Houston area resulted in congested roadways; a typical 4-hour drive from Houston to Dallas was reportedly taking in excess of 24 hours. Although fuel shortages, medical issues, and personal comfort needs complicated the effort, all roadways in the anticipated hurricane impact zone were cleared of motorists 12-hours before landfall. In October 2005, the Texas Governor appointed a 14-member task force to, in part; make recommendations on how to improve evacuation plans for future emergencies in Texas. The task force recommended that TxDOT and the Texas Department of Public Safety (DPS) jointly develop contra-flow plans for major evacuation routes. Traffic managers and law enforcement agencies throughout the state worked together to develop the required plans, including the installation of traffic monitors. Prior to this event, it was assumed that the evacuations would only occur in the coastal regions that might likely flood due to storm surge. The evacuation plans and roadway capacity for this scenario was more than sufficient to handle traffic demands as the evacuees traveled a distance of typically less than 100 miles. However, the Hurricane Rita evacuation included a significant increase in the volume of traffic departing from regions that are typically not in danger of a flooding event; many of these drove 200–300 miles to their intended destination.

In the spring 2006, TxDOT began the installation of traffic sensing equipment to have the capability to monitor traffic operations at critical points along critical evacuation routes in southeast Texas. In addition to the ability to receive real-time traffic information, cameras were installed at these locations to provide snapshot images of the roadway. Selected locations along the freeways in the rural areas were also equipped with radar sensors to provide real-time traffic volume and speed information to TranStar. Using existing video detection equipment (VIVDS) already installed at signalized intersections, relatively inexpensive and expedited installations were accomplished with only the addition of cellular modems and video servers in signal cabinets. Table 9 presents a summary of this equipment that was deployed in the Houston and Beaumont regions to facilitate evacuations.

Table 9. TxDOT Installed Hurricane Cameras and Traffic Sensors.

Roadway Limits	Approximate[1] Distance (miles)	Number of Devices: Cameras[2] CCTV	Number of Devices: Cameras[2] VIVDS	Number of Devices: Sensors[3]
Houston Region				
I-10 West				
Luling to Katy	110	13	-	9
US 290 Northwest				
Giddings to Waller	70	8	4	4
SH 36/US 59				
Needville to Rosenberg	19	3	16	-
SH 6				
SH 6 @ FM 521 in Arcola	-	-	4	-
SH 146				
SH 146 @ FM 646 in Bacliff	-	-	4	-
I-45 North				
Huntsville to Conroe	37	10	-	6
SH 71				
SH 71 @ US 90 in Columbus	-	1	-	2
Beaumont Region				
US 59				
Nacogdoches to Cleveland	95	3	20	-
SH 105				
SH 105 @ SH 321 in Tarkington	-	1	-	-
US 90/SH 146				
Dayton to Livingston	57	1	7	-
US 69				
Woodville to Lumberton	44	4	12	-
FM 105				
Evadale to Vidor	14	2	-	-
SH 87				
Deweyville to Newton	43	1	4	-
I-10 East				
Orange to Baytown	82	8	-	6
Totals	-	55	71	27

[1]Distances not reported for locations along a roadway that are not consecutively adjacent.
[2]There are two types of cameras: a) CCTV—these have PTZ capabilities, b) VIDS—views from traffic signal video detection cameras.
[3]Sensors include data for both directions of travel.
Source: Reference (*6*).

The 27 traffic monitoring sensors and 126 locations where CCTV snapshot images were available played an important role in managing the traffic during the evacuation of the Houston region in the September 2008 Hurricane Ike event. Radar sensors installed along US 290 in the urban area as part of another effort were also used to monitor evacuation traffic in conjunction with the toll-tag monitoring system. TxDOT staff working at Houston TranStar were able to monitor traffic operations along the roadways such that evacuating traffic was moving smoothly throughout the region. Although traffic did slow down for several hours during the peak evacuation traffic push, the ability of the real-time traffic monitoring allowed for appropriate dispatch of resources as needed to better manage evacuation traffic flow. In fact, the decision of traffic management engineers to not implement any contraflow operations along I-45 North and I-10 West from the Houston area was facilitated by the information from the traffic flow sensors and views from the video monitors in the areas outside the immediate Houston region. Although the network of monitoring equipment installed in 2006 proved to be adequate for the 2008 evacuation, it has been recommended that 280 stations be installed in the near-term and an additional 158 planned for in the long-term throughout Texas (*6*). These additional installations would provide for expanded monitoring capabilities in parts of the State that were not covered in the 2006 expansion to the rural areas.

The existing expanded sensor network worked quite well during the 2008 Ike evacuation. Reviews of the data streams indicated that the sensors continued to send data to TranStar via the cellular network essentially until after hurricane landfall. As the electrical service throughout the region began to fail, data flows from the traffic sensors and CCTV cameras ceased. In the days following the storm's landfall, the equipment began operating and again sending traffic volume and speed information as well as video snapshot images.

Each of the sensors that communicate to TranStar sends data to the traffic management center at 30-second intervals. Because of this regular activity, it is also possible to monitor and evaluate the reliability of the cellular communication network. Because the majority of these sites are located in the rural regions, there may be less cellular network coverage capacity when compared to the immediate Houston area. With increasing use of wireless devices requiring data services access the cellular network, the amount of remaining bandwidth to transmit the sensor data may be reduced during an evacuation scenario when compared to a normal traffic day. To examine this possible impact, a review of the quantity of data received from the sensors in the rural regions as well as those along US 290 in the urban area was completed. Ranges of communication reliability were developed to allow for comparisons among the sites. It is common to have less than absolute 100 percent communication for a day at each of the sites; a 100 percent communication would result in 2,880 30-second transmissions from each sensor on a daily basis. TTI staff completed a review of the communication frequency for the Ike event and determined that during the time of peak traffic evacuation along the roadways, there appeared to be a significant reduction in data flows from the roadway sensors along the evacuation routes. Although many locations experienced sporadic communication reductions throughout the three-day time period examined, there was a significant reduction in at all sites during the 10 a.m. to 1 p.m. time period on Thursday, September 11, 2008. As there were no issues regarding receiving the data at TranStar, it is assumed that this may have been related to the overall cellular network instead of site-specific issues. As electrical power was restored to the greater Houston region in the weeks after Hurricane Ike, the data flow from the sensors to TranStar began to increase. This update depended on when electrical power was restored to the roadways where the sensors were located.

CHAPTER 7: SELECTING THE DYNAMIC TRAFFIC ASSIGNMENT MODELING TOOL

The objective of this task was selecting an appropriate dynamic traffic assignment tool for the analysis and evaluation of hurricane evacuation strategies. Researchers conducted a literature review and evaluated the feasibility of using various traffic analysis tools as the traffic network model for hurricane evacuation. They identified DynusT/Dynasmart-P as the most applicable and appropriate dynamic traffic assignment (DTA) tool for the majority of the traffic analysis modeling required in this project. Furthermore, the Houston-Galveston regional transportation network—the region that the Project Monitoring Committee identified as the desired demonstration area for the TxDOT RMC 6121 research—and the major evacuation roadways serving this metropolitan region have already been coded for the Dynasmart-P model during a previous research study. This network will be updated for application to the current project, thereby leveraging resources for the modeling task and allowing the researcher to focus increased attention on evacuation cases being modeled.

OVERVIEW OF DYNAMIC TRAFFIC ASSIGNMENT

In a modeling process, the goal of traffic assignment is to determine the network traffic flows and conditions that result from the interactions between the route choices drivers make in going from their origin to their destination, and the congestion that results from their travel over the network. DTA reflects the reality that traffic networks are generally not in a steady state by representing time variations in traffic flows and conditions. This is particularly true in light of evacuation modeling in this study, as volumes are almost always heavily in excess of capacity on evacuation routes and congestion is prevalent. Dynamic user equilibrium (DUE) requires two general extensions of the static user equilibrium concept. First, drivers are assumed to know future travel conditions over the network and, in choosing an origin-destination (OD) route, they are assumed to minimize travel time that they will actually experience (i.e., minimizing experienced travel time). The second extension recognizes that in a dynamic approach, the user equilibrium condition of equal travel times on used paths applies only to travelers who depart at the same time between the same OD pair.

WHY APPLY DTA TOOLS FOR EVACUATION MODELING?

DTA models offer dynamic network equilibrium modeling capability that is unavailable in static traffic assignment and most microscopic traffic simulation models. In the hurricane evacuation process, the underlying characteristics motivating the use of DTA is that there exist both changes of demand-and-supply conditions significant enough to induce spatial and temporal traffic flow shifts, as a consequence of travelers wanting to use different routes or departure times in response to informed and/or anticipated operating conditions. Hence, the DUE procedure needs to re-estimate new vehicle routes. Furthermore, because such traffic flow pattern shifts are likely to take place over a large geographic area and over a long time period, mesoscopic simulation-based DTA models such as DynusT are more efficient to run than microscopic traffic simulation in capturing area-wide traffic flow changes.

Given the time-dependent nature of demand and network characteristics, DTA models are primarily used to estimate dynamic traffic flow patterns over the vehicular network. DTA models also provide a large catalogue of detailed outputs that describe time-dependent network states, typically at both the system level and linklevel. DTA models also provide a capability to graphically display these network characteristics and statistics. The route trajectories DTA models collected can be used to develop non-conventional statistics and performance estimates that the analyst may need to describe the performance of the network.

DYNASMART-P SELECTION CRITERIA

DynusT is a DTA modeling tool developed under the sponsorship of the Federal Highway Administration (FHWA). It is capable of determining time-variant link traffic conditions by reflecting the effects of various types of demand-and-supply conditions. DTA tools can assist emergency managers, and transportation officials in making critical decisions. The researchers used the decision-making process that the FHWA outlined in arriving at the decision to use DynusT. The modeling components considered were:

- Geographic scope: Houston-Galveston region and major evacuation routes.
- Facility types: Arterial, highway, freeway, HOV lane, and ramps.
- Travel mode: SOV, HOV, and bus.
- Management strategy: Evaculane, full-scale contraflow, corridor-based contraflow, work zone impacts, incident impacts, and Advanced Traveler Information Systems (ATIS).
- Traveler response: Mode choice, departure time choice, evacuation decision choice, and destination choice.
- Performance measures: Level of service (LOS), speed, travel time, queue length, evacuation clearance time, and trajectory mapping.

The selection criteria the researchers used in this task were:

- The availability of the background network can be leveraged from previous research work when using DynusT.
- Availability of software, technical support, and working experience with the Dynasmart-P developers.
- The DynusT development is relatively mature compared to other competing DTA models, and the results achieved in the literature have been well received by practitioners and researchers.

The objectives of the research project's hurricane evacuation DTA models are to identify the best evacuation strategies for a given set of inputs, and provide evacuation time estimates (ETEs) for different evacuation strategies. Through the DTA modeling process and interpretation of the results, the researchers will be able to gain greater insight into the following key questions:

- What is the clearance time required to safely evacuate the public for a given evacuation strategy?
- Which roads should be utilized for the evacuation?
- Where are the choke points along the evacuation routes?

- How can we improve the efficiency of the evacuation process?

CHALLENGES IN USING DTA MODELS

The following are some major challenges identified as part of feasibility analysis of using DTA models for evacuation analysis in this task:

Supply Side

- Appropriate representation of networks.
- Simplified but realistic representation of intersection traffic control.

Demand Side

- Time-dependent origin-destination trip tables.
- Traveler behavioral responses (e.g., at-risk population response, prior experience, and compliance rates).
- Convergence of dynamic traffic assignment results.
- Calibration and validation issues.

The research team's decades of experience with past simulation modeling efforts and the technical and modeling support of the DynusT developer will ensure successful application of DTA tools for the evacuation case studies used to support contraflow decision making.

CHAPTER 8:
DECISION SUPPORT SYSTEM PROTOTYPE CONCEPT OF OPERATIONS

SCOPE OF PROTOTYPE

The purpose of the prototype decision support system (DSS) is to develop an understanding of the potential scope, characteristics, and components of a production DSS to help officials decide when contraflow operations are warranted to manage evacuation demand as opposed to alternative evacuation strategies (such as evaculanes).

The prototype DSS is envisioned as a web-based application that enables users to play back hypothetical or real hurricane events and go through scenarios to arrive at the optimal decision on whether to conduct contraflow operations. The prototype DSS will not duplicate capabilities already available in existing decision support systems such as HURRicane EVACuation (HURREVAC).

BACKGROUND

Decision Support Systems

Texas agencies use a number of tools that assist in hurricane emergency evacuations. One of those tools is HURREVAC, which the Federal Emergency Management Agency (FEMA) and the United States Army Corps of Engineers (USACE) started in 1988.

HURREVAC tracks hurricanes on computer screens (Figure 13) using data from the National Hurricane Center (NHC) and enables users to determine when to make evacuation decisions. To assist in this process, HURREVAC determines the arrival of gale (34-knot or 39 mph) winds using NHC projections with an adjustment for a direct-hit or worst-case scenario. The system estimates clearance times (i.e., the time it takes to evacuate populations) using data such as the Saffir-Simpson hurricane category scale, anticipated public response, and occupancy data. A local hurricane evacuation study, usually performed by USACE, HWS, and FEMA, produced the basic data for clearance time calculations. Finally, the system subtracts the clearance time from the gale arrival time to reach a suggested evacuation decision time. This approach is based on the need to evacuate vulnerable populations before the gale winds arrive. The start of gale winds is usually known when causeways begin to flood, cutting off escape routes, and tree limbs start to fall, blocking roads.

In addition to tracking the eye of the storm, the graphical interface can display the range of gale winds around the storm, as well as real-time weather data. The system also displays storm surge flood graphics (where available), using data from the National Weather Service (NWS) Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model. The system can also estimate traffic data on evacuation routes, compliance rate, and tourist occupancy. Currently, HURREVAC does not have the capability to overlay the location of traffic sensors or display real-time data from local transportation management centers (TMCs).

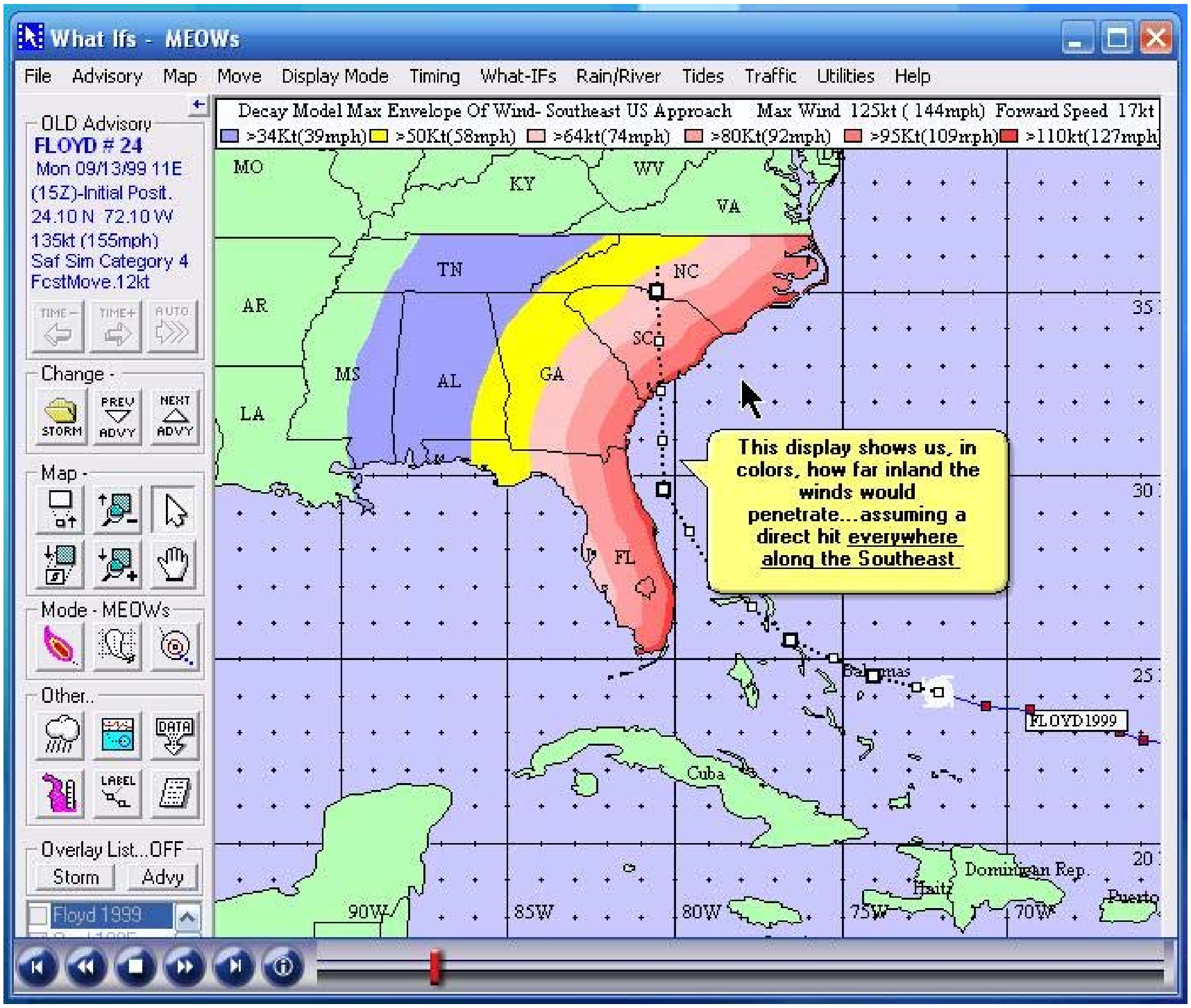


Figure 13. Sample HURREVAC Display.

Current Contraflow Procedures

The first formal contraflow plan developed in Texas was in 1999 on I-37 between Corpus Christi and San Antonio. Contraflow operations were also used during Hurricane Rita in 2005 but were implemented on the fly. On the heels of the 2005 hurricane season, formal contraflow plans were developed for the entire Houston-Galveston region. The current threshold for considering contraflow operations is when a hurricane category is 3 or higher. Under these conditions, the final decision to order contraflow operations depends on factors such as hurricane size, current traffic conditions, and available personnel for highway patrol. Making a contraflow decision involves numerous discussions with a large number of stakeholders. During Hurricane Ike (2008), decision makers were very close to calling for contraflow operations, but decided against it.

In the Houston-Galveston area, the designated contraflow routes are I-45, I-10, and US 290. The general contraflow procedure on these corridors is as follows:

- **I-45 (north).** Contraflow operations begin at South Loop 336 near Conroe. Flushing prior to contraflow is as follows:
  - Texas Department of Public Safety (TxDPS) troopers begin flushing the southbound lanes of I-45 just south of US 287. Traffic is directed to SH 34 and US 287. A chase vehicle travels south on I-45 and meets troopers at US 79 in Buffalo.
  - Troopers begin flushing the southbound lanes of I-45 at US 79 in Buffalo. Traffic is directed to either US 79 or the I-45 southbound frontage road. A chase vehicle travels south on I-45 and meets troopers at SH 75.
  - Troopers begin flushing the southbound lanes of I-45 north of SH 75/SH 19. Traffic is directed to SH 75. A chase vehicle travels south on I-45 to the contraflow origination point near SH 242.
- **US 290 (northwest).** Contraflow operations begin at Mueschke Road in Harris County. TxDOT deploys barricades and/or cones on all private driveways and county roads to facilitate one-way traffic flow. Farm-to-Market (FM) roads are also barricaded, with some traffic being allowed to merge with the one-way traffic flow. Flushing of US 290 eastbound lanes begins east of Giddings city limits. It is possible to change this location to Austin or Brenham as the situation dictates.
- **I-10 (west).** Contraflow operations begin east of FM 359 in Brookshire. If this plan is activated, I-10 eastbound lanes are reversed to carry two lanes of westbound traffic. Traffic on the contraflow lanes is able to exit I-10 at selected locations. The contraflow lanes end at Loop 1604 in San Antonio.

CONCEPT FOR THE PROPOSED SYSTEM

The purpose of the prototype DSS is to develop an understanding of the potential scope, characteristics, and components of a production DSS to help officials decide when contraflow operations are warranted to manage evacuation demand as opposed to alternative evacuation strategies (such as evaculanes). The prototype DSS is envisioned as a web-based application with the following functionality:

- Display characteristics (e.g., wind speed, direction of the hurricane and its distance from land), and other relevant information about an approaching hurricane.
- Adjust risk levels associated with various evacuation factors.
- Enable users to play back hypothetical or real hurricane events and go through scenarios to arrive at the optimal decision on whether to conduct contraflow operations.
- Display results of mesoscale-level simulation runs (e.g., average speeds, travel times, volumes, and other performance measures), in a variety of formats including tables, maps, hyperlinks, and charts.
- Include a web-based mapping component [in principle, based on the Microsoft Bing Map application programming interface (API) for consistency with TranStar's Bing-based implementation].
- Display traffic data from TranStar website (e.g., real-time speed and average travel time, traffic volumes, incidents, road closures, and constructions).

- Recommend a contraflow operation based on data such as storm characteristics, traffic, and infrastructure conditions.

Additional reasons to prefer a web-based interface include the following:

- Minimal installation requirements on client computers [only a decent web browser and (if necessary) a plug-in component would be necessary].
- Potential for access to the application from a variety of devices such as desktop computers, laptop computers, and smart phones.

SYSTEM OVERVIEW

Through TranStar, the Houston area has several years of experience using web-based products to disseminate real-time and archived traffic data to the public. Recently, TranStar implemented a Microsoft Bing-based interface to display traffic data. As Figure 14 shows, the system displays traffic data such as incidents, current speeds, images from cameras, construction, road closures, bus stop locations, transit centers, and messages on message boards. The website updates traffic data every three minutes.

