THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

TECHNICAL REPORT 0-7123-1
TxDOT PROJECT NUMBER 0-7123

Define a Statewide Plan for a Sustainable Real-Time Travel Time Network for Texas Hurricane Evacuations and Safe Citizen Return

Kyle Bathgate
Lu Xu
Kangni Jiang
Jingran Sun
Jake Robbennolt
Shidong Pan
Zhe Han
Michael Murphy
Stephen Boyles
Zhanmin Zhang
Randy Machemehl

January 2024
Published August 2024

https://library.ctr.utexas.edu/ctr-publications/0-7123-1.pdf

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-24/0-7123-1		

4. Title and Subtitle	5. Report Date
Define a Statewide Plan for a Sustainable Real-Time Travel Time Network for Texas Hurricane Evacuations and Safe Citizen Return – Final Report	Submitted: January 2024 Published: August 2024
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Kyle Bathgate, Lu Xu, Kangni Jiang, Jingran Sun, Jake Robbennolt, Shidong Pan, Zhe Han, Michael Murphy, Stephen Boyles, Zhanmin Zhang, Randy Machemehl	0-7123-1

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Center for Transportation Research The University of Texas at Austin 3925 W. Braker Lane, 4th Floor Austin, TX 78759	11. Contract or Grant No. 0-7123

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Implementation Division 6230 E Stassney Lane Austin, TX 78744	Technical Report September 2021 – January 2024
	14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract

Texas coastal areas are prone to hurricanes, which pose a threat to life, public safety, and critical infrastructure. Mass evacuation can be ordered to relocate residents to safety areas in advance of a hurricane. Access to accurate real-time traffic information can aid public agencies with evacuation operations and evacuees with decision making. To ensure that the Texas Intelligent Transportation System (ITS) can sufficiently assist with evacuation travel, this study examines the existing state of the system and proposes methods that can be used to study potential ITS expansion. A detailed survey was conducted amongst Texas residents to understand how they use real-time traffic information during evacuations. A hurricane evacuation study simulation was implemented to identify critical links in the evacuation roadway network that may benefit from ITS device deployments. Asset management methods were employed to prioritize ITS device location alternatives, and a life cycle cost assessment was performed to estimate the installation and maintenance costs of devices under various scenarios. Finally, recommendations are provided to enhance the resilience of the information transfer system. The findings of this study provide TxDOT with a better understanding of the existing issues regarding a real-time traffic monitoring system during evacuations and provide methods that can be used to develop a comprehensive plan for improving ITS capabilities on evacuation routes in Texas.

17. Key Words	18. Distribution Statement
Hurricane evacuation, real-time traffic monitoring, intelligent transportation systems, resilience, network modeling, asset management, life cycle cost assessment	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	149	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Define a Statewide Plan for a Sustainable Real-Time Travel Time Network for Texas Hurricane Evacuations and Safe Citizen Return – Final Report

Kyle Bathgate
Lu Xu
Kangni Jiang
Jingran Sun
Jake Robbennolt
Shidong Pan
Zhe Han
Michael Murphy
Stephen Boyles
Zhanmin Zhang
Randy Machemehl

CTR Technical Report:	0-7123-1
Report Date:	Submitted: January 2024
Project:	0-7123
Project Title:	Define a Statewide Plan for a Sustainable Real-Time Travel Time Network for Texas Hurricane Evacuations and Safe Citizen Return
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
3925 W. Braker Lane, 4th floor
Austin, TX 78759

http://ctr.utexas.edu/

Disclaimers

Author's Disclaimer: 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 Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Research Supervisors: Stephen Boyles, Zhanmin Zhang

Acknowledgements

The research team is grateful to Wade Odell and Darrin Jensen (TxDOT RTI), Ugonna Ughanze (TxDOT Houston District), Valerie Taylor (TxDOT/Houston TranStar), America Garza (TxDOT Corpus Christi District), Camille Marek (TxDOT Yoakum District), Abderrahmane Maamar-Tayeb (TxDOT Design Division, Hydraulics Section) for their project guidance. The research team would also like to thank the TxDOT employees who participated in the workshops and interviews and who provided us with valuable information and data that was integral to the success of this project. Finally, the researchers would like to thank the Texas Department of Public Safety (DPS) for their participation and assistance.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Background

Hurricane events pose many challenges for transportation systems; one of which is the evacuation of large population centers. In Texas, large-scale evacuations are relatively infrequent yet have occurred numerous times in recent decades. An infamous example is Hurricane Rita, which made landfall near Texas in September of 2005. Officials in the Beaumont and Houston regions ordered a mass evacuation in an effort to save lives. It is estimated that over 2 million people evacuated prior to Rita's landfall (Knabb, Brown, & Rhome, 2006). The evacuation was so widespread that massive gridlock conditions occurred. Evacuees were left stranded on the roadways as vehicles ran out of gas and broke down, stopping the flow of traffic.

A key issue with evacuations is traffic congestion which results in longer travel times (Dow & Cutter, 2002). TxDOT has implemented measures to aid mass evacuation for hurricane events. The agency has designated routes as evacuation corridors in the eastern and coastal regions of the state. TxDOT has also equipped certain corridors with additional features, namely Evaculane and contraflow routes. Evaculanes are highway corridors that can use the shoulder as an additional travel lane. Contraflow routes are evacuation corridors where the "inbound" travel lane directions are reversed to increase the available roadway capacity. The implementation of contraflow lanes in the TxDOT hurricane evacuation plan occurred after the evacuation for Hurricane Rita (Ballard et al., 2008). Agencies may also open toll lanes during evacuations.

In addition to physical measures to increase capacity, TxDOT has implemented measures to increase the availability and accuracy of real-time information on Texas roadways using Intelligent Transportation System (ITS) devices. Accurate information regarding the real-time status of route congestion, traffic incidents, and other travel conditions helps officials better coordinate evacuation operations and helps residents decide when to evacuate or what route to take to their destination. Texas traffic management centers, such as TranStar in Houston, commonly use Pan-Tilt-Zoom (PTZ) Closed Circuit Television (CCTV) cameras to monitor the traffic conditions throughout the roadway network in real-time. Hurricane evacuation routes may be fitted with PTZ cameras and other sensors to track real-time traffic conditions along these routes (Borchardt & Puckett, 2008).

While data collection is important during evacuation events, evacuees must also be able to access the information. TxDOT provides an online webpage, called DriveTexas, to the public which offers real-time roadway condition and incident updates. DriveTexas provides information on evacuation routes and details on active Evaculane and contraflow roadways during an evacuation. TxDOT also operates dynamic message signs (DMS) along roadways as another measure to disseminate real-time traffic information to drivers during both regular operations and evacuation events.

Real-time traffic information collected by ITS devices and other traffic monitoring devices is one data source that traffic management officials may use to aid evacuation safety and efficiency. Therefore, sufficient investment into the technology used for real-time traffic monitoring is vital to ensure that future evacuation efforts have the resources needed to prevent congested evacuation corridors and preserve human life. Owing to the existing ITS network size, system age, and limited financial resources for system maintenance, technical and economic difficulties persist regarding the sustainable operation and future expansion of real-time traffic monitoring systems for evacuation monitoring and safe return in Texas.