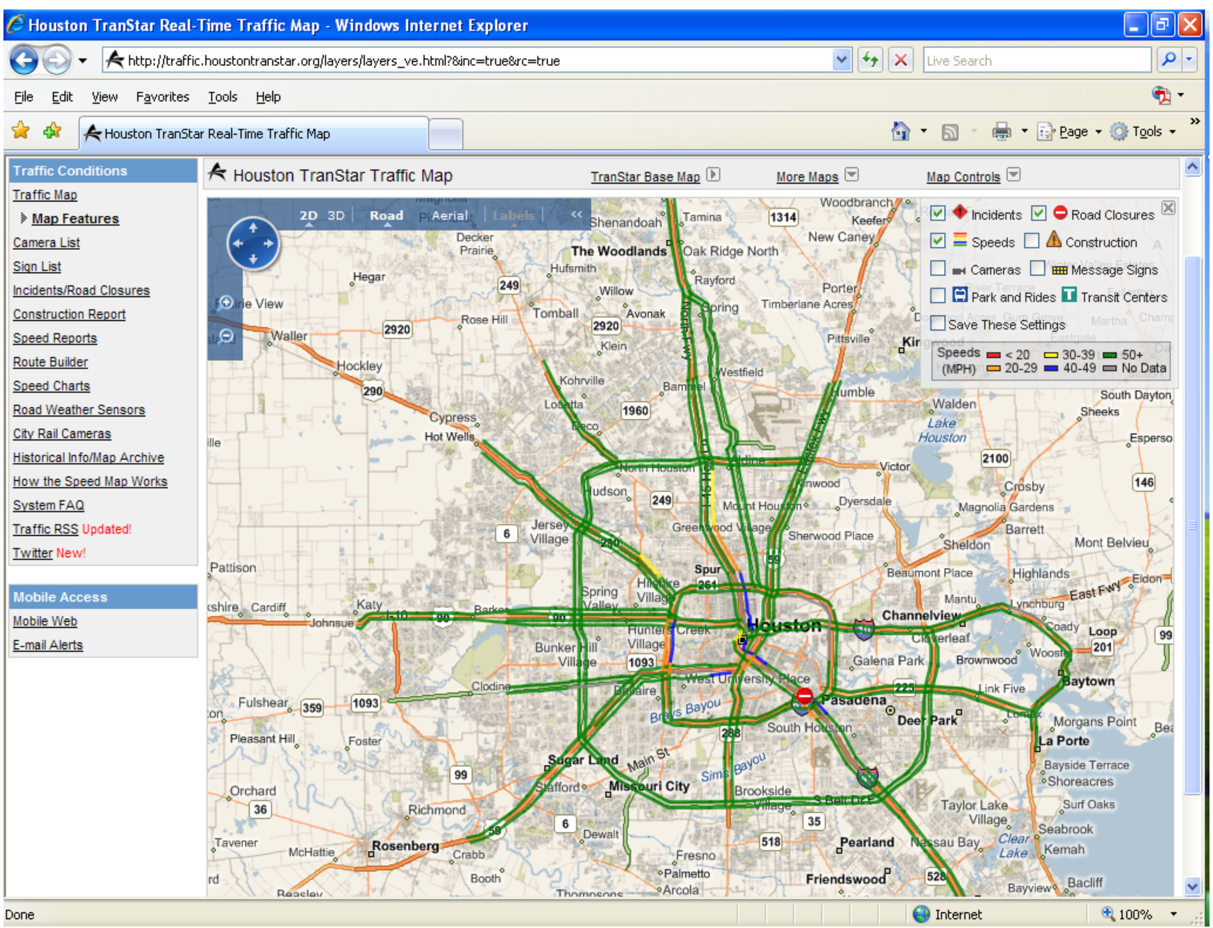


Figure 14. TranStar Bing-Based Interface.

TranStar provides access to selected data using extensible markup language (XML) data feeds, which are available at http://traffic.houstontranstar.org/datafeed/datafeed_info.html. Access to the data requires TxDOT review and approval, which includes providing the Internet protocol (IP) address of the server that will be consuming data feeds from TranStar. The following four data feeds are available:

- **Speed and travel time data from the automated vehicle identification (AVI) system**. This data feed includes two files:
  - Speeds and travel times for roadway segments in the AVI traffic monitoring system (updated once per minute).
  - Description of roadway segments in the speed and travel time data feed (updated as the system configuration changes, usually no more than once per day).
- **Sensor data feed**. Sensor data are data collected by radar units deployed throughout the Houston region. The system collects volume, speed, occupancy, and classification data per lane. This data feed includes two files:
  - Data file from sensors in the TranStar network (updated every 30 seconds).
  - Description of sensor configurations in the sensor data feed (updated as the system configuration changes, usually no more than once per day).
- **Incident data feed**. Operators at TranStar continuously monitor incidents on Houston area roadways. The data feed describing the status of each monitored incident is updated every minute.
- **Lane closure data feed**. TxDOT reports scheduled lane closures on their facilities daily. The data feed describing the status of each lane closure is updated every minute.

The prototype DSS will build upon and otherwise leverage the TranStar system by developing an interface "on top of" a TranStar Bing-based map (Figure). The system will include the following components:

- A mapping component (based on Microsoft Bing technology) shows current traffic condition in the Houston/Galveston area, e.g., average travel time, speed, incidents, constructions, and road closures on each major highway in the area.
- The system shows data about an approaching hurricane, such as wind speed, direction, distance from land, and flood levels. The interface also includes a tool for users to evaluate the available data in a sequential manner to obtain a DSS recommendation whether to pursue contraflow operations.
- The system enables users to play back hypothetical or real hurricane events.
- A simulation result component displays the results of mesoscale-level simulation runs, e.g., average speeds, travel times, volumes, and other performance measures, in a variety of formats including tables, maps, hyperlinks, and charts. The DSS does not run mesoscale-level models. Rather, it provides an interface to display the results of past simulation runs.

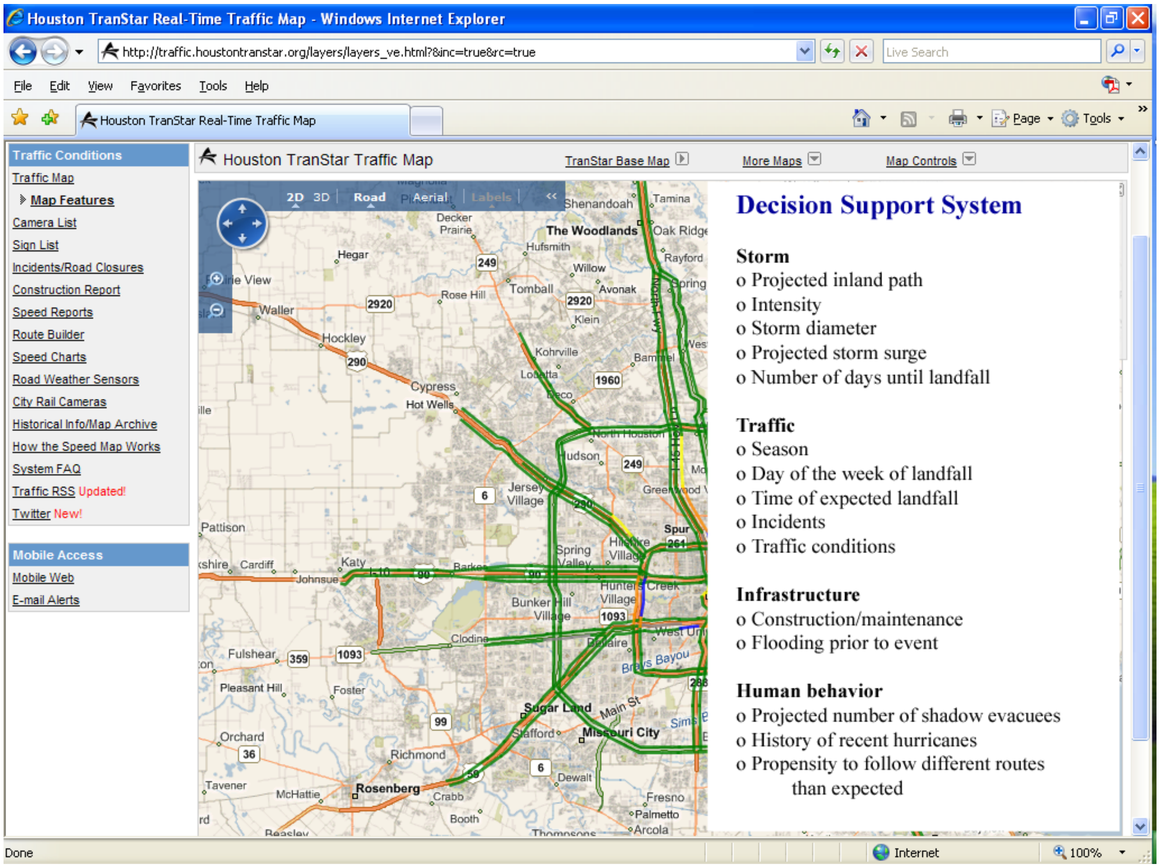


Figure 15. Prototype DSS Interface.

The prototype will obtain weather and hurricane data from the National Oceanic and Atmospheric Administration (NOAA) website. The data, which are available at http://www.nhc.noaa.gov/index.shtml, include data in XML (accessible by applications such as ESRI ArcGIS and Google Earth), Really Simple Syndication (RSS) (accessible by web browsers such as Microsoft Internet Explorer or Firefox), and ESRI-compatible GIS format. The GIS data include the following feature classes:

- Point and line feature classes that describe the projected path of the storm's eye.
- Apolygon feature class that describes the storm's uncertainty cone.

DSS DEVELOPMENT

Contraflow Decision Factors

A preliminary analysis of factors to include in the DSS resulted in the following list of domains and domain factors that could have an impact on contraflow decisions:

- Storm factors:
  - Projected location of the northeast part of the storm.
  - Projected inland path.

  - Storm category: 1, 2, 3, 4, or 5.
  - Storm diameter.
  - Projected storm surge.
  - Number of days until landfall: 5 days (no impact on decision), 4 days (low impact), 3 days (high impact), 2 days (low impact), and 1 day (no impact on decision).
- Traffic factors:
  - Season: June–mid-August (lower impact on decision; schools not in session), mid-August–October (higher impact on decision; schools are in session).
  - Day(s) of the week of primary evacuation: Weekday (higher impact on decision; weekday traffic conditions), weekend (lower impact on decision; weekend traffic conditions).
  - Time of expected landfall: a.m. peak, off peak, p.m. peak, night time.
  - Incidents: Major incidents (higher impact on decision), minor incidents (lower impact on decision).
  - Traffic conditions: Light (no impact on decision), normal (low impact on decision), heavy (higher impact on decision), and extremely heavy (highest impact on decision).
- Infrastructure factors:
  - Construction or maintenance activities.
  - Flooding prior to event.
- Human behavior factors:
  - Projected number or percentage of shadow evacuees (i.e., people who evacuate who do not need to evacuate).
  - History of recent hurricanes (i.e., the "Katrina" effect).
  - Propensity to follow different routes than expected.

Some of these factors (e.g., storm category) are quantitative factors that enable a straightforward conversion into a contraflow decision matrix. Other factors (e.g., history of recent hurricanes) are not quantitative factors that make it difficult to incorporate into a contraflow decision matrix.

DSS Alternatives

The following three methods were considered to manage the contraflow decision-making process within the DSS:

- Logistic regression.
- Weighted linear additive model.
- Expert system-based approach.

Logistic Regression

Logistic regression is a statistical tool used to predict the probability of occurrence of an event in situations in which the dependent variable is binary (i.e., a categorical variable that has two values such as "yes" or "no"). The independent variables can be of any type, including continuous, categorical, and binary. The decision to order a contraflow operation is essentially binary (i.e., the possible values are "yes" and "no"). The independent variables, such as storm intensity, diameter, location, and traffic conditions, can be continuous, categorical, or binary variables. From this perspective, it may be possible to define a logistic regression model to predict the logarithmic odd of deciding to order a contraflow operation as follows:

$$z = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k + \cdots b_n X_n \quad (1)$$

where

$$z = ln[odds(DC)] = ln\left[\frac{prob(DC)}{prob(nonDC)}\right] \quad (2)$$

In Equations (1) and (2),

z = logarithmic odd of deciding whether to order a contraflow operation DC;

X_k = independent variable; and

b_k = parameter, which could be obtained using logistic regression.

A fundamental disadvantage of this approach is the lack of historical data to determine the numerical values of all the parameters.

Weighted Linear Additive Model

A strategy to deal with the lack of historical data to determine the parameters in Equation (1) is by polling a group of experts and stakeholders as to the relative importance of each of the variables (i.e., contraflow decision factors) in Equation (1). In this case, Equation (1) becomes simply an additive linear model in which each decision factor is affected by a weighting factor (decided upon collectively by stakeholders), and *z* becomes the composite result of adding each factor affected by its corresponding weighting factor.

A disadvantage associated with a simple weighted linear additive model is the assumption that all factors influence the decision-making process concurrently. In reality, some factors preclude other factors. In other cases, a factor may become relevant after certain decision thresholds have been crossed. Nevertheless, a weighted linear additive model has a number of advantages (including its simplicity), which means it is not possible to rule it out automatically. It is likely that some components of a weighted linear additive model will need to be incorporated into the final DSS design, which this research will help to evaluate.

Expert System-Based Approach

This approach involves classifying relevant combinations of factors into three severity levels according to the anticipated impact making a contraflow decision: Severe, Alert, and Low (Figure 16). The final output can also be categorized into the same category levels. In general, a combination of factors classified as Severe increases the likelihood of selecting contraflow operations.

Figure 16. Categories to Measure the Impact of Contraflow Decision Factors.

A short discussion about each factor and the corresponding number of potential decision scenarios follows. For simplicity, the discussion only considers some of the factors. For *storm* factors, 20 scenarios result from combining four "uncertainty cone" regions (Figure 17) and five hurricane category levels:

- Projected inland path: 1 (Region 1), 2 (Region 2), 3 (Region 3), and 4 (Region 4).
- Hurricane category: 1, 2, 3, 4, or 5.

Each scenario can be assigned a Low, Alert, or Severe level. For example, for a location in Region 1 and a Category 5 hurricane, the scenario would be classified as Severe. In contrast, for a location in Region 4 (in Figure 17), even if the hurricane category were 5, the case would be classified as Low for the Houston-Galveston region.

For *traffic* factors, nine scenarios result from combining three traffic speed cases and three incident condition scenarios. Each scenario can be assigned a rating of Low, Alert, or Severe.

- Traffic speed: 1 (<20mph), 2 (<40mph), and 3 (≥40mph).
- Incidents: 1 (major incident), 2 (minor incident), and 3 (no incident).

For *infrastructure* factors, 27 scenarios result from combining three construction/maintenance cases, three flooding scenarios prior to event, and three projected storm surge scenarios. Each scenario can be classified as a Low, Alert, or Severe level.

- Construction/maintenance: 1 (major), 2 (minor), and 3 (none).
- Flooding prior to event: 1 (major), 2 (minor), and 3 (none).
- Projected storm surge: 1 (>9 in), 2 (>4 in), and (≤4 in).

In the case of *human behavior* factors, nine scenarios result from a combination of three shadow-evacuee-percentage scenarios and three recent hurricane scenarios. Each scenario can be assigned a Low, Alert, or Severe level rating.

- Projected percentage of shadow evacuees (can be done by survey prior to the event): 1 (>20 percent), 2 (>10 percent), and 3 (≤10 percent).
- History of recent hurricanes: 1 (>5 years), 2 (>2 years), 1 (≤2 years).

Region 1: Location is within the three-day cone of uncertainty (area in red).

Region 2: Location is between the three-day and five-day cone of uncertainty (area in yellow) or to the right of the cone of uncertainty.

Region 3: Location is to the left of the cone of uncertainty. The anticipated damage would be lower than on the right side of the cone of uncertainty. Region 3 also includes the area to the right of Region 2.

Region 4: Location is to the left of Region 3.

Figure 17. Projected Inland Path Scenario.

After evaluating all the possible combinations of factors within each factor domain and assigning a severity level to each scenario (Severe, Alert, or Low), the next step involves using a sequential approach for tabulating aggregated classifications (Figure 18).

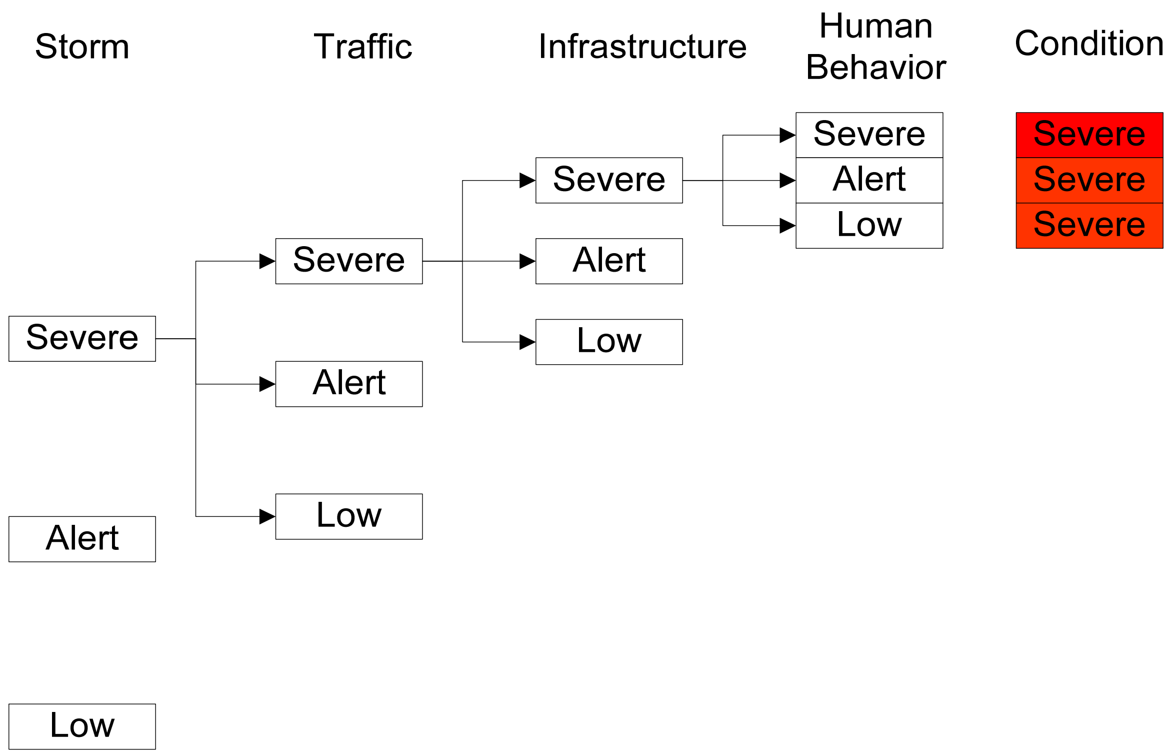


Figure 18. Final Classification of Severity Levels.

OPERATIONAL ENVIRONMENT

The prototype DSS will be developed and tested on TTI servers in College Station. One of the servers is a development server, which will be used to develop the prototype. The other server is a test server that will be used to test the prototype. A third server is a dedicated Oracle server. These servers are Intel-based Dell PowerEdge servers with dual Xeon processors. Researchers can connect to the servers via a 100 megabit network. The operating system installed on these servers is Windows Server 2003 Standard SP2. The web server is Microsoft's Internet Information Services (IIS).

SUMMARY OF IMPACTS

Potential benefits a production DSS could have on contraflow decision making and operations, which the prototype DSS will help to identify, include the following:

- **Texas Department of Public Safety (DPS)**. The production DSS would enable DPS to make suggestions to the mayor or county judge about whether, when, and where a contraflow should be implemented.
- **TxDOT**. The production DSS could help TxDOT officials provide recommendations and/or assist with the decision to order a contraflow. It could also assist with the implementation of logistical strategies, e.g., providing fuel to stranded motorists and providing information to motorists.

- **Houston-Galveston Area Council (HGAC).** The potential benefit to HGAC would be an aid to their ongoing efforts of localized analyses related to hurricane (and overall emergency) evacuation scenarios.
- **City of Houston.** The production DSS would help Houston officials to make a timely and accurate decision on contraflow operations.

CHAPTER 9:
IDENTIFY AND RUN SCENARIOS FOR TRAFFIC SIMULATION AND COMPONENTS

This chapter describes the simulation scenarios proposed in this study. The experiment is designed to collectively capture varying levels of demand and supply characteristics during the evacuation of Houston-Galveston region.

PLANNED EVALUATION SCENARIOS

Table 10 summarizes the proposed evaluation scenarios to be evaluated using DynusT. The simulation experiment is designed based on varying levels of demand and supply conditions. The plan involves the evaluation of a total of 15 scenarios. Table 10 describes 12 scenarios derived from a full factorial combination of four levels of supply characteristics and three levels of demand characteristics.

In addition, three special scenarios will be evaluated as summarized in Table 11. These scenarios are intended to model the historical evacuation events as well as common capacity-reducing conditions. First, the results from these special scenarios will serve as a benchmark for comparison of simulation results with the field data observed from historical events. In addition, the field implementation of contraflow during Hurricane Rita did not demonstrate visible benefit as many capacity-reducing incidents on the evacuation routes severely hampered it. The simulation of capacity-reducing events will help quantify the extent and scale of impacts of such events on evacuation performance and provide more insight into a catalyst/need for contraflow.

The scenarios will be evaluated using DynusT mesoscopic models. The evacuation performance observed from the simulation results will be incorporated into the prototype decision support tool for contraflow decisions. Detailed scenario descriptions are provided in the subsequent section.

Table 10. Planned Evaluation Scenarios.