1.2. Research Objectives

As real-time information plays a crucial role in evacuation events, it is pertinent to ensure that the ITS devices in evacuation corridors can adequately perform during hurricanes. Developing asset management strategies for the installation, maintenance, and operation of these devices is needed to improve future Texas hurricane evacuations. The existing level of implementation, user preferences for the usage of real-time data, and gaps in the current traffic monitoring system need to be understood to determine the most effective device deployment strategies.

The overall goal of this study is to evaluate the effectiveness of the existing Texas real-time traffic monitoring system and make recommendations for system expansion and upgrades, while also accounting for the costs and capabilities of the proposed system. Specific objectives are as follows:

- Determine the existing capabilities of the real-time evacuation monitoring system,
- Identify evacuation monitoring techniques employed by other state agencies, other US states, and other countries,
- Make recommendations for system improvement, by updating existing devices or installing new ones,
- Estimate costs for the proposed improvements and make recommendations on priority scheduling,
- Determine the maintenance and operating costs of the proposed improvements, and
- Develop recommendations for resilient communication during evacuation events.

1.3. Work Plan

To accomplish the research objectives, UT/CTR implemented a work plan consisting of seven main tasks. The work plan is organized into three phases: (1) data collection to further the understanding of the existing status and needed improvements of the hurricane evacuation traffic monitoring system in Texas, (2) asset management techniques to provide potential improvement strategy alternatives and maintenance budgeting plans, and (3) formulation of recommendations based on the project findings. Efforts to improve traffic monitoring operations as well as public information dissemination were investigated. UT/CTR performed extensive survey distribution and analysis as part of these efforts. Network simulation modeling was also conducted to identify critical evacuation route links. Numerous workshops were held with members of TxDOT to incorporate agency employee perspectives into the findings. Asset management techniques were used extensively to estimate future costs and budget requirements for the ITS devices. Figure 1.1 shows the structure of the work plan and project tasks. Each task comprises one chapter of this final report.

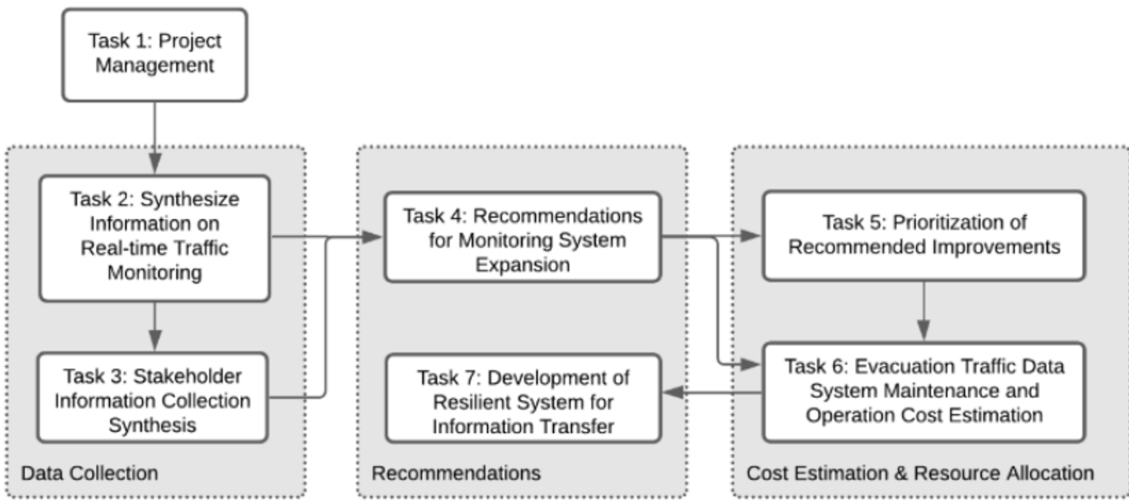


Figure 1.1: Structure of the project work plan and tasks

Chapter 2. Synthesize Information on Real-Time Traffic Monitoring

2.1. Introduction

The primary goal of this chapter is to collect and synthesize information from relevant sources regarding real-time traffic monitoring in evacuation events. This literature review focuses on three specific aspects, as follows:

- Examine existing real-time traffic monitoring systems for evacuations,
- Identify critical information needed during evacuations, and
- Review the implementation of innovative technology in evacuation monitoring systems.

To fully understand the current state of evacuation monitoring processes and technologies, the research team conducted a thorough review of existing resources and methods employed by the Texas Department of Transportation (TxDOT), other agencies in the state of Texas, other U.S. states, and other countries. In addition, the review focuses on identifying critical data needed by public officials and determining the necessary information for preparing and guiding evacuees in advance of and during an evacuation. Furthermore, the research team also examines how emerging technologies may be incorporated into the existing evacuation monitoring system. Finally, the data sources section contains information on the data sets pertinent to this project.

2.2. Existing Real-Time Traffic Monitoring in Evacuations

Prior to the 21st century, public planning agencies relied on the development and calibration of trip generation models, traffic departure time models, destination selection models, and traffic route assignment models to simulate large-scale evacuations. While these models are still being used to establish and revise plans and policies, traffic counting and vehicle surveillance technologies offer a great deal of promise in emergency management (Southworth, 1991). Since the 1990s, Intelligent Transportation Systems (ITS) have been developed and implemented in the United States. ITS primarily consist of a sensing system, a communication system, roadside units comprised of different types of sensors, a traffic signal control system, and a notification system that includes car navigation and alerts (Khalid et al., 2016). To perform real-time traffic monitoring, all of these systems should work seamlessly to direct people away from the disaster site efficiently and safely.

2.2.1. Methods Used by TxDOT

Texas has experienced numerous major hurricanes that caused substantial damage and loss of life. A critical aspect of the evacuation process is the efficient operation of the transportation networks. Following Hurricane Rita in 2005, the Texas Office of Homeland Security issued a report with specific suggestions for enhancing evacuation procedures and other elements of preparedness. To improve traffic control and management during a mass evacuation, former Governor Rick Perry directed TxDOT to coordinate with other emergency management agencies to develop several traffic control and management strategies, including developing contraflow plans, implementing solutions to reduce congestion, and prioritizing infrastructure projects along evacuation routes (USDOT & USDHS, 2006). The state of Texas has improved hurricane evacuation routes and developed various tools to enhance evacuation operations for its coastal regions (Ballard & Borchardt, 2006).

TxDOT is responsible for maintaining major evacuation routes for the five districts along the Gulf of Mexico coast: the Beaumont District, Corpus Christi District, Houston District, Pharr District, and Yoakum District (TxDOT, 2021). Figure 2.1 shows major evacuation routes, potential contraflow routes, and Evaculane routes planned in the five districts along the coast.

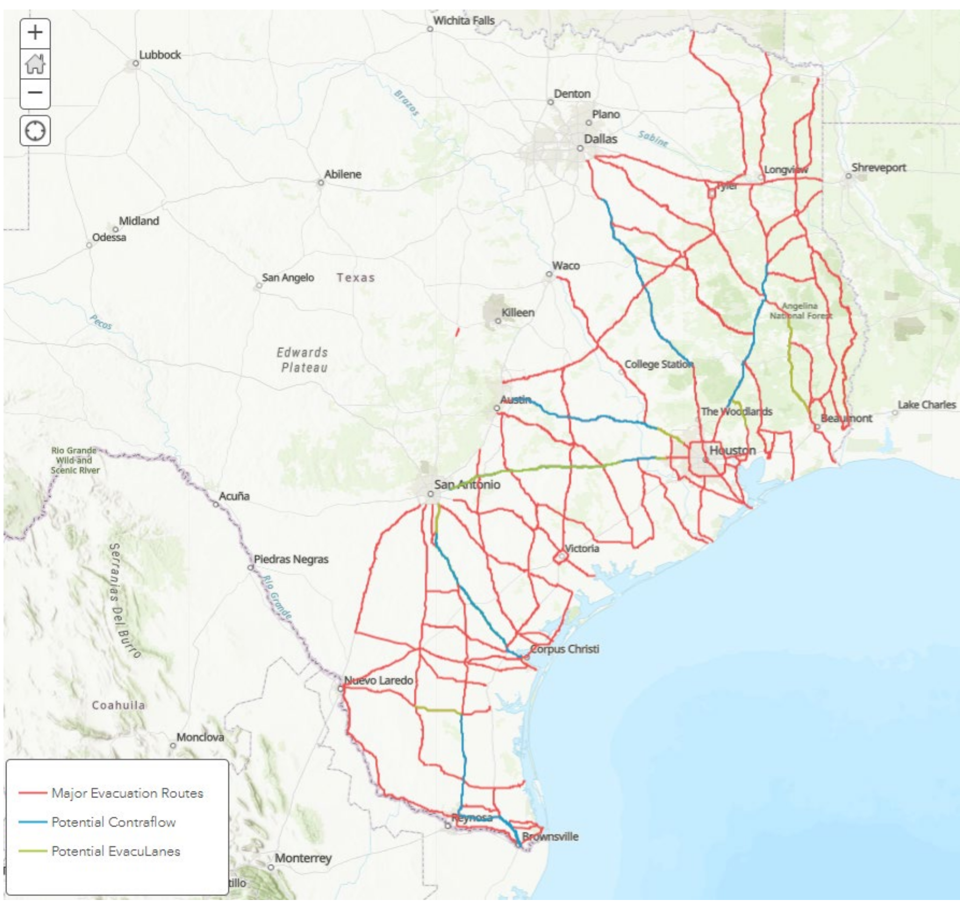


Figure 2.1: Map of major evacuation routes, potential contraflow routes, and Evaculane routes within Texas (TxDOT, 2016)

After the historic 2004 hurricane season, TxDOT conducted a research project to investigate traffic operation recommendations for hurricane evacuation regarding the development of contraflow, emergency shoulder lanes, traffic signals, ITS, and motorist information systems (Ballard & Borchardt, 2006). Following the 2006 report, Ballard et al. (2008) inventoried various ITS strategies that have been used and whose implementation was planned for four of the districts (Beaumont, Corpus Christi, Houston, and Yoakum District) by interviewing and surveying the public officials who had previously experienced hurricane evacuations. Table 2.1 presents a summary of plans and ITS deployments that have been developed and implemented.

Table 2.1 – Summary of strategies used by districts

Districts	Beaumont District	Corpus Christi District	Houston District	Yoakum District
Planning and Management Strategy				
ITS Implementation Plan	No	Yes	Yes	No
Traffic Management Center (TMC)	No	No	Yes	No
Existing Communication with Other State Agencies	No	Yes	Yes	Yes
Traffic Monitoring Strategy				
Automated Vehicle Identification	No	No	Yes	No
Vehicle Sensors	No	No	Yes	No
Closed Circuit Television (CCTV) Cameras	Yes	Yes	Yes	Yes
Traffic Flow Control Strategy				
Contraflow Lanes/Evaculane	Yes	Yes	Yes	Yes
Lane Control Signals	No	No	No	No
Ramps Meters	No	No	Yes	No
Information Disseminating Strategy				
Dynamic Message Signs (DMS)	Yes	Yes	Yes	Yes
Highway Advisory Radio (HAR)	No	No	Yes	No

It is crucial to achieve efficient and accurate real-time data collection and transmission during hurricane evacuations. TxDOT's Traffic Monitoring System collects traffic volume data through both short-term traffic counting (such as pneumatic tube counts) and continuous traffic counting programs and the agency is obligated to report data to the Federal Highway Administration (Federal Highway Administration, 2016). Most of the sensors currently in use for long-term traffic counting are intrusive, including induction loops, quartz sensors, bending plates, and piezoelectric sensors. TxDOT also uses High Definition (HD) radar length-based technology for vehicle classification. Figure 2.2 shows the locations of permanent count stations in the state of Texas.