Supply Scenario	Demand Scenario		
	Low (D1)	**Medium (D2)**	**High (D3)**
Base network (S1)	• Hurricane Category 2. • High background demand. • Low evacuation demand. • Roadways operate at full capacity. • Evaculane and contraflow are not activated.	• Hurricane Category 3. • Moderate background demand. • Moderate evacuation demand. • Roadways operate at full capacity. • Evaculane and contraflow are not activated.	• Hurricane Category 4. • Low background demand. • High evacuation demand. • Roadways operate at full capacity. • Evaculane and contraflow are not activated. • *Worst-case scenario for evacuation performance.*
Evaculane activated (S2)	• Hurricane Category 2. • High background demand. • Low evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Contraflow is not activated.	• Hurricane Category 3. • Moderate background demand. • Moderate evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Contraflow is not activated.	• Hurricane Category 4. • Low background demand. • High evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Contraflow is not activated.
Evaculane and partial contraflow activated (S3)	• Hurricane Category 2. • High background demand. • Low evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Partial contraflow is activated.	• Hurricane Category 3. • Moderate background demand. • Moderate evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Partial contraflow is activated.	• Hurricane Category 4. • Low background demand. • High evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Partial contraflow is activated.
Evaculane and full contraflow activated (S4)	• Hurricane Category 2. • High background demand. • Low evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Full contraflow is activated. • *Best-case scenario for evacuation performance.*	• Hurricane Category 3. • Moderate background demand. • Moderate evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Full contraflow is activated.	• Hurricane Category 4. • Low background demand. • High evacuation demand. • Roadways operate at full capacity. • I-10 evaculane is activated. • Full contraflow is activated.

Table 11. Special Evaluation Scenarios.

Special Scenario	Demand Characteristics	Supply Characteristics
Hurricane Rita Evacuation	• Low background demand. • High evacuation demand.	• Full contraflow activated on I-10 and I-45. • No I-10 evaculane.
Hurricane Ike Evacuation	• Moderate background demand. • Low evacuation demand.	• I-10 evaculane activated. • No contraflow.
Capacity-Reducing Events with Evaculane Activated	• Moderate background and evacuation demand.	• No contraflow. • Evaculane activated. • Presence of capacity-reducing incidents on major evacuation routes.

The following section describes the proposed simulation scenarios. The scenario acronyms correspond to the demand/supply characteristics labeled in Table 10.

Scenario D1/S1

This scenario represents the Hurricane Category 2 approaching the Houston-Galveston area. Mandatory evacuation has been issued only for the low-lying areas with high risk of flooding. The background demand is high as residents have been well-informed of the situation and there has been no recent adverse hurricane experience. The shadow evacuees are expected to be minimal. The evacuation demand originated mostly from mandatory evacuation areas. The roadways are in good condition and operate at the near to full capacity. The contraflow and evaculane plans are not activated.

Scenario D1/S2

This scenario represents the Hurricane Category 2 approaching the Houston-Galveston area. Mandatory evacuation has been issued only for the low-lying areas with high risk of flooding. The background demand is high as residents have been well-informed of the situation and there has been no recent adverse hurricane experience. The shadow evacuees are expected to be minimal. The evacuation demand originated mostly from mandatory evacuation areas. The hurricane projected path has changed abruptly, causing the agencies to issue the evacuation order in less than the desirable timeframe. The I-10 evaculane operation has been activated to mitigate the congestion on the I-10 outbound direction. The roadways are in good condition and operate at the near to full capacity; therefore, contraflow plans are not activated.

Scenario D1/S3

This scenario represents the Hurricane Category 2 approaching the Houston-Galveston area. Mandatory evacuation has been issued only for the low-lying areas with high risk of flooding. The background demand is high as residents have been well-informed of the situation and there has been no recent adverse hurricane experience. The shadow evacuees are expected to be minimal. The evacuation demand originated mostly from mandatory evacuation areas. The hurricane projected path has changed abruptly, causing the agencies to issue the evacuation order in less than the desirable timeframe. The roadways are in good condition and operate at the near to full capacity. To ensure sufficient evacuation clearance time, partial contraflow plan on I-45 and evaculane on I-10 have been activated.

Scenario D1/S4

This scenario represents the Hurricane Category 2 approaching the Houston-Galveston area. Mandatory evacuation has been issued only for the low-lying areas with high risk of flooding. The background demand is high as residents have been well-informed of the situation and there has been no recent adverse hurricane experience. The shadow evacuees are expected to be minimal. The evacuation demand originated mostly from mandatory evacuation areas. The roadways are in good condition and operate at the near to full capacity. The hurricane projected path has changed abruptly, causing the agencies to issue the evacuation order in less than the desirable timeframe. The roadways are in good condition and operate at the near to full capacity. To ensure sufficient evacuation clearance time, full contraflow plans have been activated along with I-10 evaculane operation. This scenario represents the best-case scenario as measured by the expected evacuation clearance time.

Scenario D2/S1

This scenario represents the Hurricane Category 3 approaching the Houston-Galveston area. Mandatory evacuation has been issued for several flood-prone areas. The background demand is average as residents have been informed of the situation and recent hurricane experience has been mild. The shadow evacuees are expected to be average. The evacuation demand is expected to be moderate as a result of mandatory evacuation. The roadways are in good condition and operate at the near to full capacity. The contraflow plan and I-10 evaculane operation are not activated.

Scenario D2/S2

This scenario represents the Hurricane Category 3 approaching the Houston-Galveston area. Mandatory evacuation has been issued for several flood-prone areas. The background demand is average as residents have been informed of the situation and recent hurricane experience has been mild. The shadow evacuees are expected to be moderate. The evacuation demand is expected to be moderate as a result of mandatory evacuation. To ensure sufficient evacuation clearance time, the evaculane on I-10 has been activated.

Scenario D2/S3

This scenario represents the Hurricane Category 3 approaching the Houston-Galveston area. Mandatory evacuation has been issued for several flood-prone areas. The background demand is average as residents have been informed of the situation and recent hurricane experience has been mild. The shadow evacuees are expected to be moderate. The evacuation demand is expected to be moderate as a result of mandatory evacuation. The roadways are in good condition and operate at the near to full capacity. To ensure sufficient evacuation clearance time, partial contraflow plan on I-45 and evaculane on I-10 have been activated.

Scenario D2/S4

This scenario represents the Hurricane Category 3 approaching the Houston-Galveston area. Mandatory evacuation has been issued for several flood-prone areas. The background demand is average as residents have been informed of the situation and recent hurricane experience has been mild. The shadow evacuees are expected to be moderate. The evacuation demand is expected to be moderate as a result of mandatory evacuation. The roadways are in good condition and operate at the near to full capacity. The hurricane projected path has changed abruptly, causing the agencies to issue the evacuation order in less than the desirable timeframe. The roadways are in good condition and operate at the near to full capacity. To ensure sufficient evacuation clearance time, full contraflow plans have been activated along with I-10 evaculane operation.

Scenario D3/S1

This scenario represents the Hurricane Category 4 approaching the Houston-Galveston area. Mandatory evacuation has been issued for a significant part of the region. The background demand is expected to be low as residents have recently witnessed adverse hurricane damage. The evacuation demand is expected to be high as a result of large-scale mandatory evacuation. The roadways are in good condition and operate at the near to full capacity. With sufficient buffer time until the predicted landfall, the agencies have decided to issue the evacuation order early. The contraflow and evaculane operations are not activated. The scenario represents the worst-case scenario as measured by the expected evacuation clearance time.

Scenario D3/S2

This scenario represents the Hurricane Category 4 approaching the Houston-Galveston area. Mandatory evacuation has been issued for a significant part of the region. The background demand is expected to be low as residents have recently witnessed adverse hurricane damage. The evacuation demand is expected to be high as a result of large-scale mandatory evacuation. The roadways are in good condition and operate at the near to full capacity. With sufficient buffer time until the predicted landfall, the agencies have decided to issue the evacuation order early and activated only the evaculane operation on I-10.

Scenario D3/S3

This scenario represents the Hurricane Category 4 approaching Houston-Galveston area. Mandatory evacuation has been issued for a significant part of the region. The background demand is expected to be low as residents have recently witnessed adverse hurricane damage. The evacuation demand is expected to be high as a result of large-scale mandatory evacuation. The roadways are in good condition and operate at the near to full capacity. To ensure sufficient evacuation clearance time, partial contraflow plan on I-45 and evaculane on I-10 have been activated.

Scenario D3/S4

This scenario represents the Hurricane Category 4 approaching the Houston-Galveston area. Mandatory evacuation has been issued for a significant part of the region. The background demand is expected to be low as residents have recently witnessed adverse hurricane damage. The evacuation demand is expected to be high as a result of large-scale mandatory evacuation. The roadways are in good condition and operate at the near to full capacity. To ensure sufficient evacuation clearance time, full contraflow plans on I-10, I-45, and US 290 have been activated along with the I-10 evaculane operation.

DEMAND AND SUPPLY CHARACTERISTICS

This study will utilize DynusT models to replicate a combination of varying levels of demand and supply characteristics to evaluate the performance of different hurricane evacuation strategies for the Houston-Galveston network. Average travel time will be used as a primary measure of effectiveness (MOEs) for comparing the results across modeling scenarios. Appropriate assumptions and realistic representation of demand and supply conditions are essential to the validity of the results.

Demand Characteristics

The trips made during evacuation events consist of two types—evacuation and background demand. The background or shadow demand refers to the travel activities that non evacuees made. These trips must be properly estimated to provide an accurate picture of total traffic during the evacuation. The background traffic during the evacuation period is likely to be significantly different from normal conditions. A previous study sponsored by TxDOT's Government Business and Enterprise (GBE) Division noted some of the following differences:

- There are no trips destined to the risk zones during the evacuation event.
- There are fewer trips originating from the risk zones that are not for evacuation.
- There are fewer trips originating from other non-risk zones with non-evacuation intention.

In the previous study, the demand was estimated for Hurricane Rita evacuation scenarios. The demand scenarios evaluated in this study will be modified from the background and evacuation demands previously estimated in the GBE study (*1*).

The simulation will be conducted for the 24-hour period that experiences the highest level of total demand. From the cumulative departure curve in the GBE study (*1*), this period took place at approximately 84 hours before the landfall where about 60percent of trips were made within the 24-hour period.

Table 12 provides the demand data used in the GBE study for Hurricane Rita's evacuation modeling. Note that the flood zone designation in this table was based on the 2005 HGAC map. Figure 19 shows the designated flood zones or zip-zones as of December 2009.

Table 13 summarizes the assumptions corresponding to each proposed demand level. These assumptions are necessary for developing time-dependent origin-destination (OD) matrices in the DynusT models. The proposed levels collectively capture a range of demand scenarios that are expected to take place during hurricane evacuation.

Table 12. Estimated Hurricane Rita Demand for Central Texas Evacuation.

Wednesday September 21, 2005 (24 hours)	Background Demand	Evacuation Demand	Total Demand
Flood Zone 1	50,062	48,742	98,804
Flood Zone 2	50,950	47,903	98,043
Flood Zone 3	65,033	239,908	304,941
Other Area	295,800	2,341,113	2,636,913
Total	398,458	2,676,856	3,075,314

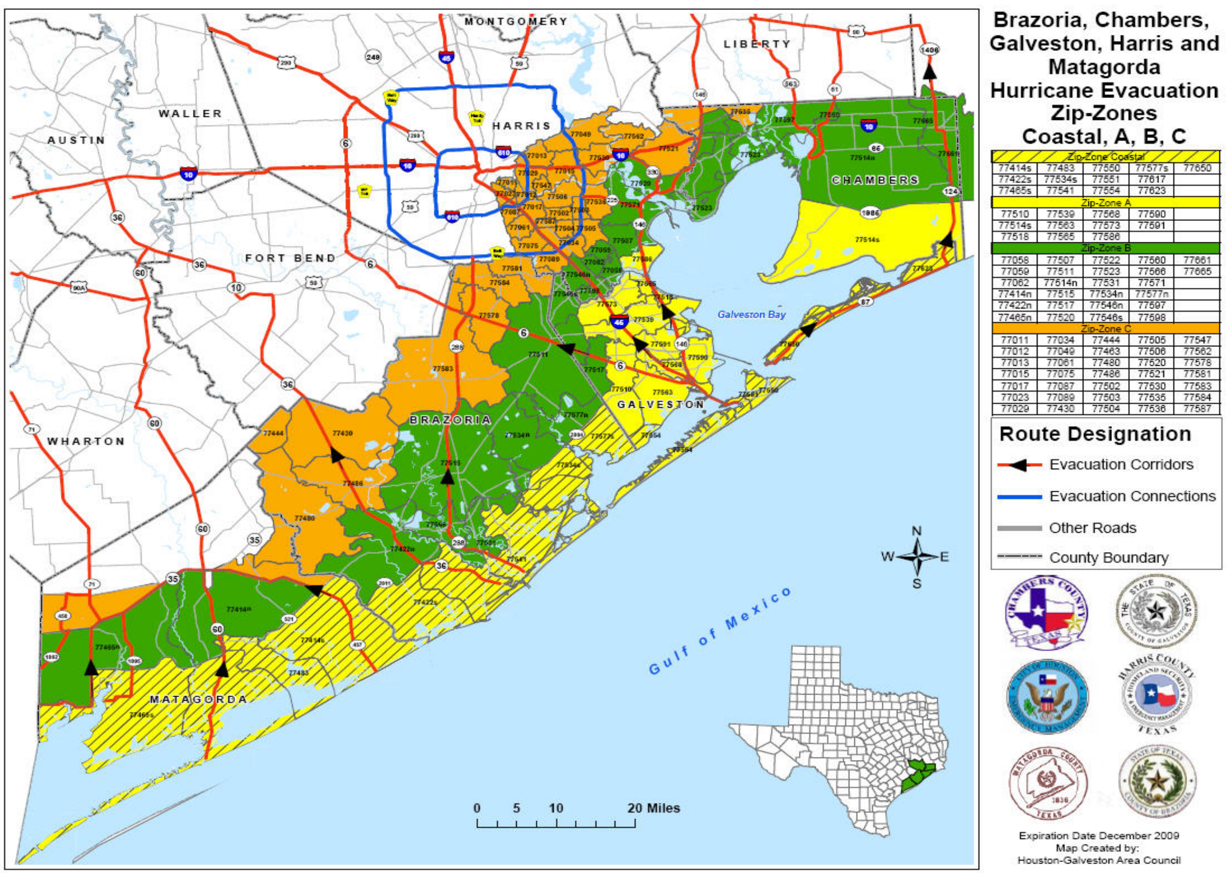


Figure 19. Houston-Galveston Area Council (HGAC) Zip-Zones.

Table 13. Proposed Demand Scenarios.

Demand Scenarios	Background Demand	Evacuation Demand
D1: Low demand (Hurricane Ike)	• 30% increase from Hurricane Rita's background demand.	• 50% of Hurricane Rita's evacuation demand.
D2: Moderate demand	• 15% increase from Hurricane Rita's background demand.	• 75% of Hurricane Rita's evacuation demand.
D3: High demand (Hurricane Rita)	• Zip-zone A: 5% of ordinary demand. • Zip-zone B: 10% of ordinary demand. • Zip-zone C: 25% of ordinary demand. • Other areas: 50% of ordinary demand. • Approximately 2.7 million vehicles per 24 hours.	• Approximately 400,000 vehicles over a 24-hour period based on estimated number of evacuees during Hurricane Rita evacuation (total estimate was 1.2 million vehicles).

Supply Characteristics

Table 14 summarizes the proposed network configurations to be evaluated in the DynusT models.

Table 14. Proposed Supply Scenarios.

Supply Scenarios	I-10	I-45	US 290
S1: Base Network	• No contraflow.	• No contraflow.	• No contraflow.
S2: Evaculane	• Evaculane from FM 359 to Loop 1604 (3 lanes westbound).	• No contraflow.	• No contraflow.
S3: Partial Contraflow	• Evaculane from FM 359 to Loop 1604 (3 lanes westbound).	• Partial contraflow from south of Loop 336 to the Walker/Madison County line at FM 2989.	• No contraflow.
S4: Full Contraflow	• Evaculane from FM 359 to Loop 1604 (3 lanes westbound). • Contraflow from FM 359 to Loop 1604.	• Contraflow from SH 242 to US 287.	• Contraflow from FM 1960 to Hempstead.
Hurricane Rita	• No evaculane. • Contraflow from FM 359 to Loop 1604.	• Contraflow from SH 242 to US 287.	• No contraflow.
Hurricane Ike	• I-10 evaculane. • No contraflow.	• No contraflow.	• No contraflow.
Special Capacity-Reducing Events	• I-10 evaculane. • No contraflow. • One 30-minute incident blocking one main lane after 2 hours of simulation.	• No contraflow. • One 30-minute incident blocking one main lane after 4 hours of simulation.	• No contraflow. • One 30-minute incident blocking one main lane after 6 hours of simulation.

CHAPTER 10: DEVELOP ALPHA-LEVEL DECISION SUPPORT PROTOTYPE

The purpose of this task was to develop the first phase (i.e., alpha level) of the complete decision support tool (DST) prototype for contraflow decision making. This phase can be viewed as a preliminary version of DST that will be modified and upgraded in later project phases as the Project Advisory Panel gives its input. This technical memorandum documents data modeling activities, concept development for the web-based tool, and screen shots from the graphical user interface of the alpha-level DST prototype.

Making a contraflow decision is a complex task that must consider a range of critical variables. It requires accurate information about an upcoming hurricane, current and estimated near-future traffic conditions, people's likely reactions to evacuation, media, and resource availability for evacuation. Therefore, researchers developed a simple and easy-to-use formula that considers three types of input data for aiding contraflow decision making. The formula is designed to produce a numerical value between 1 and 10 based on user-supplied input data that includes storm characteristics, current traffic conditions, and the recent history of hurricanes. The research team used these three inputs, also known as *domain factors***,** to develop a model whose general formula is expressed as:

$$\begin{aligned} Severity\ level = {} & weight(storm) * storm_{value} + \\ & weight(traffic) * traffic_{value} + \\ & weight(humanBehavior) * humanBehavior_{value} \end{aligned}$$

Here, weights are the relative importance of each factor among the three domain factors. A higher weight means the factor has a higher influence in contraflow decision making. Model developers conducted two sets of surveys to complete the formula, as this chapter will discuss.

Utilizing datasets of survey responses, researchers produced a preliminary, web-based version of the decision support prototype. The web-based interface was developed using Microsoft® Bing Map, discussed here in this chapter. This interface is one of the key components of the DST framework researchers had developed and serves as the communicator between the framework and its users (planners and evacuees). With this tool, planners will be able to generate evacuation plans, evaluate alternative plans and scenarios, answer many what-if questions, and announce the evacuation plan to evacuees. In addition, evacuation information can be widely distributed to evacuees via the web-based interface. This information includes evacuation schedules and routes essential to avoid confusion and traffic gridlock during the evacuation process.

FIRST-LEVEL DATA MODELING

Introduction

The research team's goal was to build a contraflow decision-making model that is easy to understand and simple to implement. Such a system requires feedback from field experts that can make a hypothetical decision for each of the possible scenarios. Therefore, analysts developed an expert (opinion)-based system for contraflow decision making. This is a simplified version of an expert system that transfers field experts' knowledge into a decision-making framework (see Figure 20). Knowledge engineers within the research team developed a set of questions related to contraflow decision making and sent them to domain experts (i.e., Project Advisory Panel members) responsible for state and local evacuation decision making. Researchers collected the responses, analyzed the data, and created a formalized and structured knowledge database.

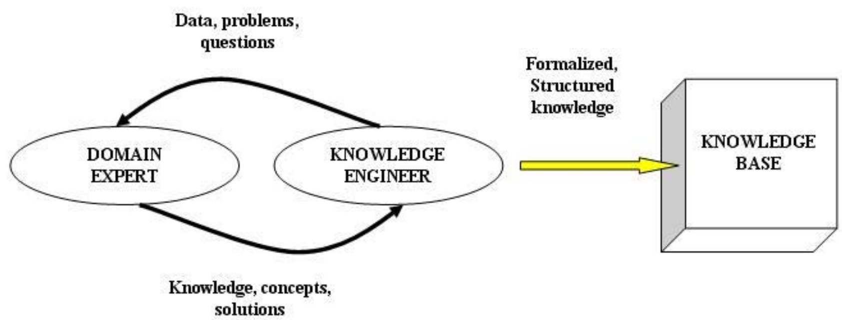


Figure 20. Typical Knowledge Acquisition Process for Building an Expert System.

A series of brain-storming meetings between researchers and the Project Advisory Panel resulted in the primary factors to consider for evacuation decision making. A preliminary analysis of these factors considering when and in which situation contraflow would be necessary resulted in four domains: storm, traffic condition, infrastructure, and human behavior. Researcher and Project Advisory Panel input further refined this list and omitted the infrastructure domain since construction orders would be halted when a hurricane is approaching. Therefore, three domain factors (storm, traffic condition, and human behavior) were used for model development; details of these factors can be found under the Concept of Operations section of this report.

Purpose of Survey Design

The final decision for contraflow can be subjective, depending on the expert's experience and perspective(s). To capture as many aspects of the domain experts' knowledge as possible, the research team designed two sets of sequential surveys/questionnaires (see Survey 1 and Survey 2) to collect expert inputs on contraflow decision making. Feedback was collected and analyzed to form a structured knowledge base database. Researchers used this database to develop rules supporting contraflow decision making for future hurricane events.

- ***First Survey (to determine the most important sub-factors):*** The first questionnaire sought to select the most important sub-factors in each domain and to calculate the importance, or weight, of each domain. Based on the conditions of the sub factors, an expert can determine an appropriate severity level of the domain. However, having a large number of sub-factors not only makes contraflow decision making more complicated, but also increases the potential number of scenarios to investigate. Furthermore, the results of the first survey were intended to reduce the number of sub-factors that are correlated within each domain so that the selected sub-factors will represent most aspects of the domain. At this stage in the project, researchers believed that two or three factors should represent each domain in the decision-making tool. For example, in the Storm domain, *Hurricane category* and *Projected inland path* might be the two most important factors that can capture the severity of the domain.
- ***Second Survey (to determine the severity level of each domain):*** Based on the results of the first survey, analysts designed the second set of questionnaires to collect the experts' knowledge (opinions) about what severity level they would assign to each domain for a specific scenario. For example, for scenarios where the hurricane category is 3, the projected percentage of regional population impacted is Medium and the projected storm diameter at landfall is Small. Questions posed to experts were intended to determine what severity level would be assigned to this scenario (on a scale from 1 to 10).