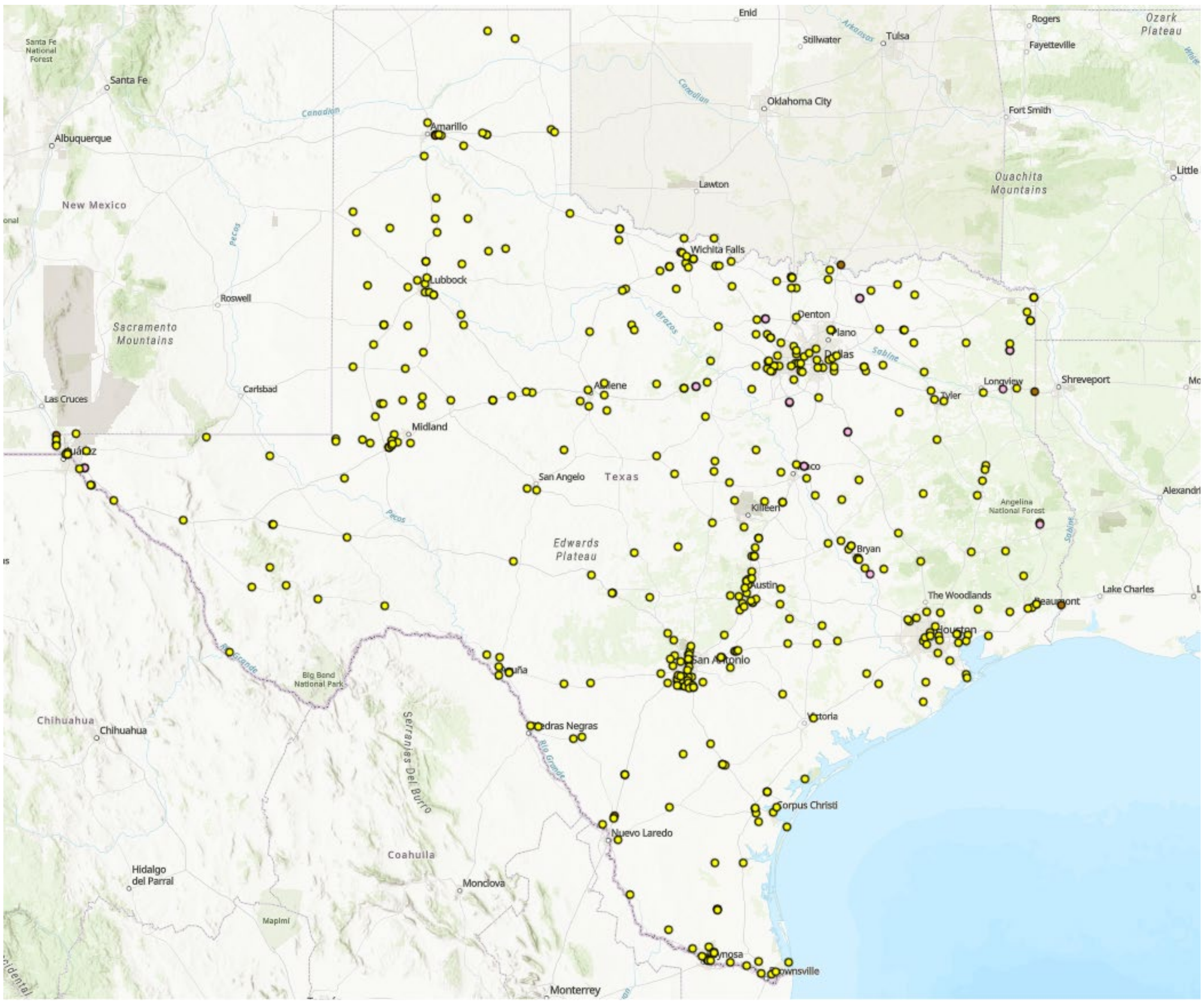


Figure 2.2: Map of TxDOT permanent count stations (TxDOT, 2016)

In addition to vehicle detection technologies, the video surveillance system is another effective tool that TxDOT uses to monitor traffic. The traffic management centers (TMCs) in Texas commonly use Pan-Tilt-Zoom (PTZ) Closed Circuit Television (CCTV) cameras to monitor the traffic conditions throughout the roadway network in real time. The TxDOT ITS website (2021) maintains a map of traffic cameras installed along major corridors for each district. Figure 2.3 shows a map of cameras installed along major corridors in the Houston District.

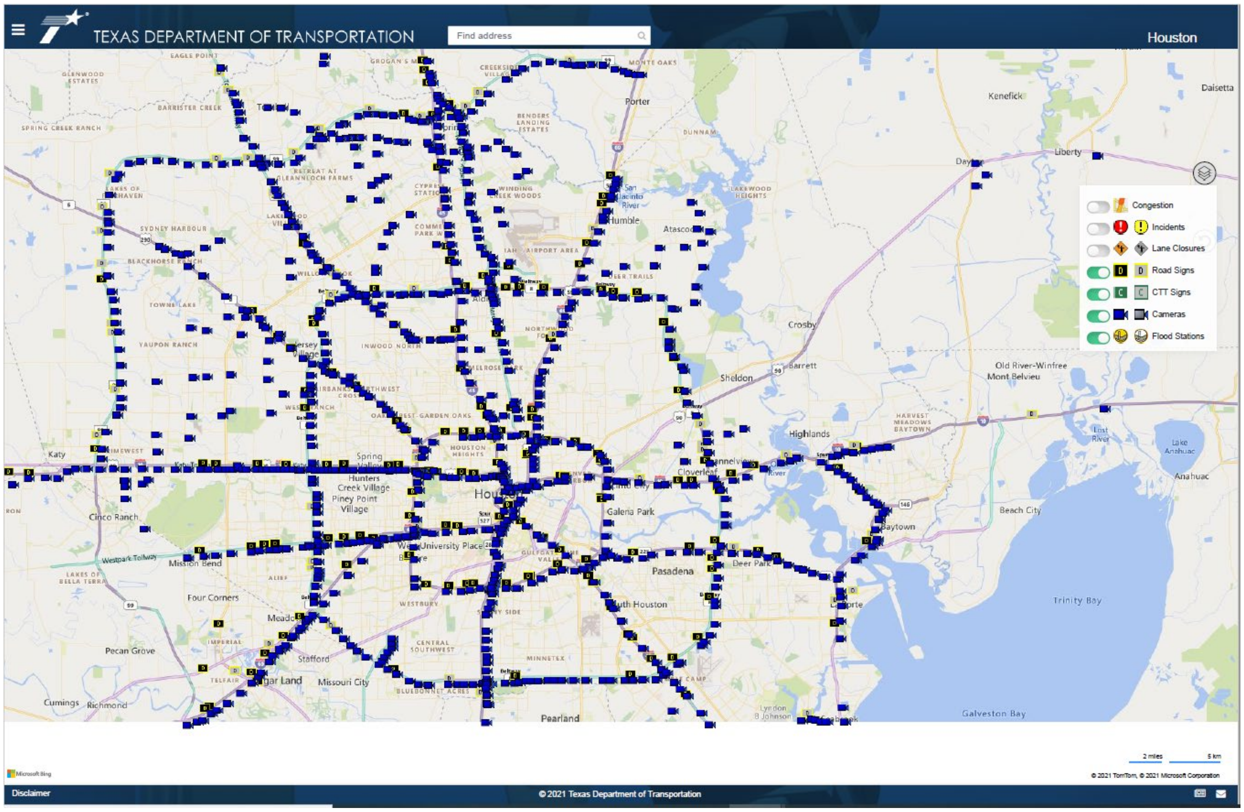


Figure 2.3: ITS field devices in the Houston District (TxDOT, 2021)

Texas has a long history of incorporating innovative ITS solutions into the TMCs of the state. However, the state must expand video and traffic monitoring capabilities beyond urban areas to allow for better traffic management in evacuations, as well as in normal traffic operations. Borchardt and Puckett (2008) provided a list of additional recommended deployments of video and sensor detection stations to allow for improved monitoring and managing of traffic during evacuation events in Texas. However, hurricanes in Texas have posed considerable challenges to the evacuation of large populations and the transmission of information from the real-time traffic monitoring infrastructure. The limited available resources and the large network size present several technical and economic difficulties, particularly in rural areas. Intrusive vehicle sensors embedded in the roadway pavement and are often large, expensive, and power-hungry. Video surveillance technologies can be mounted on existing transportation infrastructures on roadways or roadsides, but their performance can be affected by weather conditions (Balid et al., 2018). To examine all possible best practices for real-time traffic monitoring networks, the following subsections survey the evacuation monitoring resources and practices used by other agencies and private companies.

2.2.2. Methods Used by Other Texas Agencies and Private Companies

For many Houston District motorists, evacuating away from coastal communities involves traveling through a major urban area, increasing the level of complexity for evacuees since the roads designated as evacuation routes are often congested with traffic demands frequently exceeding capacity. Houston TranStar maintains several ITS devices and has implemented a real-time flood warning system that uses flood sensing technology overlaid with traffic condition data to predict which roadway segments may flood in extreme precipitation events. Initially, traffic management centers used ITS technology such as inductive loop detectors to count vehicles and estimate travel times. In recent years, this technology has been replaced by more innovative approaches such as Anonymous Wireless Address Matching (AWAM), where the passive Bluetooth signals from passing vehicles are used to estimate the speed and travel time of drivers on road segments. Some Texas cities, such as San Antonio, use side-fire radar to monitor vehicle counts and speeds. Table 2.2 details the traffic management systems currently present in Texas's major metropolitan areas.

Table 2.2 – Selected traffic management centers in Texas metro areas

Center	Locations Covered	Agencies Involved	Technology in Use
Combined Transportation, Emergency & Communications Center (CTECC)	Austin	City of Austin, Travis County, TxDOT, Capital Metropolitan Transportation Authority	Traffic detectors, environmental sensors, dynamic message signs, CCTV cameras, video image processing systems
Dallas District Traffic Management Center (DalTrans)	Dallas/Ft. Worth	City, county, and town governments in Dallas Metroplex, TxDOT, DART	Dynamic message signs, CCTV, traffic flow sensors
San Antonio TransGuide	San Antonio	City of San Antonio, TxDOT, VIA Metropolitan Transit	Side-fire radar and Bluetooth readers (AWAM) as traffic counters, PTZ CCTV, dynamic message signs, travel time comparison signs
Greater Houston Transportation and Emergency Management Center (TranStar)	Houston/Harris County	City of Houston, Harris County, METRO, TxDOT	CCTV, Anonymous Wireless Address Matching (AWAM) via passive Bluetooth, dynamic message signs, real-time flood warning system

Although public agencies have planned to expand their traffic monitoring system networks over the years, gaps in data coverage remain and some public agencies have considered filling the gaps using data from the private sector. AirSage, a private company producing real-time traffic data from wireless phone signaling data, claimed that they developed a wireless traffic monitoring system tool that could be used in rural areas and during blackouts (Wilson-Goure, Houston, & Vann Easton, 2006). Middleton et al. (2012) from the Texas Transportation Institute (TTI) team reviewed numerous private companies and summarized each provider's primary data sources in Table 2.3.

Table 2.3 – Provider primary data sources, from Middleton et al., (2012)

Provider	GPS-Enabled Vehicles	Cellular Probes	Fixed Point Sensors	Others
AirSage		Yes		
CellInt		Yes		
Delcan		Yes		
Inrix	Yes	Yes	Yes	
NAVTEQ	Yes	Yes	Yes	
OnStar	Yes			
SpeedInfo			Yes (radar)	
TomTom	Yes	Yes	Yes	
Total Traffic Network	Yes	Yes	Yes	Airborne/Mobile Spotters, Cameras
TrafficCast	Yes		Yes	Bluetooth

2.2.3. Methods Used in Other U.S. States

According to a 2005 report prepared by the National Oceanic and Atmospheric Administration (NOAA), Florida, Texas, Louisiana, North Carolina, and South Carolina were the top five states experiencing hurricane events between 1856 and 2004 (Blake et al., 2005). Most of these states' transportation departments use ITS for hurricane evacuations. State Departments of Transportation (DOTs) usually obtain hurricane information from NOAA and work closely with other emergency management agencies for evacuation operations. Many DOTs collect real-time traffic data through vehicle sensors and cameras to determine road conditions and the best route for evacuation. DOTs also offer real-time roadway conditions and incident updates to the public through online service and radio systems.

In addition to these practices, individual states have been investing in a variety of technologies that are suitable for their particular situations. The Florida Department of Transportation (FDOT) (Haas et al., 2009) developed a model deployment called "*i*Florida" to examine how "widespread availability of real-time transportation information would enhance the security and reliability of the surface transportation system," especially during a hurricane evacuation. The North Carolina Department of Transportation (NCDOT) Division of Aviation (2018) has conducted experiments using Unmanned Aircraft Systems in emergencies. FDOT and NCDOT also started working with private companies to incorporate data gathered from connected vehicles into emergency response. The Louisiana Department of Transportation and Development (DOTD), Louisiana State University (LSU), the United States Geological Survey (USGS), and private-sector companies joined forces to create traffic, weather, flood, and bridge scour monitoring systems for critical routes within the state (Wolshon & Levitan, 2002). The South Carolina Department of Transportation (SCDOT) tested a video-based traffic monitoring system that used vehicle tracking to more accurately and effectively identify and count motorcycles traveling side by side or close behind one another (Kanhere et al., 2010).

Many regions of the Western U.S. are prone to seasonal wildfires. Wildfire events may result in large-scale evacuations of communities in the wildland-urban interface (Melendez, Machiani, & Nara 2021). Many transportation agencies in rural areas where wildfires are expected to occur do not have the infrastructure to collect the data necessary for making critical decisions. Melendez et al. (2021) conducted research using data from the 2017 Lilac Wildfire in California to demonstrate that cell phone user location data can be analyzed to predict traffic flow on evacuation routes that are not serviced by a network of traffic sensors.

Furthermore, many state agencies are working with private companies to fill data gaps. The Connected Citizens Program of crowdsource navigation software Waze is cooperating with DOTs in states such as Oregon, Alabama, Massachusetts, Louisiana, and California to provide data to their traffic control systems (Hill, 2016). The data collected from road users in areas where roadside sensors or cameras are not present or feasible can greatly increase the agencies' ability to provide accurate real-time traffic information to the general public (Mail Tribune, 2015).

2.2.4. Methods Used in Other Countries for Evacuations

Doha, the largest metropolitan area in Qatar, has faced severe traffic congestion due to the country's rapid urbanization. A research team from Qatar University proposed a low-cost, real-time traffic information system for Doha using GPS probe–based traffic data collection technology (Al-Abdallah et al., 2010).

Hara and Kuwahara (2015) from Tohoku University conducted research to analyze the possibility of using vehicle and smartphone GPS data to understand people's behaviors and reasons for causing traffic congestion after the 2011 Great East Japan Tsunami. As a result of the devastating earthquake and tsunami, power and traffic infrastructures were unable to function properly. The only accessible information came from individuals' probe vehicles and smartphone GPS data. In many circumstances, a significant natural disaster destroys many infrastructure sensors, making it impossible to capture precise dynamic information about people and vehicles' mobility. The findings of the research advised that probe vehicle data be included in future disaster preparedness planning. GPS, on the other hand, might be a source of error.