Survey 1

Personal Information
Name:
Organization:
Position:
Years in this position:
Phone:
Email address:
The purpose of this questionnaire is to rate your professional opinion of the importance of each noted item in association with its influence on contraflow decisions in Houston-Galveston region.

Please indicate the importance level of each domain: 1: not at all important, 2: not very important, 3: important, 4: very important, 5: critically important	**Importance Level**				
	1	**2**	**3**	**4**	**5**
Storm characteristics					
Traffic conditions					
Human behavior factors					

Please indicate the importance level of each factor: 1: not at all important, 2: not very important, 3: important, 4: very important, 5: critically important		**Importance Level**				
		1	**2**	**3**	**4**	**5**
Storm	Projected inland path					
	Storm category					
	Storm diameter					
	Projected storm surge					
	Number of days until landfall					
Traffic	Season					
	Day of the week of landfall					
	Time of expected landfall					
	Incidents					
	Traffic conditions					
Human Behavior Factors	Projected number or percentage of shadow evacuees					
	History of recent hurricanes					
	Propensity to follow different routes than expected					

Comments:

Survey 1 was distributed among the panel members, and researchers tabulated the results from the completed surveys. Table 15 shows the result of the first survey that reflect input from seven different panel members.

Table 15. Results of Survey 1.

	Domain	Importance score (1 to 5)	Weight (0 to 1)
	Storm characteristics	4.500	0.350
	Traffic conditions	4.667	0.364
	Human behavior factors	3.667	0.286
	Sub-factor	**Importance score (1 to 5)**	**Rank**
Storm	Projected inland path	4.333	1
	Storm category	4.333	1
	Storm diameter	4.333	1
	Projected storm surge	4.167	2
	Number of days until landfall	4.000	3
Traffic	Season	3.167	4
	Day of the week of landfall	3.167	4
	Time of expected landfall	3.800	3
	Incidents	3.833	2
	Traffic conditions	4.400	1
Human behavior	Projected number or percentage of shadow evacuees	4.000	2
	History of recent hurricanes	4.333	1
	Propensity to follow different routes than expected	3.333	3

Based on the results of the first survey, normalized importance levels (weight) of factors are: 0.350 for storm, 0.364 for traffic, and 0.286 for human behavior. These findings indicate that the traffic condition has the highest priority, followed by storm factors and human behavior factors.

The following are the most important sub-factors in each domain:

- Storm (estimated 72 hours prior to landfall).
  - Projected Percentage of Regional Population Impacted (PPRPI).
  - Projected Storm Category (PSC) at landfall.
  - Projected Storm Diameter (PSD) at landfall.
- Traffic on highways I-45, I-10, and US 290.
  - Traffic Conditions (TC).
  - Incidents.

- Human behavior factors.
  - History of recent hurricanes.

For designing the second survey, the researchers needed to define levels for each sub factor within each domain. Accordingly, the levels of each sub-factor were categorized as:

Storm (Estimated 72 Hours prior to Landfall)

- Projected Percentage of Regional Population Impacted (PPRPI)
  - Low <20 percent.
  - Medium ≥ 20 percent and ≤ 50 percent.
  - High >50 percent.
- Projected Storm Category (PSC) at landfall.
  - Category 1.
  - Category 2.
  - Category 3.
  - Category 4.
  - Category 5.
- Projected Storm Diameter (PSD) at landfall.
  - Small <140 miles.
  - Medium ≥ 140 miles and ≤ 420 miles.
  - Large >420 miles.

Traffic on highways I-45, I-10, and US 290

- Traffic conditions (TC).
  - Normal Speed ≥ 40 mph.
  - Congested (Medium) Speed >20 mph and <40 mph.
  - Stop-N-Go (Heavy) Speed ≤ 20 mph.
- Incidents.
  - None.
  - Minor Less than 50 percent of main lanes are blocked or less than one hour incident duration.
  - Major Greater than 50 percent of main lanes are blocked or greater than one hour incident duration.

Human Behavior Factors

- History of recent hurricanes.
  - Low No hurricane in the past 5 years.
  - Medium At least one severe hurricane in the past 5 years.
  - High At least one severe hurricane in the past 2 years.

Based on the levels defined above, researchers produced 45, nine, and three scenarios for the Storm, Traffic condition, and Human Behavior domains, respectively (see Survey 2). Researchers requested that panel members evaluate the severity level of each scenario in each domain by assigning a number from 1 to 10, with 1 being the least severe and 10 being the most severe.

Survey 2

Name:	
Organization:	
Position:	Years in this position:
Phone:	Email address:

Storm:

No	PPRPI	PSC	PSD	Storm Severity level	Comments
1	Low	Category 1	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
2	Low	Category 1	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
3	Low	Category 1	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
4	Low	Category 2	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
5	Low	Category 2	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
6	Low	Category 2	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
7	Low	Category 3	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
8	Low	Category 3	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
9	Low	Category 3	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
10	Low	Category 4	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
11	Low	Category 4	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
12	Low	Category 4	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
13	Low	Category 5	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
14	Low	Category 5	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
15	Low	Category 5	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
16	Medium	Category 1	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
17	Medium	Category 1	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
18	Medium	Category 1	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
19	Medium	Category 2	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
20	Medium	Category 2	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
21	Medium	Category 2	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
22	Medium	Category 3	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
23	Medium	Category 3	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
24	Medium	Category 3	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
25	Medium	Category 4	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
26	Medium	Category 4	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
27	Medium	Category 4	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
28	Medium	Category 5	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
29	Medium	Category 5	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
30	Medium	Category 5	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
31	High	Category 1	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
32	High	Category 1	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
33	High	Category 1	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
34	High	Category 2	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	

35	High	Category 2	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
36	High	Category 2	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
37	High	Category 3	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
38	High	Category 3	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
39	High	Category 3	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
40	High	Category 4	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
41	High	Category 4	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
42	High	Category 4	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
43	High	Category 5	Small	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
44	High	Category 5	Medium	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
45	High	Category 5	Large	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	

Traffic:

No	Traffic condition	Incident	Traffic severity level	Comments
1	Normal (Speed ≥ 40 mph)	None	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
2	Normal (Speed ≥ 40 mph)	Minor	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
3	Normal (Speed ≥ 40 mph)	Major	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
4	Congested (Speed > 20 mph and < 40 mph)	None	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
5	Congested (Speed > 20 mph and < 40 mph)	Minor	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
6	Congested (Speed > 20 mph and < 40 mph)	Major	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
7	Stop-N-Go (Speed ≤ 20 mph)	None	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
8	Stop-N-Go (Speed ≤ 20 mph)	Minor	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
9	Stop-N-Go (Speed ≤ 20 mph)	Major	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	

Human Behavior:

No	History of recent hurricanes	Human Behavior severity level	Comments
1	No hurricane in the past 5 years	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
2	At least one severe hurricane in the past 5 years	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	
3	At least one severe hurricane in the past 2 years	Least severe ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ Most severe	

Table 16 shows the results of the second survey for the storm domain that are based on the collective feedback from 10 different panel members. The severity level of each scenario within the storm domain is shown in the column Severity Level (l_S).

Table 16. Results of Survey 2 (Storm Domain).

No	PPRPI	PSC	PSD	Severity Level (l_S)
1	Low	Category 1	Small	1.25
2	Low	Category 1	Medium	1.50
3	Low	Category 1	Large	2.00
4	Low	Category 2	Small	2.00
5	Low	Category 2	Medium	2.63
6	Low	Category 2	Large	3.38
7	Low	Category 3	Small	3.63
8	Low	Category 3	Medium	4.38
9	Low	Category 3	Large	4.88
10	Low	Category 4	Small	5.00
11	Low	Category 4	Medium	5.63
12	Low	Category 4	Large	6.00
13	Low	Category 5	Small	6.13
14	Low	Category 5	Medium	6.63
15	Low	Category 5	Large	7.00
16	Medium	Category 1	Small	2.25

No	PPRPI	PSC	PSD	Severity Level (l_S)
17	Medium	Category 1	Medium	2.38
18	Medium	Category 1	Large	3.13
19	Medium	Category 2	Small	3.13
20	Medium	Category 2	Medium	3.88
21	Medium	Category 2	Large	4.50
22	Medium	Category 3	Small	5.00
23	Medium	Category 3	Medium	5.75
24	Medium	Category 3	Large	6.50
25	Medium	Category 4	Small	6.50
26	Medium	Category 4	Medium	7.25
27	Medium	Category 4	Large	7.75
28	Medium	Category 5	Small	7.50
29	Medium	Category 5	Medium	8.13
30	Medium	Category 5	Large	8.63
31	High	Category 1	Small	2.88
32	High	Category 1	Medium	3.50
33	High	Category 1	Large	4.00
34	High	Category 2	Small	4.38
35	High	Category 2	Medium	5.25
36	High	Category 2	Large	6.13
37	High	Category 3	Small	6.13
38	High	Category 3	Medium	6.88
39	High	Category 3	Large	8.13
40	High	Category 4	Small	8.00
41	High	Category 4	Medium	8.50
42	High	Category 4	Large	9.25
43	High	Category 5	Small	9.00
44	High	Category 5	Medium	9.38
45	High	Category 5	Large	9.63

Survey 2 results for the traffic and human factor domains are shown in Table 17 and Table 18, respectively. Variables l_T, l_H are the respective severity level of each scenario within the traffic condition and human factor domains.

Table 17. Results of Survey 2 (Traffic Domain).

No	Traffic condition	Incident	Severity Level (l_T)
1	Normal	None	1.25
2	Normal	Minor	2.63
3	Congested	None	3.63
4	Congested	Minor	4.63
5	Congested	Major	6.00
6	Stop-N-Go	None	6.38
7	Stop-N-Go	Minor	7.63
8	Stop-N-Go	Major	9.00

Table 18. Results of Survey 2 (Human Factor Domain).

No.	History of recent hurricanes	Severity Level (l_H)
1	No hurricane in the past 5 years	3.75
2	At least one severe hurricane in the past 5 years	5.75
3	At least one severe hurricane in the past 2 years	8.13

Based on the results collected from Survey 2, analysts calculated the overall weighted severity level ($\mathcal{H}$) as a number between 1 and 10 using the following formula:

$$\mathcal{H} = w_S * l_S + w_T * l_T + w_H * l_H$$

The weight for each domain factor was obtained from the results of Survey 1 (as shown in Table 15).

Normalization of the Overall Weighted Severity Level

Based on the survey results, the theoretical minimum value for the evacuation severity level is 1.965 (not 1):

$$min = w_S * l_S + w_T * l_T + w_H * l_H = 0.350 * 1.25 + 0.364 * 1.25 + 0.286 * 3.75 = 1.965$$

and the theoretical maximum severity value is 8.972 (not 10):

$$max = w_S * l_S + w_T * l_T + w_H * l_H = 0.350 * 9.63 + 0.364 * 9.00 + 0.286 * 8.13 = 8.972$$

Therefore, the research team normalized this scale from the current range [1.965, 8.972] to [1,10]. The recalculation was performed using the following formula:

$$\frac{10 - 1}{max - min} = \frac{x - 1}{\mathcal{H} - min}$$

or

$$x = \frac{9(\mathcal{H} - min)}{max - min} + 1$$

In the above equations, x is the normalized severity level in the range of [1, 10] and max and min are the overall weighted severity levels calculated using the value 10 for the most severe case and the value 1 for the least severe case.

Therefore,

$$x = \frac{9}{8.972 - 1.965}(\mathcal{H} - 1.965) + 1$$

The final calculation can be displayed graphically using a color-coded gauge illustrating the need for contraflow operations. Figure 21 shows an example of this gauge.

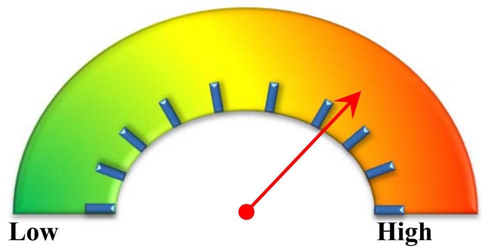


Figure 21. Example "Contraflow Need" Gauge.

As an example, consider an upcoming hurricane with the following specifications:

- Storm (estimated 72 hours prior to landfall).
  - Projected Percentage of Regional Population Impacted (PPRPI): 40 percent (Medium).
  - Projected Storm Category (PSC) at landfall: 3.
  - Projected Storm Diameter (PSD) at landfall: 174 miles (Medium).
- Traffic on highways I-45, I-10, and US 290.
  - Traffic Conditions (TC): 35 miles/hour (Congested).
  - Incidents: None.
- Human Behavior Factors.
  - History of recent hurricanes: 1 hurricane within two years (High).

This scenario matches the 23rd scenario of the storm domain as shown in Table 15, and the severity level of the storm domain is $l_S = 5.75$. Similarly, the severity level of traffic and human behavior can be retrieved as $l_T = 3.63$ and $l_H = 8.13$ from Table 17 and Table 18, respectively. Therefore, the overall weighted severity level ($\mathcal{H}$) of the hurricane is

$$H = w_S * l_S + w_T * l_T + w_H * l_H = 0.350 * 5.75 + 0.364 * 3.63 + 0.286 * 8.13 = 5.659$$

Then, the normalized weighted severity level of 5.659 in the range of [1, 10] would be calculated using the normalization formula as

$$x = \frac{9}{8.972 - 1.965} (5.659 - 1.965) + 1 = 5.745.$$

Therefore, the normalized value of 5.745 will be displayed (perhaps using a colored gauge indicator within the decision support tool), rather than the original value 5.659.

PROTOTYPE WEB-BASED DECISION SUPPORTING SYSTEM (DSS)

To finalize criteria for the contraflow decision-making process, researchers gathered feedback from the Project Advisory Panel and conducted a literature review on the state-of-the-practice regarding contraflow decision-making processes from other agencies. Findings regarding these practices and processes are summarized in Table 19. All agencies agree that no contraflow is needed to accommodate the traffic re-entry after the storm.

Table 19. Summary of State-of-the-Practice for Contraflow Decisions.

Agencies	Criteria
Florida DOT	• Sufficient threat • Category 4/5 hurricane is forecasted to impact at least 1 region in the state • Extreme vulnerability • Mandatory evacuation for Category 4/5 storm surge evacuation zones • Available time • Arrival of tropical storm force winds at least 25 hours from Florida coast • Will the regional evacuation plan be sufficient without the addition of contraflow operations (Category 4/5)? • State and local emergency managers concur that failure to implement contraflow will threaten a greater number of vulnerable residents
Alabama DOT	• Emergency evacuation plans • Type of evacuation – mandatory versus voluntary • Size of evacuation area • Number of evacuees expected • Location of expected storm landfall • Expected storm strength at landfall
FHWA Evacuation Primer	• Median openings on highways • Work zones • Exit/entrance ramp openings and closures • Night contraflow operations • Sign placements • Personnel availability • Routes for emergency vehicles, including entry for incoming response resources • Condition of lanes designated for outbound vehicles • Impact of contraflow on other roadways including parallel routes

Taking into consideration the input from the current project's advisory panel and best practices from other agencies nationwide, researchers designed a prototype decision support system (DSS) that captures both qualitative and quantitative components of the decision-making process. The web-based prototype DSS is built on the ASP.net platform with a Microsoft Virtual Earth interface. The DSS features two components:

- Contraflow recommendation tool.
- Real-time decision support information tool.

The web-based contraflow recommendation tool accounts for the subjective criteria of the decision-making process. Researchers developed this tool based on the survey of professionals from emergency management and transportation agencies. Importance values (weights) were then assigned for each factor considered critical for activating contraflow plans. The tool incorporates the procedure described in the previous section to compute an evacuation severity score, which is an indicator of the need for contraflow. The real-time decision support information component addresses the quantitative elements of the contraflow decision-making process. This component provides critical real-time information that emergency management professionals and decision makers typically need to better assess the real-time traffic conditions, and includes the latest hurricane forecast to determine the best operational strategies in light of evacuation needs.

Contraflow Recommendation Tool

There are two types of inputs required for the contraflow recommendation algorithm—static and real-time data. The real-time inputs are primarily traffic conditions and hurricane forecast feeds. These inputs will be retrieved in real-time and updated at regular intervals. The updating intervals will be more frequent as the time remaining to landfall approaches. The static inputs are those data that users must determine and enter manually. History of recent hurricanes is an example of static input.

The contraflow recommendation component takes all the required inputs to compute the overall severity score, which is then used to quantitatively determine the need for contraflow. Figure 22 displays a preliminary design of the graphical user interface (GUI) for the input factors overlaid on a Microsoft® Bing Map of the Houston region of southeast Texas. Figure 23 shows details of the input factors for contraflow decision-making support.

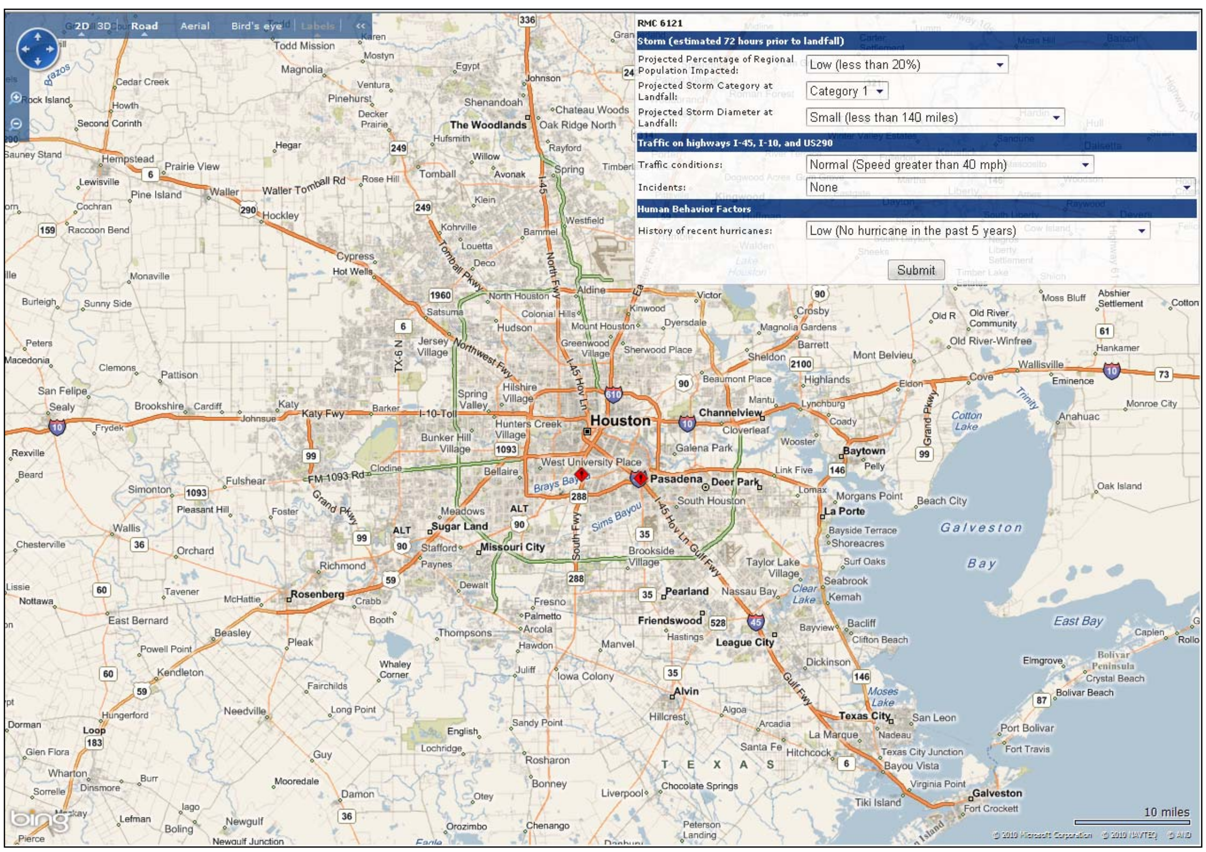


Figure 22. Interface of Input Factors Overlaid on the Traffic Information Map.

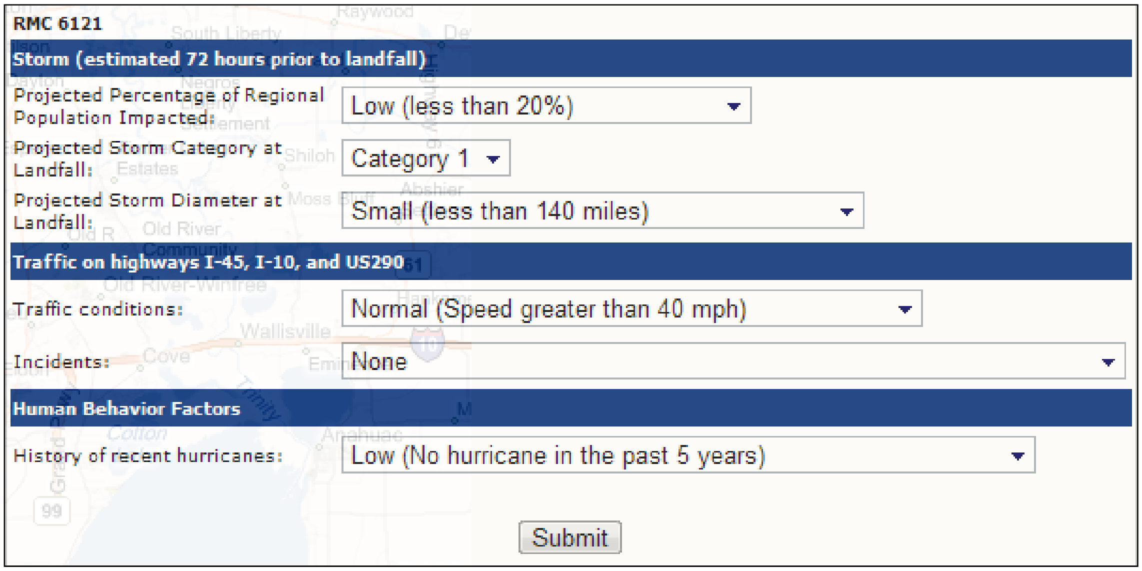


Figure 23. Detailed Input Factors for Contraflow Decision Support.