2.3. Identify Critical Information Needed during Evacuations

The various traffic monitoring devices used in Texas, other U.S. states, and other countries are implemented to serve the vital purpose of monitoring traffic conditions during evacuation and citizen return to impacted areas. With this goal, it is important to consider the specific purposes that traffic monitoring can fill during extreme weather events, for both public officials responsible for ordering and coordinating evacuations, and the members of the public who are evacuating and wish to make safe, informed decisions. Figure 2.4 portrays the hurricane evacuation use case and role of real-time traffic monitoring.

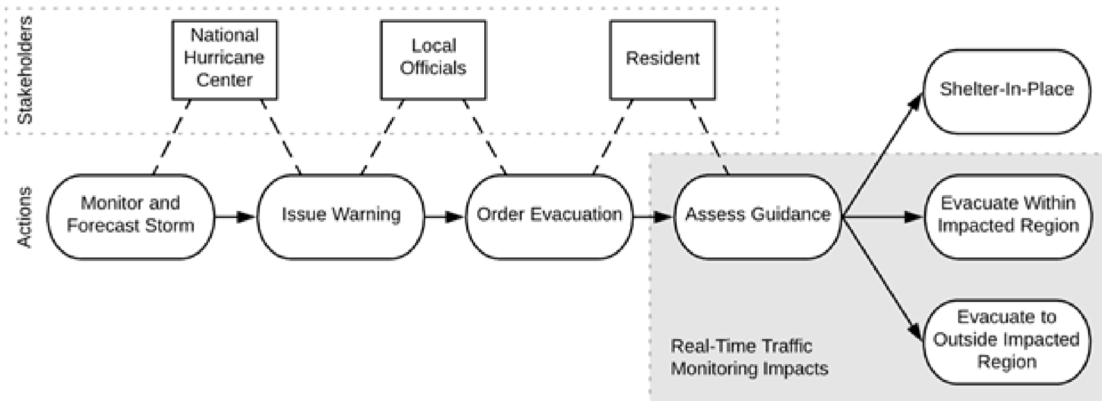


Figure 2.4: Hurricane evacuation use case process. Adapted from Boyd et al., (2014)

2.3.1. Information Needed by Public Officials

Government officials must make informed decisions to order mandatory evacuations when extreme weather events are imminent. In Texas, State Government Code Section 418.185 designates county judges and municipality mayors as the officials responsible for ordering mandatory evacuations (Mandatory Evacuation, 2021). This section of the code also indicates that the Texas governor may help to enforce the evacuations once they are announced. This is different from other U.S. states, where the governor themself may order an evacuation. The reason given for this difference in Texas is that county judges and mayors have a better understanding of local conditions and capabilities in times of hazardous weather and so they are given the responsibility to make these decisions.

Another section of the state government code, 418.048, details the responsibility of the Texas Division of Emergency Management (TDEM) to monitor extreme weather forecasts to remain up to date with weather conditions and hazards (Monitoring Weather, 2021). Additionally, state government code 418.050 states that TDEM is responsible for creating a phased reentry plan for impacted areas and a credentialing process to be used for ensuring that certain groups of people reenter at the desired times (Phased Reentry Plan, 2021).

Cyclone activity in the North Atlantic is monitored by the National Hurricane Center (NHC), which is a subagency within NOAA. NHC provides updates on cyclone storms and issues hurricane watches approximately 48 hours prior to the expected landfall of tropic storm–level winds (NOAA, 2010). Around this time, mandatory evacuations are announced by local county judges or mayors for locations that are forecast to experience intense storm surge or extreme winds. Many communities in coastal locations have pre-existing plans regarding the order of evacuation by geographic location. The Houston-Galveston Area Council (H-GAC) maintains plans detailing evacuation zones and routes for the Houston region (Houston-Galveston Area Council, 2021). Zip codes located along the coast are in the priority zone for evacuation, followed by locations that are further inland, as shown in Figure 2.5. Local law enforcement is tasked with assisting the public during the evacuation.

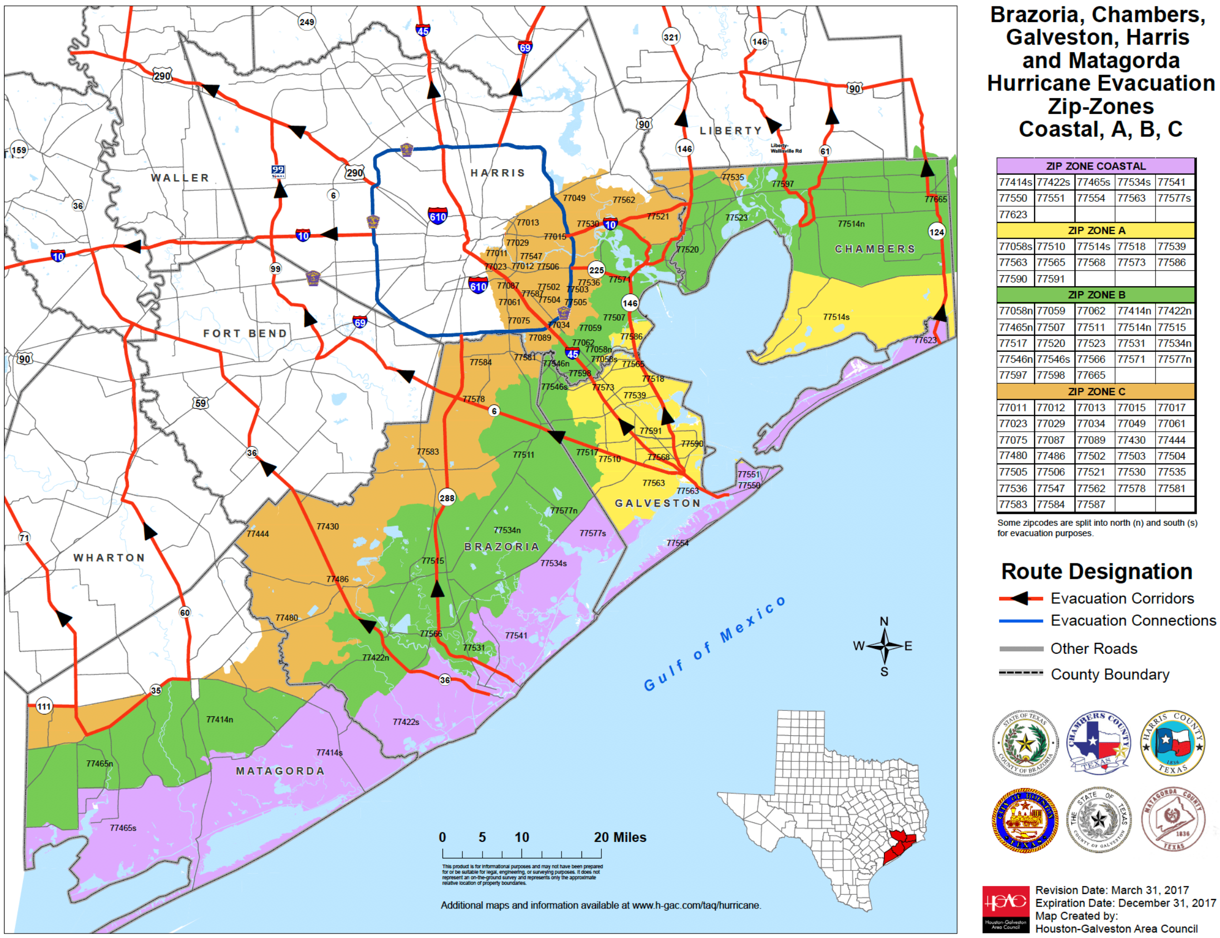


Figure 2.5: Hurricane evacuation zip-zones in the Houston-Galveston region (Houston-Galveston Area Council, 2021)

The zip code–based evacuation system was created to ensure that those in immediate danger (i.e., closer to the coast) can evacuate in a timely manner. If citizens from all locations were to evacuate simultaneously, intense traffic congestion would result in evacuees being unable to exit exposed locations in time.

TxDOT also aids in evacuation events. TxDOT has pre-planned routes identified as evacuation corridors in the eastern and coastal regions of the state. TxDOT has designated certain corridors as routes with additional features to aid in evacuations, namely Evaculane and contraflow routes. Evaculanes are highway corridors, typically interstate routes, that have the capability to use the shoulder as a travel lane. Prior to full use of the Evaculanes, the shoulders must be cleared of any debris to allow for safe travel. Contraflow routes are evacuation corridors where the lanes “inbound” to the hurricane exposed locations have their travel direction reversed to increase the available roadway capacity for "outbound" evacuation. The implementation of contraflow lanes in the TxDOT hurricane evacuation plan occurred after Hurricane Rita (Ballard et al., 2008). TxDOT coordinates the implementation of contraflow lanes and alerts the public to the status and availability of these routes, a critical concern in the hurricane evacuation process.

Other information needed by TxDOT and government officials relates to the status of evacuation routes. It is likely that most Evaculane and contraflow routes will have a high density of vehicles and therefore severe unidirectional congestion (Menon et al., 2020). However, TxDOT may provide assistance by operating courtesy patrols to assist distressed drivers or vehicles that have broken down or run out of fuel (Texas Division of Emergency Management, 2021). Locating these distressed vehicles is one data need that can be fulfilled by traffic monitoring systems. As telecommunications may fail during inclement weather events, alternative methods for identifying drivers in need of assistance are necessary. Additionally, understanding conditions at the entrances and exits of Evaculane and contraflow systems is necessary to ensure a seamless transition for users traveling on evacuation corridors and regular roadways, as bottlenecks may form at the terminus of these routes (Ballard and Borchardt, 2006). Therefore, the key takeaway is that visual observation of evacuation corridors at a regular interval is desired to provide TxDOT with "eyes on the ground" regarding evacuation route conditions during extreme weather events. This indicates that traffic cameras or other sensing technology capable of relating information on route speed and density are needed. These systems also need to be resilient to high volumes of users and extreme weather hazards, to ensure that they can function during high wind or flood events.

Government officials also need access to certain information for safe citizen return post-evacuation. Understanding what areas are safe for humans to return to is the first priority. A lack of critical resources, such as fuel, food, electricity, and other vital supplies, may make an area unsuitable for return (Besson, 2012). Studies have shown that indirect deaths, such as those from electrocution, heart failure, and other causes that occur after the hurricane has passed, may be greater than the direct deaths caused by the hurricane in some instances (Rappaport & Blanchard, 2016). Once an area is deemed safe, TxDOT requires information on which routes are safe for citizens to drive on to return to their homes. Hurricanes may sweep bridges out of their abutments and submerge roadways with floodwater. Those returning to their homes may also need to avoid other hazards, such as downed power lines, and monitoring capabilities are needed to identify these hazards. This is yet another factor that shows that traffic monitoring capabilities must be resilient and able to withstand extreme hurricane hazards.

Table 2.4 summarizes the information requirements for public agencies during evacuations. The information obtained from traffic monitoring systems is used by officials to respond to events and implement corrective measures. However, there remains a gap in literature regarding how this information is used by public officials to make decisions. For example, CTR was not able to identify specific targets used as cutoffs for ordering evacuations or allowing citizens to return to their homes after extreme weather events.

Table 2.4 – Summary of information needed by government officials during evacuation events

Information	Organization	Description
Storm arrival time	County judges and mayors, TDEM	The single most important factor for evacuation is the expected arrival time of tropical storm conditions. Local officials must order mandatory evacuations far enough in advance of the arrival of these conditions to allow citizens adequate time to evacuate.
Expected severity	County judges and mayors, TDEM	The expected severity of a storm determines if an evacuation must be called and for what areas. This also impacts the locations that TDEM must mobilize in and the extent of such mobilization.
Areas likely to be impacted	County judges and mayors, TDEM, TxDOT	Understanding which areas will be impacted helps to inform local officials which zip codes require evacuation. This also influences TDEM and TxDOT's understanding of where to mobilize employees for emergency response deployment and assistance.
Evacuation route congestion	TxDOT	TxDOT can communicate route travel time and alternate route availability to evacuees to ensure that drivers are out of impacted areas within the hurricane clearance time.
Location of distressed vehicles	TxDOT	TxDOT courtesy patrols need to be able to locate vehicles that have malfunctioned or run out of fuel in order to assist them.
Location of route hazards	TxDOT	TxDOT must identify evacuation and safe return routes that are clear of debris, downed power lines, etc.
Route availability	TxDOT, TDEM	TxDOT needs to know what routes are safe for citizens to use to return to afflicted areas. TDEM is responsible for staging safe reentry using a credential system.

2.3.2. Information Needed by the General Public

Texas residents who live in coastal areas require information on evacuation orders and impending storm systems to make informed decisions about if they should evacuate, what route they should take to evacuate, where they should evacuate to, and when they should return after the hurricane has passed.

Many academic studies have focused on examining how individuals decide to evacuate and who leaves in these situations. Studies have shown that the perceived severity of a storm is the best indicator for determining if individuals will evacuate, followed by the physical quality of the individual's household structure (Smith & McCarty, 2009). This finding was also supported by Burnside et al. (2007), who investigated the role of information dissemination in hurricane evacuation decisions. This study also found that the inclusion of visual imagery in evacuation announcements and the source providing the evacuation announcement were important factors in decisions to evacuate. The findings also stated that people who have evacuated in previous hurricanes are likely to do so in future events. These findings were further supported by Hasan et al. (2010), who used a mixed logit model to examine the influence of several variables on household evacuation decisions. It was found that a number of factors, such as household location, evacuation news source, number of children, household structure type (i.e., mobile home or permanent structure), previous evacuation experience, and if the notice of evacuation is mandatory or optional, all influenced decisions. These factors were confirmed by further studies (Dash & Gladwin, 2007; S. K. Huang et al., 2015). These results imply that individuals likely require information about the expected severity of a storm, and that the status of an evacuation order (mandatory versus optional) must be clearly announced by a reputable source.