Once all the inputs are entered into the tool, the recommendation results will be displayed as shown in Figure 24. Note that the current incidents are also displayed on the map along with the speed charts at selected locations on the major highways. Real-time incident characteristics will be displayed when the users hover the mouse over incident icons.

The severity level is displayed as a color-coded bar that goes from No Contraflow (least severe) to Contraflow (most severe). The intermediate options between these two are evaculane and partial contraflow operations.

Real-Time Decision Support Information Tool

The real-time decision support information component is designed to display concurrently with the contraflow recommendation. These real-time information elements are intended to provide decision makers with current freeway network conditions as well as the predicted performance for different evacuation strategies. This information can be summarized into four categories as shown in Table 20.

Table 20. Real-Time Decision Support Information.

Category	Decision-Making Support Information
Hurricane characteristics	• Time remaining (hours) to tropical storm (TS) force winds • Time remaining (hours) to hurricane force wind • Time remaining (hours) to the landfall
Evacuation strategies	• List of evacuation options – base case, evaculane, partial contraflow, and full contraflow. • Report the number of vehicles evacuated and average travel time over the anticipated peak 24-hour evacuation period (begins at 84 hours out) for the base case (do-nothing option). • Report % in travel time savings and % increase in the number of vehicles evacuated with respect to the base case.
Real-time traffic characteristics	• Speed profiles • Hourly volume profiles • Hourly directional split profiles • The profiles will be displayed for current day versus 3-month average on the same day of the week at selected locations on I-10, I-45, and US 290.
Incident characteristics	• Incident severity • Type of incident • Number of mainlanes blocked • Number of vehicles involved • Predicted incident duration (using the calibrated hazard model from 0–5485)

The performance of different evacuation strategies will be reported in terms of average travel time and number of vehicles evacuated over the peak 24-hour evacuation period. The performance measures were obtained from mesoscale simulation models with varying demand and supply conditions. The results from the pre-run model scenarios will be tabulated into the database and can then be queried by the users along with other real-time decision support information. Analysts can update the database values as needed and will be able to add more scenarios as the results become available. Table 21 shows an example display of the performance for different evacuation options for a given hurricane/evacuation event.

Table 21. Example Display of Predicted Evacuation Performance.

Strategies	Travel Time (Combined)	Vehicles Evacuated (vehicles per day)	I-10 Travel Time	I-45 Travel Time	US 290 Travel Time
Base Case (BC)	250 minutes	380,000	270 minutes	290 minutes	200 minutes
Evaculane (EL)	−5%	+5%	−5%	−5%	−5%
Partial Contraflow (PC)	−8%	+8%	−8%	−8%	−8%
Full Contraflow (CF)	−15%	+16%	−15%	−15%	−15%

Four different evacuation strategies evaluated in this study are:

- Base case or do-nothing option.
- Evaculane—activate US 290 and I-10 evaculanes.
- Partial contraflow—activate US 290 and I-10 evaculanes and partial contraflow on I-45.
- Full contraflow—activate evaculanes and full contraflow on I-10, I-45, and US 290.

The prototype DSS is scalable in that authorized users can incorporate additional evacuation strategies beyond the current scope of this study into the system in the future. Figure 24 and Figure 25 show an example of speed profiles for the current day along with the trailing three-month average speed for that day of the week at three strategic locations along US 290. These real-time traffic data are retrieved from Houston TranStar data feeds.

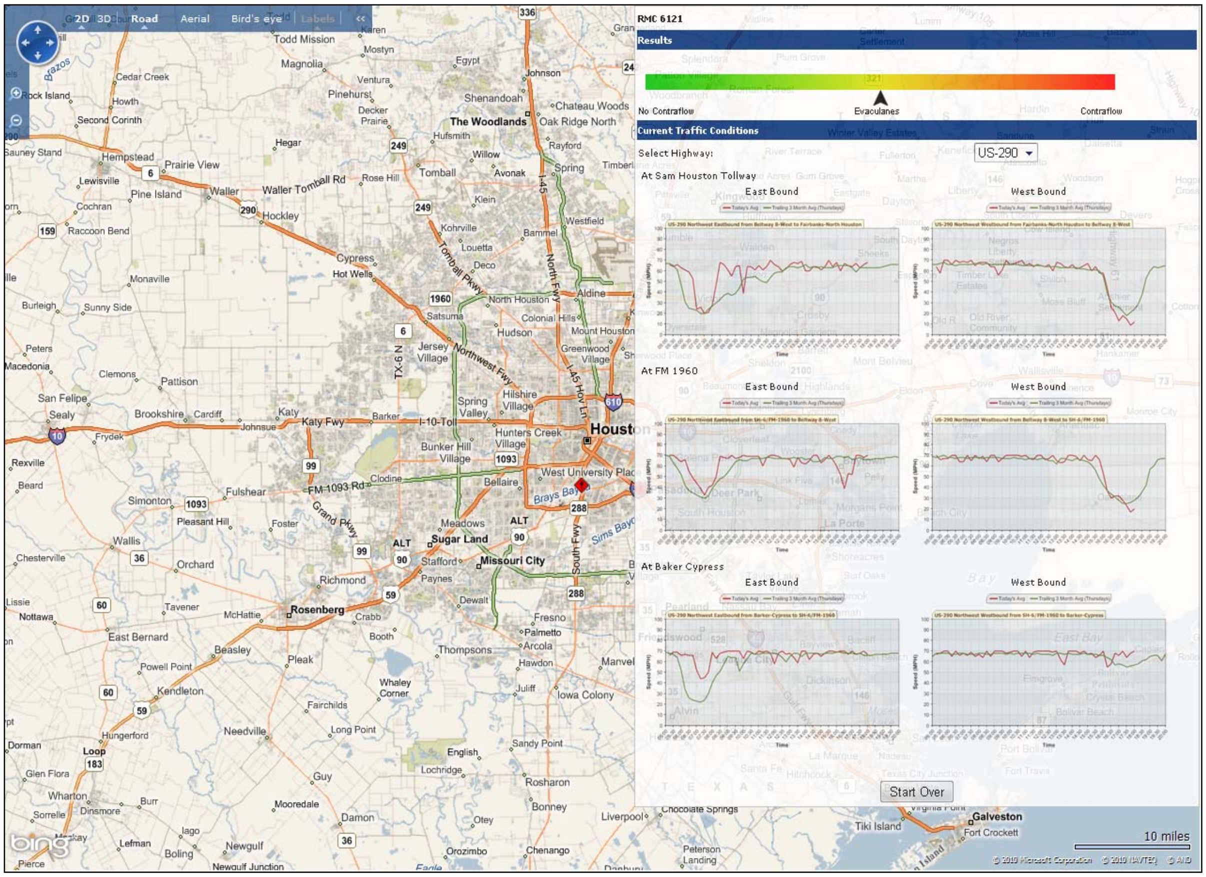


Figure 24. Example of Contraflow Recommendation and Decision Support Information.

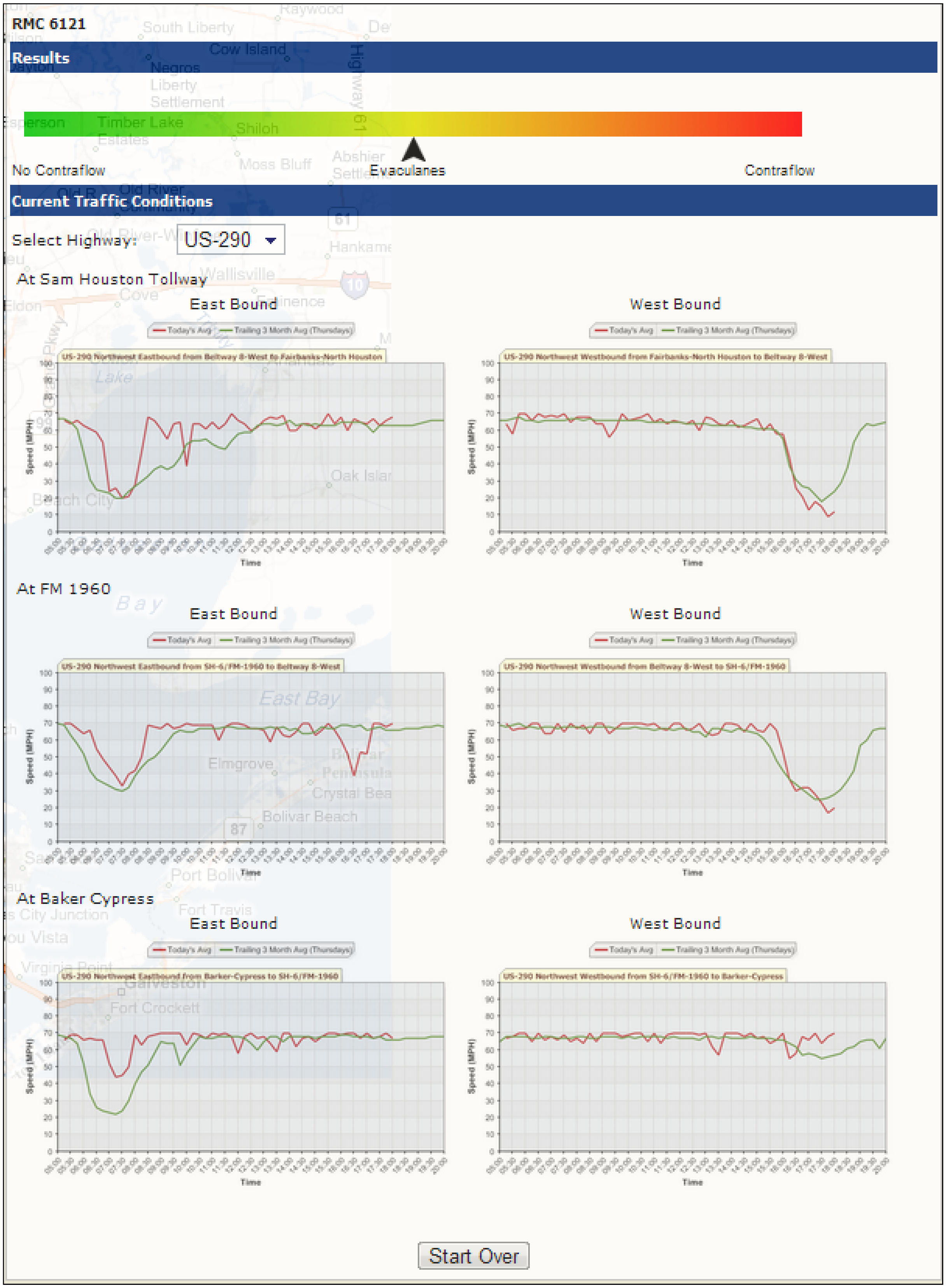


Figure 25. Detailed Output Interface and Real-Time Traffic Conditions.

Incident Duration Prediction

The real-time decision support tool also features incident duration prediction capability for a given incident. Previous TxDOT research recommended hazard-based duration models for predicting incident durations based on incident characteristics (*3*). The research team incorporated such a model into the decision support system.

Incident characteristics as well as other data attributes available from the incident database can be incorporated into the hazard models. These variables are typically referred to as "covariates" in modeling terminology. These covariates can be incorporated into the hazard-based models, and doing so affects the probability of either increasing or decreasing incident duration.

The distributions typically used in this type of model include lognormal, logistic, log logistic, and Weibull models. For example, when using a Weibull distribution, which is a more generalized form of the exponential distribution, the density function is defined as:

$$f(t) = \lambda P(\lambda t)^{P-1} e^{-(\lambda t)^P}, \lambda > 0, P > 0 \tag{3}$$

and the corresponding hazard function is:

$$h(t) = (\lambda P)(\lambda t)^{P-1} \tag{4}$$

For Weibull, the parameter P specifies the shape of the hazard function. If $P > 1$, the hazard is monotonically increasing in duration. If $P < 1$, it is monotonically decreasing in duration. If $P = 1$, the hazard is constant in duration, and the Weibull distribution becomes the exponential.

The natural way to relate a covariate vector $\boldsymbol{x}$ to a parameter λ while satisfying the positivity constraint is to take:

$$\log \lambda_i = \beta^T \mathbf{x}_i, \ \lambda_i = e^{\beta^T \mathbf{x}_i} \tag{5}$$

For the Weibull distribution, the hazard function becomes:

$$h(t) = Pt^{P-1} e^{P\beta^T \mathbf{x}} \tag{6}$$

Using Houston incident data archives from 2004 to 2007, the researchers calibrated a simplified model for predicting incident durations for accidents with at least one mainlane blockage. Other types of incidents were not considered because (a) they have less impact on the mainlane traffic flow, (b) the variability of their durations are likely to be influenced by factors beyond incident characteristics (e.g., incident response time can be large for vehicle breakdown on the shoulder lane), and (c) the sample sizes are relatively smaller when compared with mainlane-blocking accidents. Once calibrated, the expected incident duration using the mean value of the Weibull distribution can be calculated as:

$$\hat{T}_i = \lambda_i = e^{\beta^T \mathbf{x}_i} \tag{7}$$

The $(1-\alpha)$ percent confidence interval of the predicted incident duration is:

$$\left[\lambda_i\left(-\ln\left(1-\frac{\alpha}{2}\right)\right)^{1/P}, \lambda_i\left(-\ln\left(\frac{\alpha}{2}\right)\right)^{1/P}\right] \quad (8)$$

The probability that an incident will last longer than some specified time t is equivalent to the value obtained from the survivor function, that is:

$$S(t) = 1 - F(t) = 1 - e^{-(t/\lambda)^P} \quad (9)$$

The calibrated equation for predicting the duration of mainlane blocking accidents on Houston freeways is:

$$\begin{aligned}\hat{T} = \exp(&3.0934 + 0.1675 \times \text{Major} + 1.0752 \times \text{Fatal} + 0.5841 \times \text{Hazmat} + \\ &0.4241 \times \text{Truck} + 0.6614 \times \text{HW} + 0.5285 \times \text{LostLoad} + 0.4063 \times \text{VOF} + \\ &0.3472 \times \text{Other} + 0.2550 \times \text{Bus} - 0.0265 \times \text{Rain} + 0.0604 \times \text{Visibility} + \\ &0.0580 \times \text{NumVeh} + 0.0656 \times \text{NumLanesBlocked} + 0.5521 \times \text{AllLanesBlocked})\end{aligned} \quad (10)$$

where

$\hat{T}$ = predicted accident duration (minutes) based on the model inputs describing its characteristics;

Major = 1 if major accident, 0 if otherwise;

Fatal = 1 if fatal accident, 0 if otherwise;

Hazmat = 1 if accident is hazmat related, 0 if otherwise;

Truck = 1 if heavy truck involved, 0 if otherwise;

HW = 1 if high water related, 0 if otherwise;

LostLoad = 1 if lost load involved, 0 if otherwise;

VOF = 1 if vehicle on fire, 0 if otherwise;

Other = 1 if denoted as other types, 0 if otherwise;

Bus = 1 if bus involved, 0 if otherwise;

Rain = 1 if raining condition, 0 if otherwise;

Visibility = 1 if visibility is limited, 0 if otherwise;

NumVeh = Number of vehicles involved in the accident;

NumLanesBlocked = Number of mainlanes blocked by the accident (Use 0 if all lanes are blocked); and

AllLanesBlocked = 1 if all mainlanes are blocked, 0 if only some lanes are blocked.

For example, if the incident is a major two-vehicle accident blocking two mainlanes, then the corresponding inputs are: Major = 1; NumVeh = 2; NumLanesBlocked = 2; and All other variables = 0. Based on these inputs, the predicted accident duration is 33.4 minutes.

Incident duration prediction will be incorporated into future examples of the evacuation decision support system. The research team will solicit feedback from the Project Advisory Panel on this feature as well as the other features and layout of the decisions support tool and its user interface to create future working versions of the tool.

CHAPTER 11: MEET WITH AND REQUEST FEEDBACK FROM STAKEHOLDERS

The diverse membership of the PMC for this project included representatives from several different divisions, districts, and geographic coastal regions of the Texas Department of Transportation (TxDOT), the Texas Division of Emergency Management (DEM) and Department of Public Safety (TxDPS), the Army Corps of Engineers, and multiple representatives of the Houston-Galveston Area Council (H-GAC)—a complete listing of which was provided in Chapter 2. As such, a great number of important stakeholders (and prospective users of the prototype application being researched and tested in this project) were regularly and fundamentally involved throughout the course of this effort. Aside from regular e-mail updates and correspondence, this entire panel met seven (7) different times as a working group. These meetings provided extremely valuable feedback and insights to the research team as this project progressed.

In addition, there was a special 3-hour meeting/workshop held by key research team staff (from TTI and University of Houston) early on in this project (April 2009). This meeting took place at H-GAC headquarters in Houston and involved several staff from H-GAC who were interested in hurricane evacuation planning issues, as well as core modeling personnel. This was a productive meeting for all parties involved. The multiple panel meetings cited previously, as well as the special workshop with H-GAC, provided adequate stakeholder feedback for this prototype phase of the effort. Accordingly, it was not deemed necessary to conduct significant additional outreach to other stakeholders (beyond the large and diverse PMC) during the course of this research.

As will be discussed further in the Conclusion, these meetings provided helpful examples of what future outreach workshops along the Texas coast might entail as part of a prospective implementation phase for this project.

CHAPTER 12:
MODIFY ALPHA-LEVEL DECISION SUPPORT PROTOTYPE

Based on the feedback from stakeholders and the results of experiments, the researchers made modifications to the decision support prototype tool that was developed earlier in the project and described previously in Chapter 10. The researchers anticipated making modifications along two general lines:

- Calibration of the contraflow decision-making model. The researchers adjusted the model to make it more realistic for evacuation problems.
- Changes to decision support prototype graphical interface or functionality. The researchers modified the website to address concerns expressed by stakeholders in Task 10. As mentioned previously, the researchers made modifications, taking into consideration the scope and limitations of the research endeavor. In particular, the prototype was focused on "function" and "architecture" rather than "feature." Other than basic graphical interface tools to support the research effort, the emphasis was given to making the prototype close to the final production level, which would be a logical part of an implementation phase. Using the structure developed in the research, a web developer can adapt and integrate the prototype into other existing hurricane evacuation applications.

CALIBRATING THE CONTRAFLOW DECISION-MAKING MODEL

In the contraflow decision-making model that was proposed in Task 9, we investigated three domain factors to determine the severity level of a hurricane. Each of the domain factors has been assigned a weight and the formula for calculating the severity level of a hurricane was developed as:

$$\begin{aligned} Severity\ level = {} & weight(storm) * storm_{value} + \\ & weight(traffic) * traffic_{value} + \\ & weight(humanBehavior) * humanBehavior_{value}. \end{aligned} \quad (11)$$

Although the weight values were calculated based on the results from Survey 1, they needed to be adjusted to reflect the real situation and what the experts are expecting in some special cases. Table 22 shows the old and the new weight values. As shown in Table 22, the first adjustment applied on the weight values was to increase the effects of two domain factors (storm and traffic) on the final decision. The old values of the weights implied that the human behavior factor had a dominant effect on the final result. However, it is not the case in real situation based on our conversion with stakeholders. Therefore, the researchers decided to decrease the weight of human behavior by half and split the decreased weight value on the other factors proportionally:

- Storm: 0.420=0.350+0.143*0.350/(0.350+0.364)
- Traffic: 0.437=0.364+0.143*0.364/(0.350+0.364)
- Human Behavior: 0.143=0.286/2

Table 22. Old and New Weight Values.

Domain	Weight (old)	Weight (new)
Storm	$w_S = 0.350$	$w_S = 0.420$ ↑
Traffic	$w_T = 0.364$	$w_T = 0.437$ ↑
Human behavior	$w_H = 0.286$	$w_H = 0.143$ ↓

According to the new weights, we updated the normalization formula.

$$min = w_S * l_S + w_T * l_T + w_H * l_H = 0.420 * 1.25 + 0.437 * 1.25 + 0.143 * 3.75 = 1.61,$$

$$max = w_S * l_S + w_T * l_T + w_H * l_H = 0.420 * 9.63 + 0.437 * 9 + 0.143 * 8.13 = 9.14.$$

$$x = \frac{9}{9.14-1.61}(\mathcal{H} - 1.61) + 1 \quad (12)$$

where

x = the normalized severity level in the range of [1, 10].
$\mathcal{H}$ = the severity level calculated in Equation (1) using the new weight values.
max and min are the overall weighted severity levels calculated using the value 10 for the most severe case and the value 1 for the least severe case.

After changing the values of weights, the normalized severity levels for some scenarios still do not reflect what experts was expecting. For example, if a hurricane with intensity of Category 4 is approaching, authorities will prepare themselves for contraflow regardless of the remaining factors. Therefore, the second adjustment we have implemented in the model is to add special rules as follows:

- If {storm intensity is Category 4 or 5} and $\{x < 5\}$, then $\{x = 5\}$.
- If {storm intensity is Category 1} and $\{x > 5\}$, then $\{x = 5\}$.

Example: Consider the following scenario:

Storm: PPRPI: Low
PSC: Category 4 ⟹ Severity Level (l_S): 5
PSD: Small

Traffic: Traffic condition: Normal
Incident: None ⟹ Severity Level (l_T): 1.25

Human behavior: History of recent hurricanes: No
Hurricane in the past five years ⟹ Severity Level (l_H): 3.75

$$H = w_S * l_S + w_T * l_T + w_H * l_H = 0.420 * 5 + 0.437 * 1.25 + 0.143 * 3.75 = 3.18$$

$$x = \frac{9}{9.14 - 1.61} (H - 1.61) + 1 = 2.88.$$

Based on Rule 1, the severity level is changed to because the storm intensity is 4.

CHANGES TO DECISION SUPPORT PROTOTYPE GRAPHICAL INTERFACE OR FUNCTIONALITY

The prototype functionality was modified to apply the changes described in Chapter 12. Figure 26 shows an example for the changes in the weights. For an incoming Category 1 hurricane with a low impacted projected percentage of regional population (PPRPI) and a small projected storm diameter (PSD), we expect the traffic condition to be stop-and-go without any incident. Moreover, we know that there was at least one severe hurricane in the past two years.

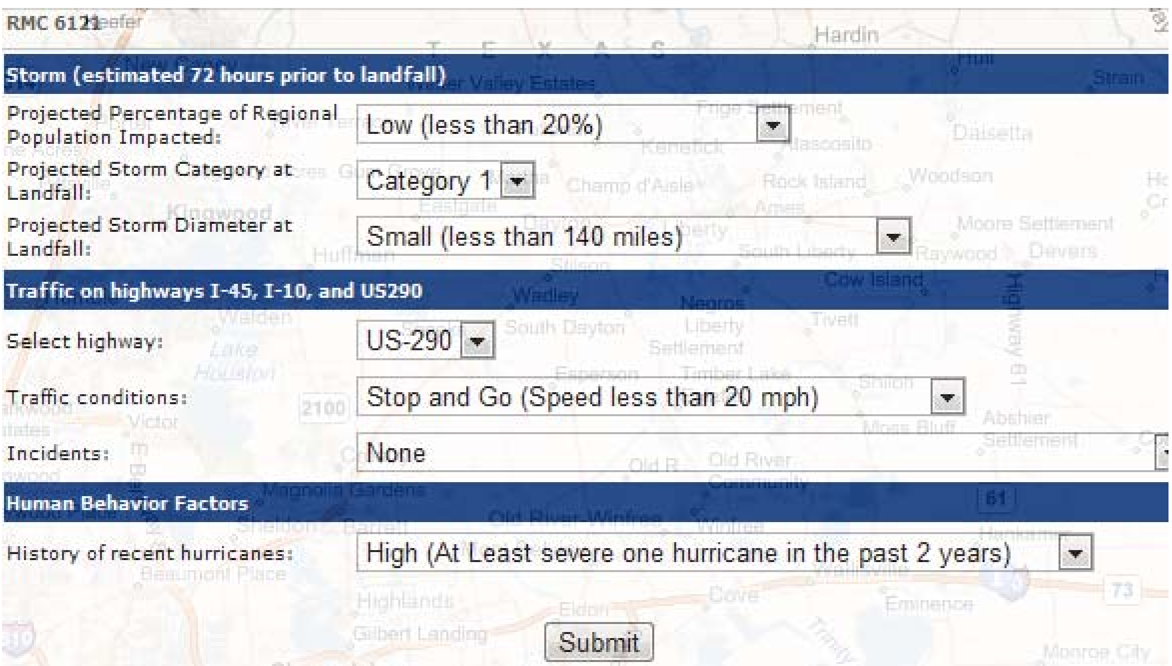


Figure 26. A Sample Case.

Based on the old weights, the normalized severity level is 5.01 (which is to consider evaculanes) as shown in Figure 27.

$$H = w_S * l_S + w_T * l_T + w_H * l_H = 0.350 * 1.25 + 0.364 * 6.38 + 0.286 * 8.13 = 5.085$$

$$x = \frac{9}{8.97 - 1.97} (5.085 - 1.97) + 1 = 5.01$$

Figure 27. Normalized Severity Level of the Sample Case Based on the Old Weights.

However, when we applied the new weights, the normalized severity level is now 4.43 (i.e., no change to the evacuation routes) as shown in Figure 28. This means that we reduced the weight on human evacuation behavior in our equation that still needs to be investigated further to better reflect the true impact of human behavior on contra-flow decision making.

$$H = w_S * l_S + w_T * l_T + w_H * l_H = 0.420 * 1.25 + 0.437 * 6.38 + 0.143 * 8.13 = 4.48$$

$$x = \frac{9}{9.14 - 1.61}(4.48 - 1.61) + 1 = 4.43$$

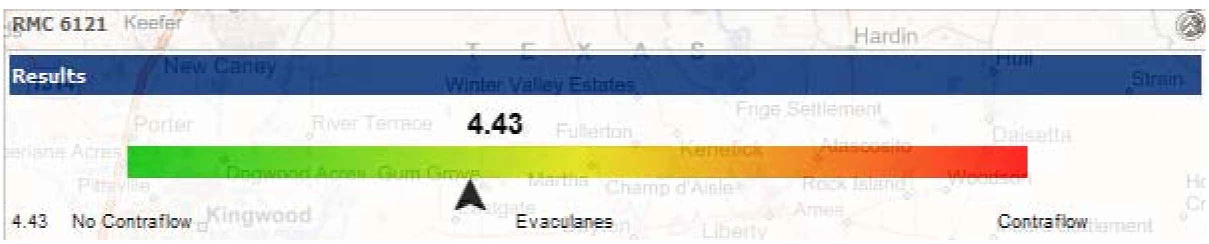


Figure 28. Normalized Severity Level of the Sample Case Based on the New Weights.

Another change applied on the prototype is on the options of incidents under normal traffic conditions. The survey results revealed that, when we have normal traffic conditions, there should not be any major incidents in the network. The prototype user interface is modified to consider this issue. Figure 29 is our previous version that had three options (*None, Minor,* and *Major*) for incident road condition when we had normal traffic conditions. The options have been reduced to *None* and *Minor* to reflect the reality that it is simply not possible to have normal traffic conditions if a major accident occurs, which is shown in Figure 30.

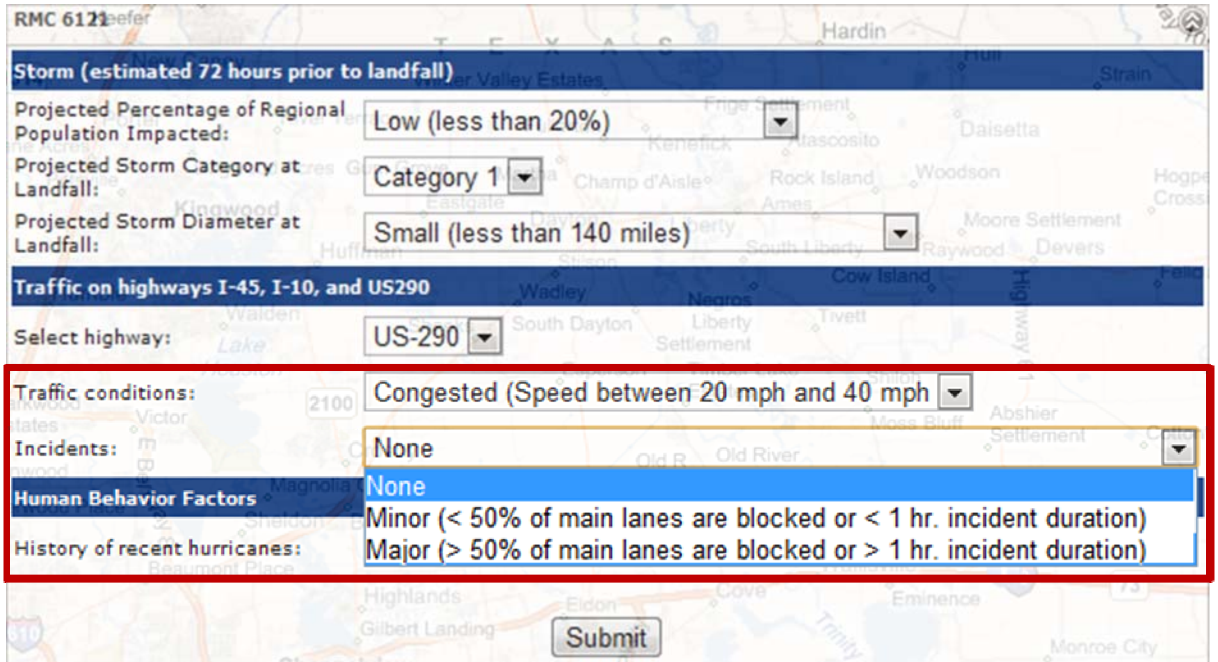


Figure 29. User Interface before the Change.

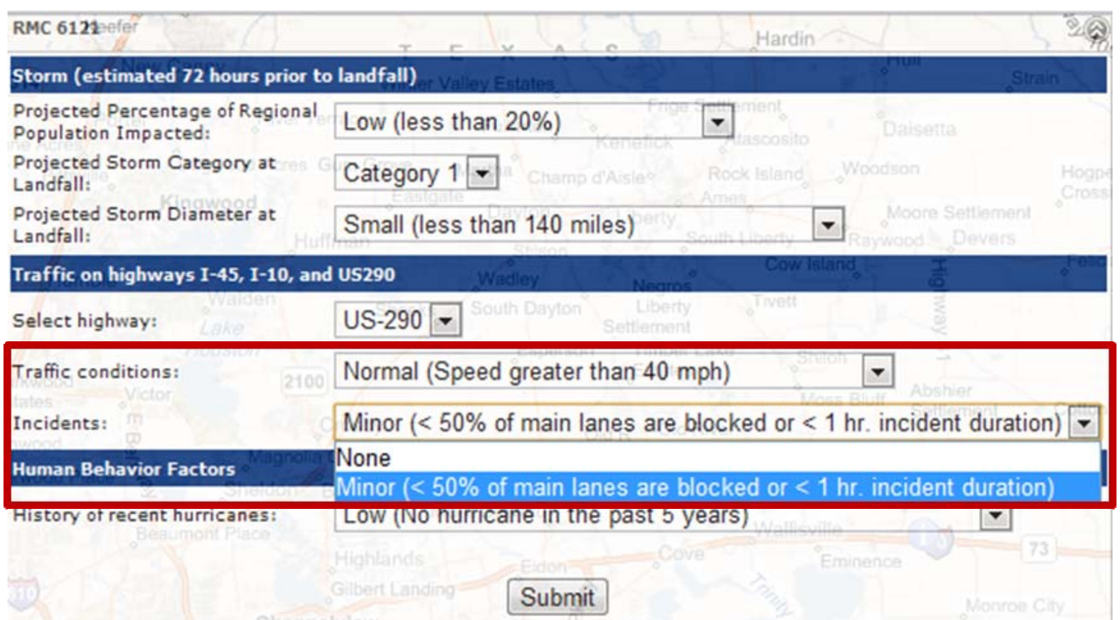


Figure 30. User Interface after the Change.

CHAPTER 13: RUN SERIES OF COMPLETE EVACUATION SCENARIOS WITH PROTOTYPE TOOL

SIMULATION SCENARIOS

Due to the size of the models, the prototype models evaluated in this study was designed to examine the effects of two primary factors that can impact the network performance during hurricane evacuation—evacuation demand and hurricane evacuation strategies.

Table 23 summarizes the demand scenarios used in the simulation models. The demand scenarios range from low to high level. Since the base model was originally developed for the Hurricane Rita study, the researchers set up additional demand levels for the simulation by generating these demand levels as percentages of the values observed from the Hurricane Rita evacuation. It is assumed that the background demand level will be inversely correlated with the evacuation demand levels. Therefore, the background demand levels were reduced when the evacuation demand is expected to be very high and vice versa when the evacuation demand is low.

Table 23. Demand Scenarios.

Demand Scenarios	*Evacuation Demand*	*Background Demand*
LO: Low	50% of Hurricane Rita's evacuation demand.	30% increase from Hurricane Rita's background demand
MD: Moderate	75% of Hurricane Rita's evacuation demand.	15% increase from Hurricane Rita's background demand
HI: High	Hurricane Rita's evacuation demand level (Approximately 400,000 vehicles over a 24-hour period at 72 hours prior to the landfall)	Hurricane Rita's background demand level (Approximately 2.7 million vehicles over a 24-hour period)
SH: Super High	125% of Hurricane Rita's evacuation demand	25% decrease from Hurricane Rita's background demand

Table 24 describes the evacuation strategies evaluated in this study. These strategies are developed and refined based on the feedback from the project advisory panel. The four evacuation strategies selected represent the most realistic evacuation options under different demand scenarios. The base case represents the existing supply conditions (i.e., no additional capacity is added to the network). The full contraflow is the scenario in which the roadway capacities are maximized by using all pave shoulders and inbound freeway links as travel lanes for evacuation. The evaculane (EL) and partial contraflow (PC) strategies represent the intermediate supply levels between the two extremes. Under the EL strategy, all the evaculanes on US 290 and I-10 are activated on the outbound direction. For the PC strategy, instead of reversing the entire I-45 southbound mainlanes, the plan calls for the contraflow of I-45 inbound links from south of Loop 336-South in Conroe to the Walker/Madison county line using FM 2889 and Spur 67. In the case of the full contraflow (CF), all the inbound lanes on I-10, I-45, and US 290 are reversed to provide additional capacity all the way to San Antonio, Dallas, and Hempstead, respectively. The evaculanes, if any, on the reversed mainlanes are assumed to be utilized as well under the CF strategy.

Table 24. Evacuation Strategies (Supply Scenarios).

Evacuation Strategies	*US 290 EL*	*I-10 EL*	*I-45 PC*	*US 290 CF*	*I-10 CF*	*I-45 CF*
BC: Base Case	-	-	-	-	-	-
EL: Evaculane	x	x	-	-	-	-
PC: Partial Contraflow	x	x	x	-	-	-
CF: Full Contraflow	x	x	x	x	x	x

* EL = Evaculane; PC = Partial Contraflow; CF = Full Contraflow

Table 25 summarizes the simulation scenarios conducted in this study. A total of 16 modeling scenarios have been developed, representing a full factorial experimental design with four demand and four supply levels. DynusT models have been used to run and analyze these 16 scenarios. The outputs from the models are further used to calibrate and develop the prototype predictive models for estimating the impacts of hurricane evacuation on the network performance.

Table 25. Simulation Scenarios.

Demand	Supply			
	BC: Base Case	EL: Evaculane	PC: Partial Contraflow	CF: Full Contraflow
LO: Low	LO_BC	LO_EL	LO_PC	LO_CF
MD: Moderate	MD_BC	MD_EL	MD_PC	MD_CF
HI: High	HI_BC	HI_EL	HI_PC	HI_CF
SH: Super High	SH_BC	SH_EL	SH_PC	SH_CF

SIMULATION MODEL DEVELOPMENT AND RUNS

Model Preparation

To model the evacuation strategies in DynusT, the network links have to be modified to represent the evaculane and contraflow operation. To model evaculane, the researchers reviewed the evacuation plan, checked the satellite images, and drove along the route to identify the locations where evaculanes are present. The researchers then modified the network by adding an extra lane on the links where evaculane is applicable. Due to a large number of links to be modified, the researchers created a link modification utility tool to assist with this task. The link modification tool took a user-specified configuration file that contains a set of links and appropriate number of lanes and then performed a search-and-replace operation on the appropriate DynusT file. Figure 31 shows the overview of the DynusT network encompassing the Houston-Galveston area and all the major routes to three destination cities―Dallas, Austin, and San Antonio. Figure 32 shows the evaculanes along US 290 on both westbound and eastbound directions. The evaculanes on the eastbound direction are designed to be operated during the contraflow operation. Figure 33 shows the example of a spreadsheet-based configuration file used to update the number of lanes on each link in the network. A pair of start node and end node defines each link. The user specifies the number of lanes in the normal operation and the evaculane mode, then toggles between these two modes by running a utility tool developed specifically for this purpose. The tool will modify the number of lanes in the DynusT network based on this configuration file.

Figure 31. Overall DynusT Network.

Figure 32. Evaculane on US 290.

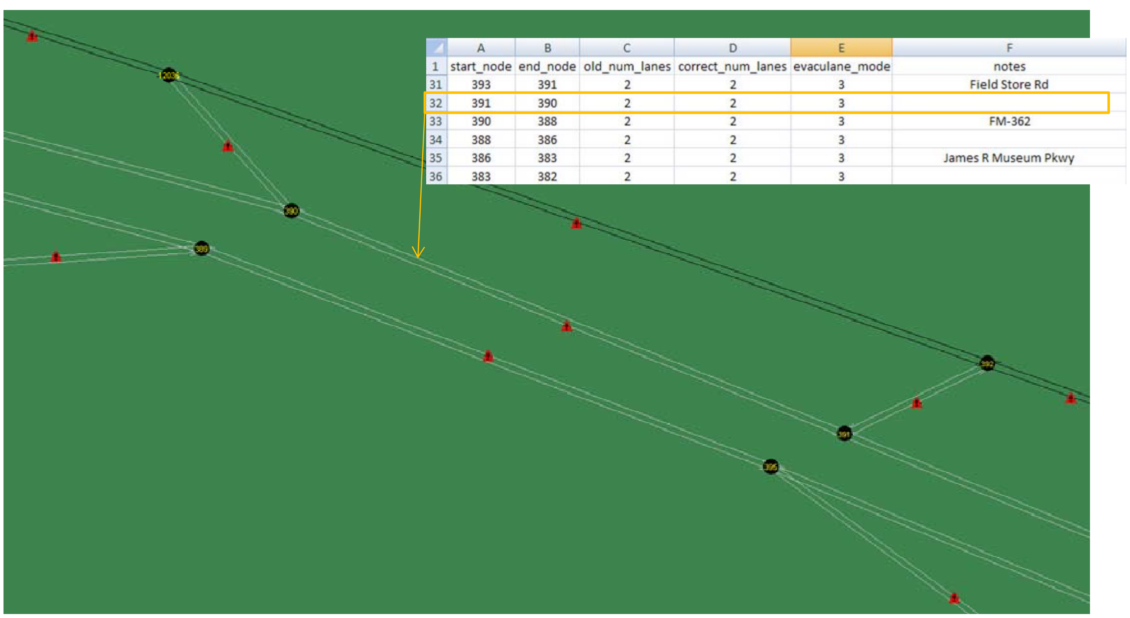


Figure 33. Representation of Evaculane in DynusT.

The contraflow operation is represented in DynusT by coding a redundant bidirectional link for every pair of nodes along the mainlanes of all three major evacuation routes (US 290, I-10, and I-45). Figure 34 shows the representation of base case versus contraflow case in the

DynusT. Every pair of nodes has bidirectional links. Under the normal operation [see Figure 34 (a)], the southbound link of the northbound direction and the northbound link of the southbound direction are closed to the traffic. To convert this into a contraflow mode with all traffic going northbound, the southbound link in Figure 34 (b) must be closed and the northbound link must be opened instead. To implement this in DynusT, the researchers placed a set of incidents on appropriate links to replicate the closing of the links to the traffic. Configuration files consisting of a set of incidents for each evacuation strategy were created to model both the normal and contraflow operation on the three major evacuation routes.

For each pair of nodes that bidirectional links were created, a set of incidents to be placed onto the network consists of three types:

- Links that are always closed to the traffic.
- Links that are closed only during normal operation.
- Links that are closed only during contraflow operation.

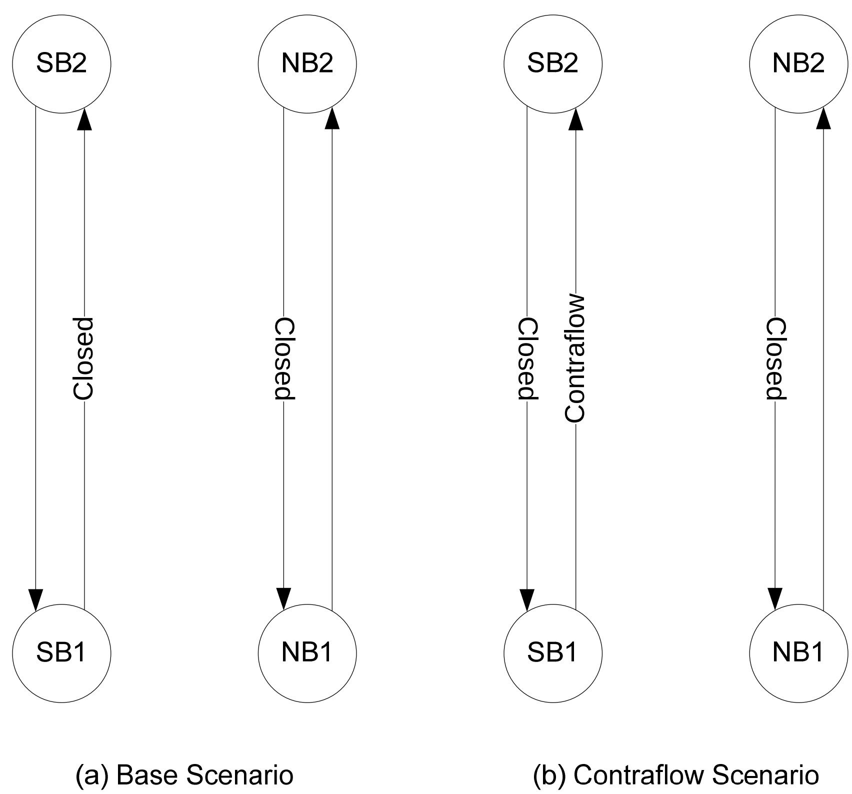


Figure 34. Contraflow Coding Scheme.

Simulation Runs

Background and evacuation traffic are the two types of travelers modeled in this study. Both traffic patterns are modeled after the original-destination trip table calibrated for the previous Hurricane Rita evacuation study. These two types of traffic behave differently when choosing the travel paths during evacuation. The background traffic refers to those trips made as part of daily routines (e.g., commuter and grocery trips). These travelers have the knowledge of alternative routes and will seek paths that reduce travel time. Once the traveler has reached the user equilibrium, the travel path becomes the habitual path. On the other hand, evacuation traffic relies on pre-trip best path information (i.e., knowing in advance which roads are closed and thus choosing the best path to avoid the congestion at the time of departure). DynusT can model multiple user classes to represent different travel behavior and responses. To replicate these two travel behaviors, the background traffic is modeled as Class 3 or User Equilibrium (UE) and the evacuation traffic is modeled using Class 5 or Pre-Trip Information.

The simulation run procedure for each scenario can be summarized as follows:

- Set the demand level and evacuation strategy corresponding to each scenario described in Table 25.
- Set the background demand as User Class 3 (UE) and the evacuation demand as Class 5 (Pre-trip information). Use passenger car for User Class 3 and truck for User Class 5. Use "Demand OD Matrix" as a vehicle generation mode.
- Run the simulation using one-shot assignment.
- After the one-shot simulation, "output_vehicle.dat" and "output_path.dat" files will be generated. The "output_vehicle.dat" file will be reused and therefore has to be renamed as "vehicle.dat". The "output_path.dat" can be ignored in this step.
- Modify the vehicle class in the "vehicle.dat" file by changing all the Vehicle Class from "Truck" to "Passenger Car."
- Check the "parameter.dat" file to make sure that "Keep Vehicle Cls = 1."
- Re-run the scenario using 15 iterative runs and "vehicle.dat" as a demand generation mode. This step takes approximately 4 days.
- Both "output_vehicle.dat" and "output_path.dat" from iterative runs will be reused in the next step. Therefore, rename these two files to "vehicle.dat" and "path.dat," respectively.
- Post-process the outputs from iterative runs by performing quality assurance check and probe vehicle insertion on the simulation outputs.
    - Quality Assurance Check: Currently DynusT cannot run using "vehicle+path" input mode if the vehicle path is greater than 280 nodes. This bug is still not fixed in the latest version. Therefore, the researchers need to run the data clean-up utility tool to remove the vehicles with the paths greater than 280 nodes and their corresponding paths from both "vehicle.dat" and "path.dat" files.
    - Probe Vehicle Insertion: Insert probe vehicles with pre-specified paths into the network at fixed time intervals to obtain true travel times from the simulation run. The probe insertion tool modified the "vehicle.dat" and "path.dat" files.
- Re-run the simulation using one-shot assignment and "vehicle+path" as a demand generation mode. This procedure will help get the true travel times from the probe vehicles on the pre-determined routes. This step takes approximately 2 hours.
- Post-process the simulation output files to extract the performance measures. The extracted measures are discussed in the next section.
- Repeat the procedure for all the scenarios.

Performance Measures

Two types of performance measures are considered in this study—regional measures and facility-based measures. The regional measures consider the overall performance of the network for the entire region. The facility-based measures focus on the performance of specific evacuation routes, which are US 290, I-10, and I-45 in this study. Both types of measures are described in Table 26 and Table 27, respectively. The outputs from the simulation runs were post-processed to extract both types of performance measures. The results are discussed in the next section.

Table 26. Regional Performance Measures.

Measures	*Description*
Average evacuee travel time	The average time it takes for all evacuees in the network to complete the trips regardless of their ODs.
Evacuation trips completed	The number of evacuation vehicles that reach the destination within the given time frame.

Table 27. Facility-Based Performance Measures.

Measures	*Description*
Travel speed	The travel speed on a facility is obtained by dividing the extracted travel time of each vehicle with the route distance, and averaged across all the vehicles extracted. All the vehicles that travel through the nodes specified in the routes are included in the calculation. The probe vehicles inserted into the network ensure that there exists adequate sample size of vehicles on every time interval of the route of interest.
Speed contour	Speed contour is a two-dimensional color-coded diagram with the time scale on a horizontal axis and a distance scale on a vertical axis. The color-coded scheme represents the average speed of vehicles observed at a particular point and time observed from a simulation run. Speed contour is useful for identifying time, location, and the extent of congestion on the evacuation route of interest.
Speed variation	Speed variation is defined as a coefficient of variation of travel speed, which is equal to the standard deviation of travel speed divided by average speed. Speed variation can be used a surrogate measure of accident risk on freeway. Higher speed variation generally indicates a higher risk of accidents due to the instability of traffic flow (e.g., stop-and-go traffic conditions) which either incidents or congestion may cause.

SIMULATION RESULTS

Database

The results from each simulation scenario were populated using MS Access database format. The purpose of the simulation database is twofold. First, the database is designed to simplify the process of querying the simulation outputs for subsequent modeling and analysis. Second, the database is designed for subsequent changes and expansion of modeling scenarios. The analyst can simply update any changes in the simulation outputs as well as add results from new simulation scenarios with minimal effort.

Demand Summary

Table 28 summarizes the number of vehicles generated under each demand scenario. The number of evacuation and background vehicles is also reported separately. Note that the level of demand under the HI scenario represents those occurred in the 24-hour period at 84 hours prior to the landfall of Hurricane Rita. The total number of vehicles reduces when the evacuation demand is higher because it is assumed that the background activities will be less under the scenarios where high evacuation demand is anticipated.

Table 28. Demand Summary.

Demand Scenario	*Evacuation Vehicles*	*Background Vehicles*	*Total Vehicles*
LO	200168	3291856	3492024
MD	300285	2908544	3208829
HI	398748	2530937	2929685
SH	498248	1894154	2392402

Both regional and facility-based performance measures were extracted from all the 16 scenarios.

Regional Performance Measures

Average Network-Wide Travel Time

The average travel times of evacuation and background vehicles are summarized using box plots shown in Figure 35 and Figure 36, respectively. The average evacuation travel times of all vehicles range from 3 to 5 hours depending on the demand and supply scenarios. Figure 35 shows a steeper slope pattern with the changes in the levels of demand, which indicates the demand level has more significant influence on the average evacuation travel time than the level of supply (evacuation strategies). In addition, the mean background travel times in Figure 36 vary only slightly with the supply scenarios. This implies that the background traffic conditions are less likely to be impacted by the evacuation strategies deployed.

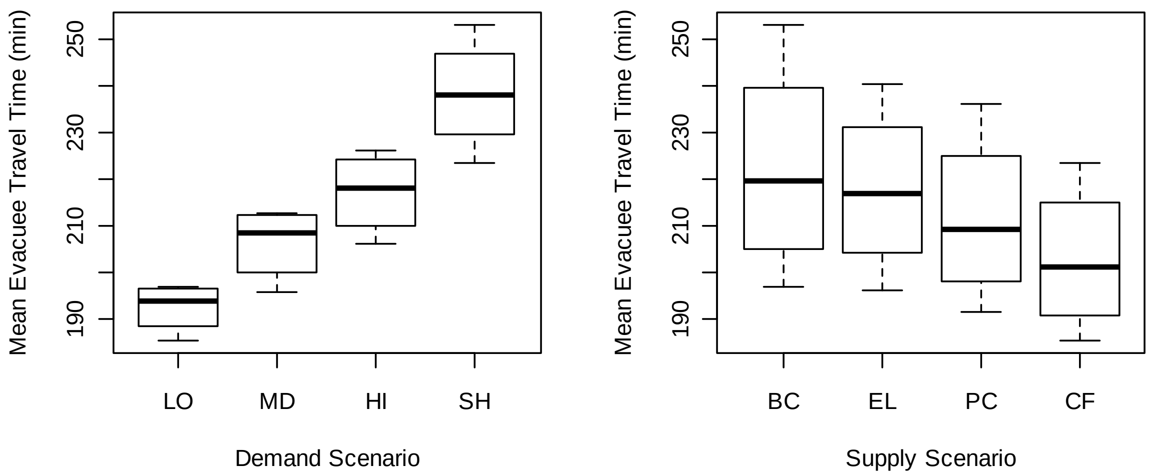


Figure 35. Mean Evacuation Travel Time.

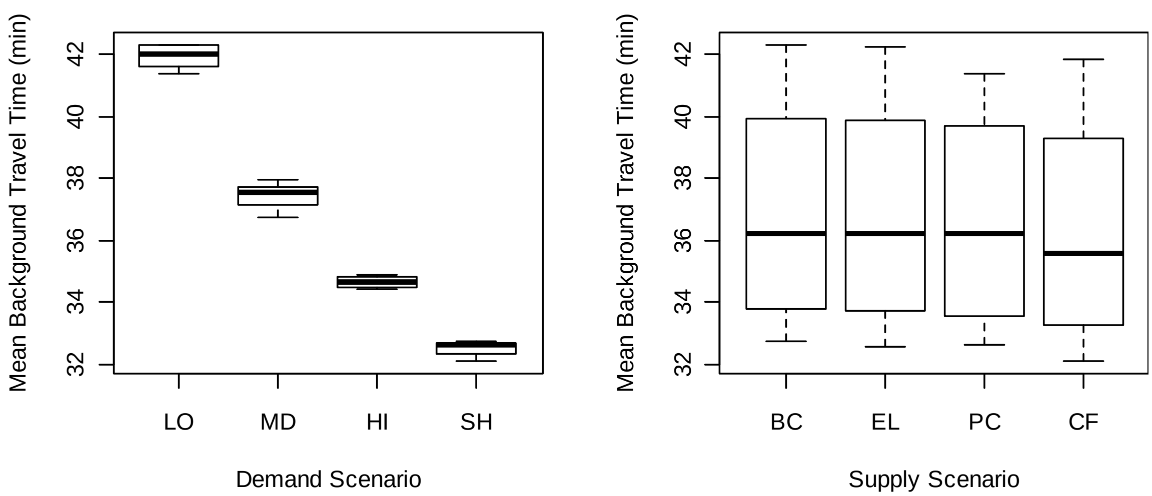


Figure 36. Mean Background Travel Time.

Table 29 shows the percentages of savings in average evacuation travel time with respect to the base travel time when an alternative evacuation strategy is implemented. For example, under moderate demand (MD) level, the average travel time for all evacuation vehicles to leave the HGAC area is 213 minutes based on normal operation (i.e., neither evaculane nor contraflow is deployed). At the same demand level, the expected travel time savings is 3.9 percent for all evacuation vehicles if the partial contraflow is implemented. This reduction in travel time could be significant, considering that this is the average saving for all vehicles that evacuated during the 24-hour period. The use of percentages instead of exact figures enables the prediction where decision makers have a reason to believe the base travel time might be different than the estimates provided.

Table 29. Average Evacuation Travel Time Savings (%).

Demand Level	*BC TT (min)*	*EL*	*PC*	*CF*
LO	197	0.5%	2.9%	5.9%
MD	213	0.3%	3.9%	8.0%
HI	226	2.0%	5.4%	8.8%
SH	253	5.0%	6.7%	11.7%

Network-Wide Travel Time Profile

Figure 37 shows the dual peak patterns for the evacuation vehicle travel time for all the demand levels, regardless of the evacuation strategies deployed. The peak-and-valley patterns are more apparent at higher demand levels. The travel time profiles also reveal that peak travel times can be reduced significantly when high-capacity evacuation strategies such as PC and CF are deployed. The amount of reduction increases with the demand levels. Note that the high demand scenario (HI) resembles the demand level experienced from Hurricane Rita evacuation. The average evacuation travel time at the peak was approximately 6.5 hours under the base case. The corresponding figure reduced by 30 to 60 minutes when full contraflow (CF) strategy is implemented. These estimated figures may appear to be lower than those reported from Hurricane Rita's experience because (a) the network conditions in the model have been upgraded to reflect the expanded US 290 and the completion of evaculane on along I-10 and US 290 and (b) the network conditions are assumed to be incident-free throughout the entire 24-hour modeling period.

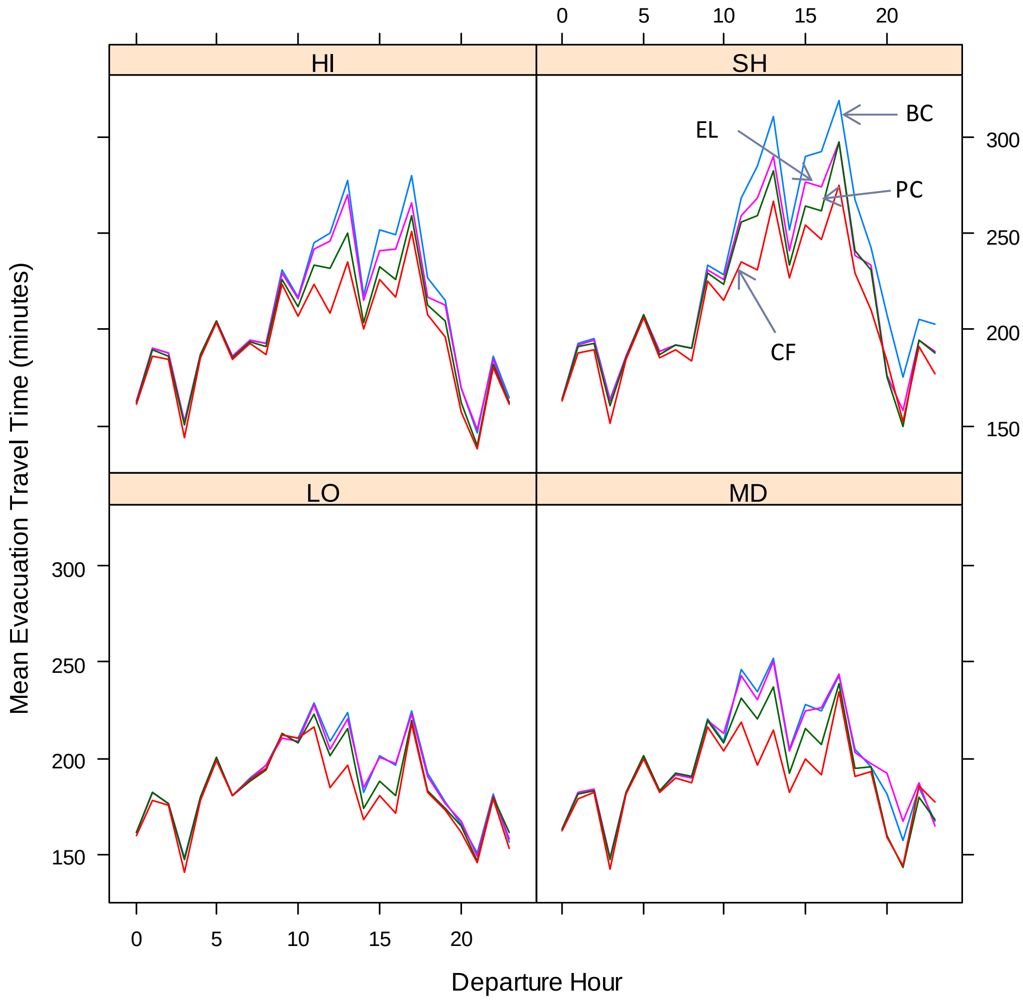


Figure 37. Evacuation Travel Time Profile.

Evacuation Trips Completed

For the 24-hour period, Figure 38 shows that the differences in the number of evacuation trips completed across different evacuation strategies are negligible. The left figure shows the absolute number of evacuation trips completed, while the right figure shows the evacuation trips completed as percentages of total evacuation demand. The small differences observed here implied that the network has sufficient capacity to handle the all levels of evacuation demand over the 24-hour period. The peak-and-valley pattern observed from the evacuation travel time profiles is a result of the fact that the traffic demand does not spread out evenly over the entire period. Figure 39 shows the cumulative difference in the number of evacuation trips completed over time. In this case, the benefits from implementing high-capacity evacuation strategies become more obvious as the demand level increases.

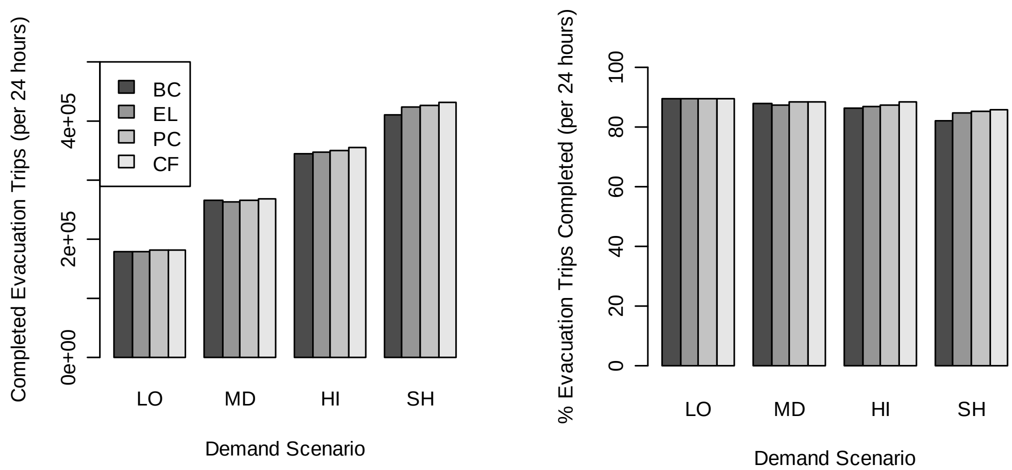


Figure 38. Evacuation Trips Completed.

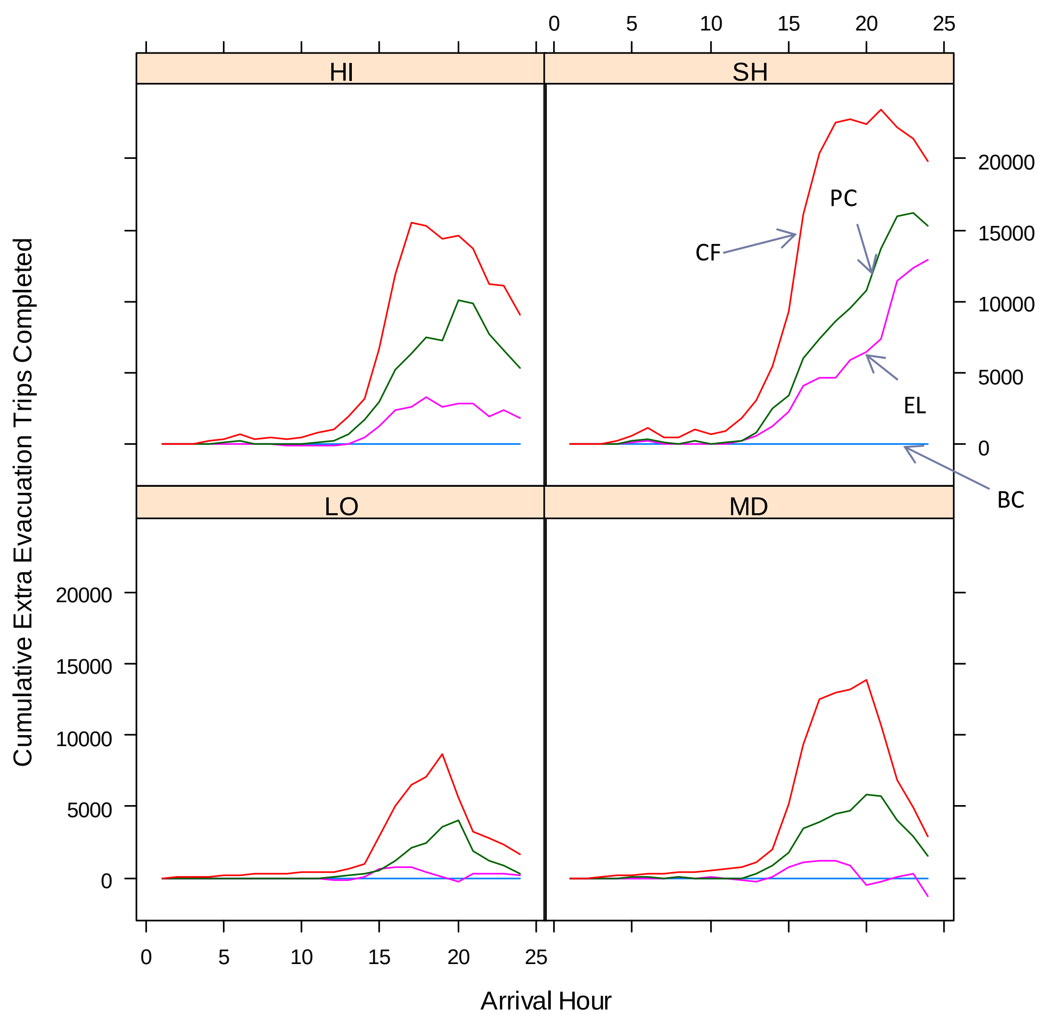


Figure 39. Cumulative Extra Number of Evacuation Trips Completed.

Facility-Based Performance Measures

The regional performance measures describe the network conditions by aggregating the data from all evacuation vehicles, regardless of their travel paths. The facility-based performance measures, on the other hand, focus on the travel conditions on specific evacuation routes, which are US 290, I-10, and I-45 in this study. To evaluate the impacts on evacuation routes, the researchers utilized only the travel times collected from vehicles with the travel paths on each of these three freeways. These vehicles also include the probe vehicles inserted into the network. The probe vehicles were placed into the network with pre-assigned paths at fixed intervals. This addressed the problem where travel time data can be missing on some intervals because no vehicles completed the trip using that specific path. Since the lengths of these routes are unequal, the travel times were converted into travel speed by dividing by the corresponding length of the route to facilitate the comparison.

Speed Profiles

Figure 40 displays the speed profiles over the 24-hour period on US 290, I-10, and I-45. Each block consists of four lines representing four supply scenarios (BC, EL, HI, SH). The visual analysis of these profiles reveals the following:

- I-45 is the most congested freeway among the three routes, regardless of the demand/supply scenarios. This is because of the bottleneck from the construction between Huntsville and Conroe.
- US 290 is the least congested route among all three. The speed drops on US 290 also did not last for an extended period compared to other routes.
- The benefit from EL strategy on all routes is minimal under low demand conditions. The EL strategy can significantly alleviate the congestion on US 290 and I-10 when the demand is moderate or higher.
- The results also suggest that the benefit gained from implementing contraflow versus evaculane on I-10 and US 290 may be minimal. Evaculane strategy is likely to provide acceptable capacity on these two routes even under high demand conditions.
- The results on I-45 suggest that partial contraflow can provide tangible improvement under moderate demand condition or higher. The full contraflow is still the best strategy for I-45 as it helps reduce both the scale and the extent of the speed drop. However, the improvement in travel condition does not appear to be significant when compared to those achieved from the partial contraflow strategy.

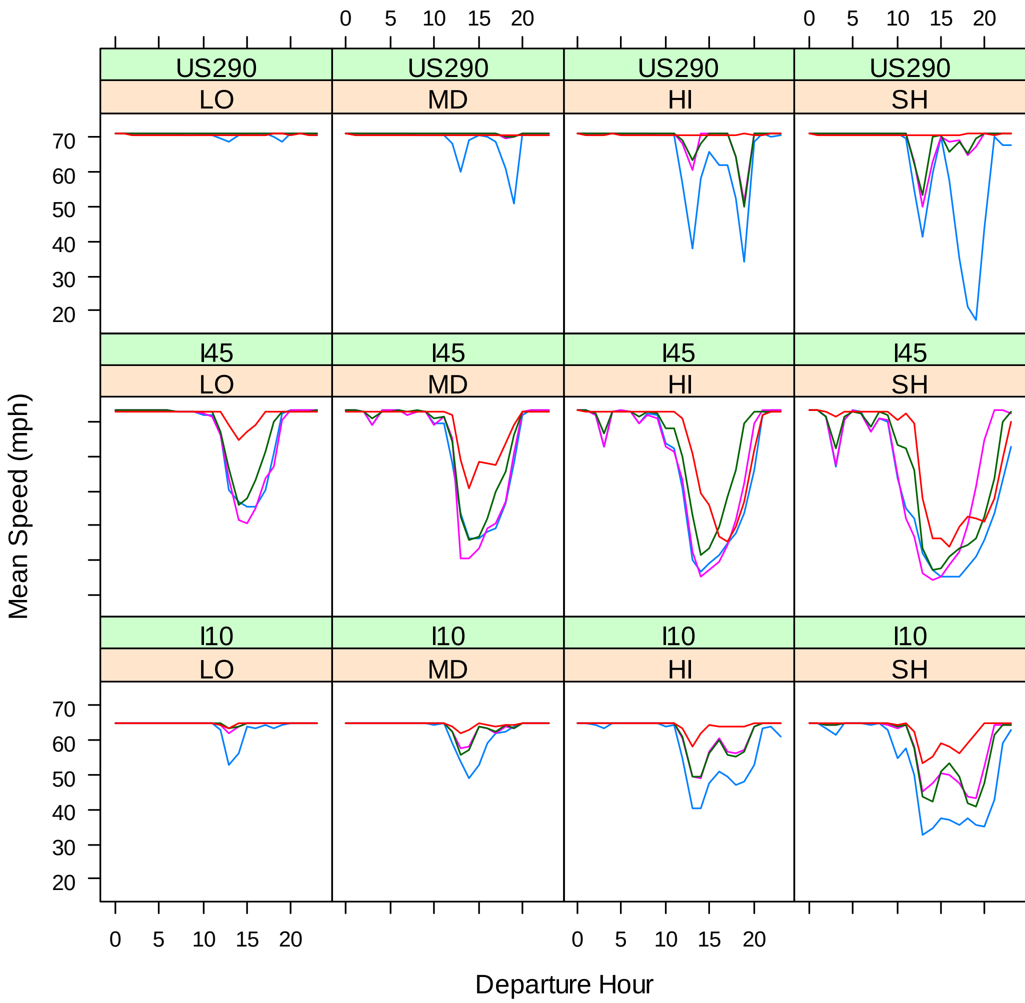


Figure 40. Speed Profiles on US 290, I-10, and I-45.

Speed Contour

The speed contours are plotted for each route (US 290, I-10, and I-45) for all 16 scenarios. The total of 16×3 = 48 speed contours was prepared as part of the simulation result database. The analyst can refer to these speed contours to identify the location, time, and extent of the congestion on each route from implementing any evacuation strategies. Figure 41 and Figure 42 show the examples of speed contours on I-45 under the base case versus the full contraflow scenario under high demand condition.

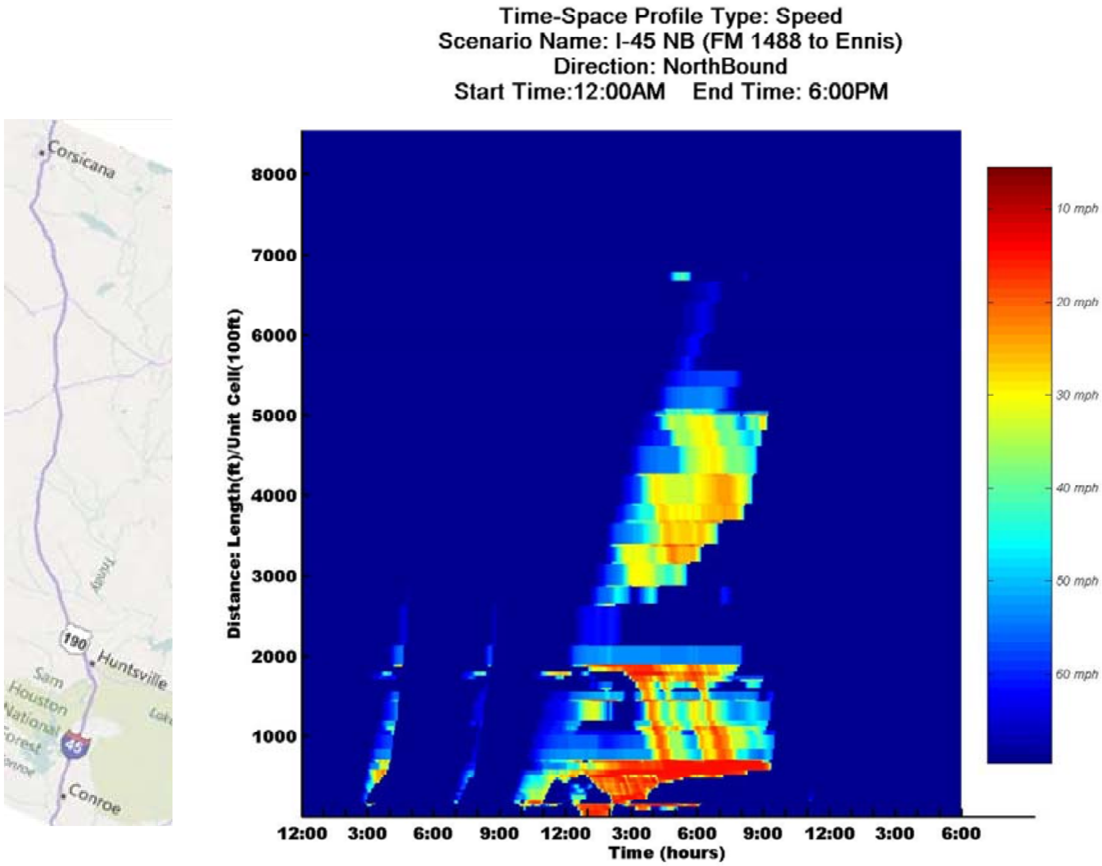


Figure 41. Speed Contour Example on I-45 (BC_HI).

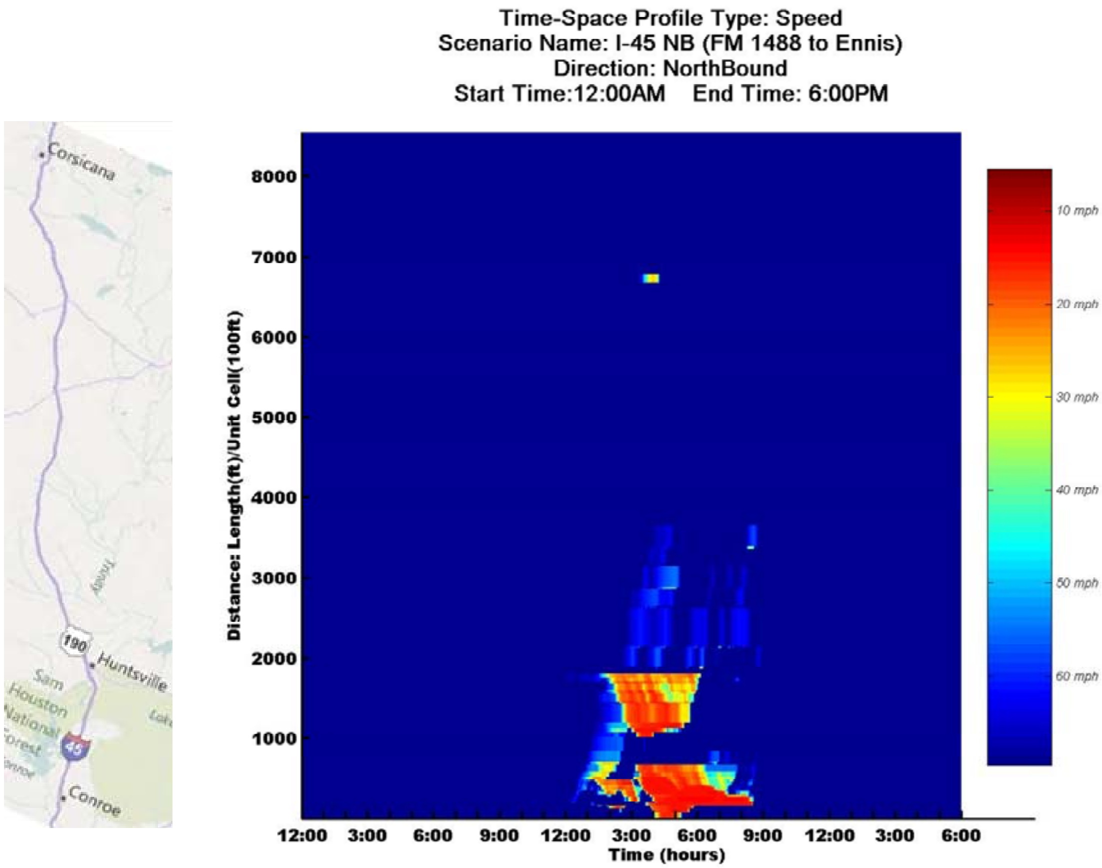


Figure 42. Speed Contour Example on I-45.

PROTOTYPE PREDICTIVE MODELS

The results from the simulation model were used to develop predictive models for providing quantitative assessment of Houston-Galveston traffic conditions as a result of evacuation. The researchers calibrated the linear regression models for predicting the travel time and speed during evacuation under different demand scenarios and evacuation strategies. These prototype models can provide the required predictions for both regional and facility-based levels.

Regional Performance Models

The analyst can use Equation 13 to predict the average evacuation travel time under the base case. The power of 2 used in the model is an empirical correction to improve the overall goodness-of-fit of the model. To predict the average evacuation travel time for alternative evacuation strategy, the analyst can use Equation 14 to estimate the travel time savings with respect to the base case value.

Prediction of Evacuation Travel Time

$$T_{Avg,BC} = 187.25 + 2.6191\left(\frac{D_E}{10000}\right)^2 \tag{13}$$

where

$T_{Avg,BC}$ = Average travel time of all evacuation vehicles (minutes); and

D_E = Expected evacuation demand over 24-hour period for the Houston-Galveston region (vehicles). D_E should be between 100,000 and 600,000 vehicles.

$$\underset{(\%)}{\Delta T} = \left(0.6419 S_{EL} + 1.3502 S_{PC} + 2.3995 S_{CF}\right)\frac{D_E}{10000} \tag{14}$$

where

ΔT = Percentage of savings in average travel time compared against the base case. Note that $\Delta T = 0\%$ for the base case;

S_{EL} = 1 if supply scenario is evaculane, 0 if otherwise;

S_{PC} = 1 if supply scenario is partial contraflow; 0 if otherwise;and

S_{CF} = 1 if supply scenario is full contraflow; 0 if otherwise.

$$T_{95th,BC} = 315.83 + 7.0818\left(\frac{D_E}{10000}\right)^2 \tag{15}$$

where

$T_{95th,BC}$ = 95th percentile travel time of all evacuation vehicles (minutes).

Facility-Based Performance Models

The analyst can use Equation 16 to predict hourly average speed on US 290, I-10, and I-45. The functional form of Equation 17 is a modification of the widely-used Bureau of Public Roads (BPR) volume-delay function. D_E/C ratio approximates the volume-to-capacity (v/c) ratio, which in this case corresponds to the ratio of evacuation demand to route capacity for a given evacuation strategy.

Prediction of Speed Profiles

The equation for predicting average speed on route *i* at hour *j* is of the following form:

$$V_{ij} = \frac{V_f}{1 + \exp\left(\alpha_{ij} + \beta_{ij} \ln \frac{D_E}{C}\right)} \tag{16}$$

where

V_{ij} = Average speed (mph) of all vehicles traveling on route *i* at hour *j*. Route *i* refers to one of the three major freeways evaluated in this study, i.e., US 290, I-10 and I-45. Hour *j* ranges from 1 to 24 (24-hour prediction period);

V_f = Free-flow speed (mph). V_f is set at 72.6 mph, which is the maximum hourly average speed observed from the simulation study;

D_E = Expected evacuation demand over 24-hour period for the Houston-Galveston region (vehicles);

C = Approximate ratio of the expected supply capacity to the base case capacity; and

α_{ij}, β_{ij} = Model coefficient estimates from the regression analysis of simulation results. The coefficients were calibrated separately for each route *i* and hour *j*.

To illustrate how to estimate the value of *C*, consider the capacity of US 290 evacuation route as an example. Under the base case, the capacity is best approximated by the narrowest segment (a bottleneck that restricts traffic flow), which is a two-lane-wide segment. Now, consider the evaculane (EL) as an alternative strategy. This strategy would add one de facto travel lane to this route. Therefore, the *C* ratio can be estimated as 3/2 = 1.5. The values of *C* for the scenarios evaluated in the simulation study are suggested in Table 30. The *C* values for PC and CF strategies on US 290 and I-10 are 2.5 because evaculane is assumed to be activated on the reversed lanes as well.

Table 30. Suggested *C* Values.

Route	*Evacuation Strategies*			
	BC	EL	PC	CF
US 290	1.0	1.5	1.5	2.5
I-10	1.0	1.5	1.5	2.5
I-45	1.0	1.5	1.5	2.0

To illustrate, assume that the analyst wishes to predict the speed on I-45 at 3 p.m. if the PC strategy is implemented. The calibrated values of α_{ij} and β_{ij} for I-45 at 3 p.m. are −18.04 and 1.45, respectively. The suggested C value for PC strategy on I-45 is 1.5 (Table 30). Therefore, the general form of the model for predicting the average travel speed on I-45 at 3 p.m. can be written as:

$$V_{\text{I-45,3PM}} = \frac{72.6}{1+\exp\left(-18.04+1.45\ln\frac{D_E}{1.5}\right)} \tag{17}$$

Spreadsheet-Based Example

The prototype predictive model is currently implemented in a spreadsheet-based format using MS Excel (see Figure 43). The analyst only needs to enter the expected evacuation demand. The prediction includes the evacuation travel time region-wide as well as the hourly average speed profiles on US 290 and I-45. The current version is built on the results of the 16 modeling scenarios, which do not consider the variation in the background demand and the capacity-restricted events such as lane-blocking incidents. It is recommended that these factors be considered in the implementation phase. The implementation strategy is described in the next section.

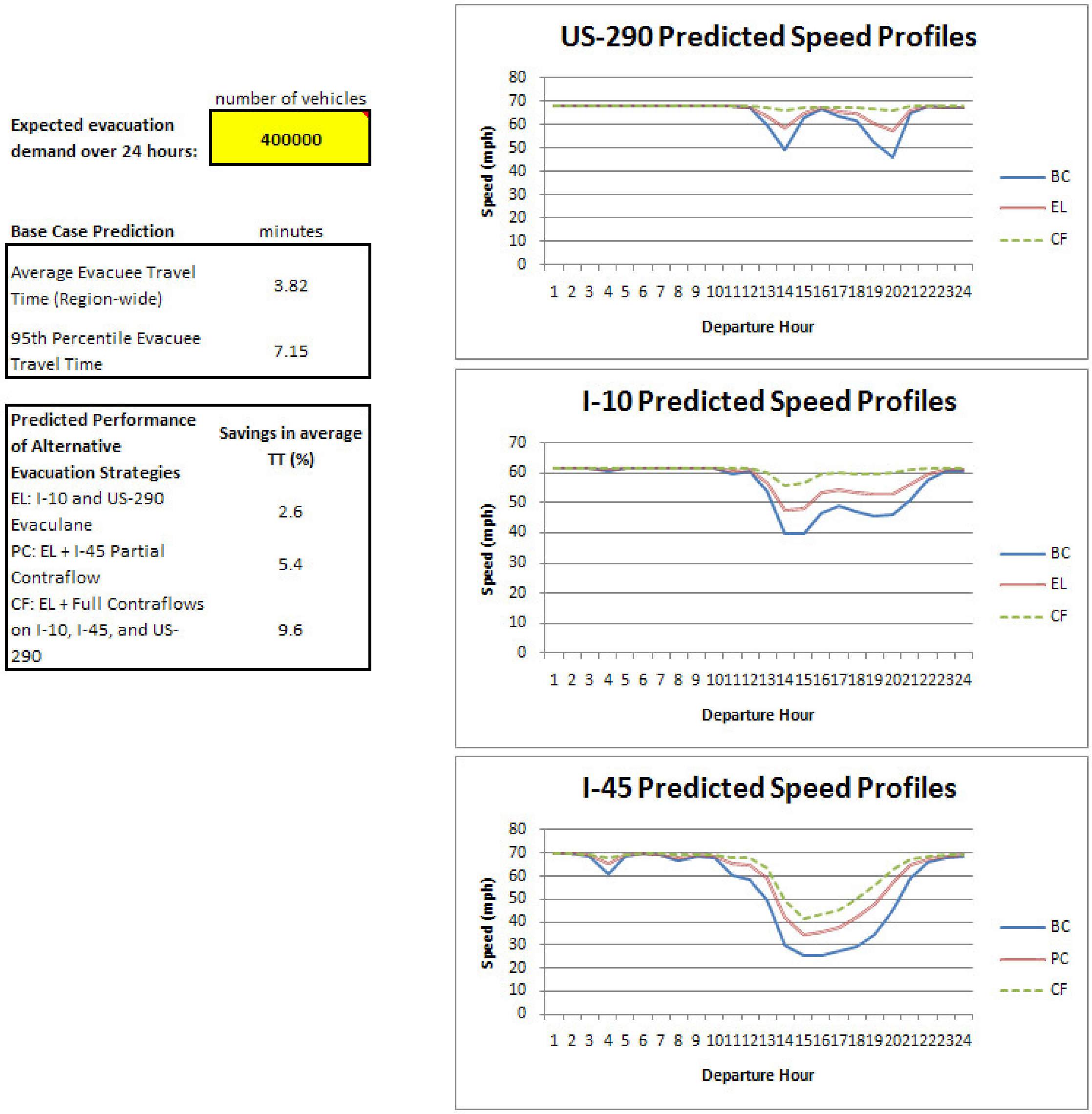


Figure 43. Spreadsheet-Based Prediction Tool.

IMPLEMENTATION PLAN

In the first stage, the team will enhance the existing prototype model for the Houston-Galveston region and implement the model in the web-based environment. Specifically, the team will perform the following tasks for the Houston-Galveston region:

- Expand the model scenarios.
- Incorporate the results from the new scenarios into the existing models.
- Implement the updated model in the web-based environment.

In the second stage, the team will implement and deploy a predictive evacuation model for the Corpus Christi region using the same type of modeling development and framework developed for the Houston-Galveston region. The team will perform the following tasks for the Corpus Christi region:

- Develop the base model.
- Perform simulation evaluation runs.
- Calibrate the predictive models using the results from the simulation.
- Implement the updated model in the web-based environment.

The details of the tasks are described in the subsequent sections.

Expand Simulation Scenarios

As part of a future implementation phase for this project, the team will propose an expansion of the DynusT models beyond the 16 scenarios developed in the project 0-6121 to address the impacts of background demand levels and capacity-restricted events such as lane-blocking incidents. The team will prepare the base model for additional runs using the utility tools developed in the project 0-6121. The simulation model requires specific computing hardware and each run takes approximately four days to complete. Our current capability to run and process the simulation models is approximately four scenarios per week. With the time and resource constraints in mind, the team will carefully design and execute the additional simulation runs using appropriate experimental design technique. The additional factors to be considered are:

- Capacity-restricted events on I-10, US 290, and I-45.
- Levels of background demand.

To illustrate the time requirement, if we consider three different capacity-restricted events and two levels of background demands on the existing 16 model scenarios, a full factorial design would require a total of $16 \times 3 \times 2 = 96$ simulation runs or approximately six months. Other experimental design schemes such as fractional factorial design could be utilized if needed with some trade-offs in the prediction power of the models.

Update Existing Predictive Models

The current version of the prototype predictive models is based on a limited number of scenarios. With the expanded model scenarios, the models will be updated to provide better prediction. Both regional and facility-based performance models will be recalibrated using the model constructs developed in the project 0-6121.

Implement the Updated Models in the Web-Based Environment

The project 0-6121 has already developed a web-based decision support tool to help with the contraflow decision. The current web-based tool is based on the rankings of qualitative decision factors gathered from multiple rounds of surveys. The team will enhance the current web-based tool with the updated predictive models from the previous step. This predictive model will complement the existing qualitative decision support tool by providing quantitative performance assessment of different evacuation strategies given expected traffic demand levels and network conditions.

CHAPTER 14:
CONCLUSION

Based on all of the work presented previously, it is the consensus of the research team and PMC that a solid foundation and starting point has been created. Stated alternatively, a very good prototype tool has been developed, and the primary goal of this research project has successfully been met.

That said, this tool is not ready for widespread implementation. As an example, 16 different scenarios were modeled and tested as part of this research. While this was a good starting point, and several of the scenarios were selected and/or otherwise constructed to simulate past hurricane evacuation scenarios (i.e., Hurricane Rita and Hurricane Ike), these events are rarely (if ever) very similar. A much broader range of scenarios will need to be developed and examined (and the decision support tool further tested for those scenarios) before there is a reasonable level of confidence that the new tool can be used on a widespread basis.

In addition, the case study/region used for this research was specifically the Houston-Galveston area. The PMC believes that other Texas coastal regions could benefit from this tool as well. Since populations, roadway infrastructure, and available data (to name just a few relevant factors) vary widely from region to region, additional background work would be needed in these other geographic areas prior to implementation. Accordingly, it is recommended that the aforementioned work to examine applications of this tool along all significantly populated areas of the Texas coast move forward as part of the TxDOT Research Implementation Program.

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