Studies have found that evacuees travel in the 48-hour clearance time between the NHC hurricane watch announcement and the landfall of tropical storm conditions, and that they typically travel during daylight hours (Huang et al., 2012). During Hurricane Ike in 2008, the median evacuation departure time was one hour after the NHC hurricane warning announcement (Huang et al., 2012).

When planning to evacuate, individuals require information on the time they should evacuate before and the route they should take. In Texas, individuals are required to leave in times of mandatory evacuation, but they are free to take any route they desire to do so. While TxDOT operates evacuation corridors with Evaculane and contraflow capabilities, residents evacuating coastal regions are not required to use these facilities. Therefore, studies have found that many evacuees will use their own knowledge in addition to official guidance when selecting evacuation routes. Studies have found that route accessibility, driver familiarity, road classification, length, and availability of fuel and shelter are all factors that determine evacuation route selection (Akbarzadeh & Wilmot, 2014). Advance knowledge of likely collision locations, which may lead to unexpected delays, may also be a factor in evacuation route choices, although to a lesser extent (Robinson & Khattak, 2012).

Lindell et al. (2011) found that most evacuees used interstate routes, but in rural areas, other arterial routes may be used. This study also found that the average evacuation distance, while varying depending on the storm, was typically around 300 km (186 miles). This study also reviewed several studies and determined that around 15 percent of evacuees stayed at public shelters, and the average length of stay post-evacuation was a little over 2 days, although these factors vary depending on the severity of the storm impacts and location (U.S. state) of the impacts.

TxDOT has direct responsibility for giving evacuees much of the information they require. Using DMS along evacuation corridors, TxDOT can inform drivers about route congestion, accidents or delays, fuel availability, and shelter locations. Traffic monitoring infrastructure can aid TxDOT with obtaining the data for some of these attributes important to evacuees, such as the congestion and traffic incident locations along the evacuation routes.

Table 2.5 – Summary of key information needed by hurricane evacuees

Needed Information	Description	Organization(s) Responsible
Storm severity	Storm severity is one of the main variables that determine if a household will evacuate. Accurate information from a reliable source is most likely to lead to evacuation.	NHC, local weather media, other official channels
Evacuation order and type (mandatory or optional)	If an evacuation order is announced, and if the order is mandatory, then individuals are more likely to decide to evacuate.	Local officials, TxDOT, TDEM, other agencies
Evacuation route factors	Evacuation route choice is determined by several variables such as route type (i.e., interstate), congestion, perceived likelihood of accidents occurring, accessibility of fuel and shelter along the route, and driver familiarity.	TxDOT, TDEM
Shelter/destination location	If drivers require shelter at a public facility, they must understand where the facility is located and if there is space available at the location.	TxDOT, TDEM

2.4. Examine the Feasibility of Innovative Technology for Evacuation

In addition to the traffic monitoring technologies currently used by other U.S. states and countries, some innovative technologies are proposed in recent literature.

2.4.1. Mobile Cellular Network

Recent literature has demonstrated methods to use mobile cellular networks as sensors for monitoring real-time physical mobility (Basyoni et al., 2017, Janecek et al., 2015). Unlike fixed sensors, such as traffic cameras, mobile sensors can be used in areas with limited infrastructure. The advantages of using cellular phone data include its wide coverage, high penetration rate, and low cost (Basyoni et al., 2017). To conquer the problem of only being able to use "active" devices (devices engaged in a voice call or data connection) for reporting traffic status, Janecek et al. (2015) proposed a novel approach to observe "idle" devices. Despite the increase in device coverage, only some vehicles can be observed from mobile phone data. Therefore, this method alone is not able to capture the complete traffic status.

2.4.2. Modeling Traffic (Estimation and Prediction)

Since traffic monitoring devices are not able to capture traffic status completely, technologies and models are required to estimate and predict the traffic based on collected data. For example, data collected by mobile cellular networks represents only a fraction of all vehicles. To estimate the total number of vehicles, models and previous traffic information are needed. These models include regression (Bin Yang et al., 2014), matrix factorization (Xin et al., 2015), and tensor decomposition (Wang et al., 2014). More advanced models used recently are support vector machines (SVM) (Asif et al., 2014), hidden Markov models (HMM) (Yang et al., 2013), dynamic Bayesian networks (Chaudhary et al., 2018), and deep learning algorithms (Lv et al., 2014). These methods use historical traffic data and limited real-time data to estimate current traffic and predict future traffic. These models are different in accuracy and computational complexity. Usually there is a tradeoff between these two factors, and they typically require different input data. When deciding which model(s) to use, these factors should be considered.

2.4.3. Unmanned Aerial Systems (UASs)

Extensive studies (Kanistras et al., 2013, Aljehani & Inoue, 2016, Elloumi et al., 2018, Liu et al., 2019) have proven that Unmanned Aircraft Systems (UAS) are a viable and less time-consuming alternative to real-time traffic monitoring and management. Employing UAS in the field during natural disaster evacuation is valuable because of their advantages in mobility, low cost, and broad range of vision. However, there are concerns regarding the surveillance capability of UAS in inclement weather. Cloudy conditions and high humidity climates can distort imagery (Haddal & Gertler, 2010), and daylight constraints create barriers to time-sensitive applications (Gao et al., 2021). A typical hurricane brings at least 6 to 12 inches (152 to 304 millimeters) of rainfall and 74 to 95 mph winds (NOAA, 1999). Although weather-resistant drones have higher tolerances in temperature (-20 °C to 46 °C), wind speed (31 mph), and precipitation (50 mm/h) (Gao et al., 2010), they are more likely to be employed before or after a storm, when weather conditions permit. A typical UAS deployment for civil applications must follow regulations from the Federal Aviation Administration and other regulatory agencies. Therefore, issues with flying UAS in civil airspace must be addressed before UAS can widely be used in real-life evacuations (Kanistras et al., 2013).

2.4.4. Connected Vehicles

The rapid advancement of connected vehicle technology offers a promising platform for traffic monitoring and data collection, particularly in urban environments. Vehicles equipped with wireless communication devices in a network of connected vehicles can transmit vehicle safety messages to other connected vehicles (Xu, 2017). Private companies have teamed with the DOTs of Alabama, Florida, Georgia, North Carolina, Tennessee, and Virginia to develop a real-time monitoring system that collects traffic data from a network of connected vehicles on roads. With the live traffic data collected by hundreds of thousands of driving vehicles within minutes, TMCs can know how to avoid congestion on major escape routes and make critical decisions during an evacuation (Wejo, 2020).

2.5. Available Data Sources for Analysis

To conduct the analyses of current evacuation traffic monitoring devices, CTR undertook extensive efforts to collect pertinent data, including maps of Texas permanent count stations, evacuation routes, and district ITS devices. The collected data sets are:

- Texas Permanent Count Station: https://gis-txdot.opendata.arcgis.com/datasets/txdot-permanent-count-stations/explore
- Texas Evacuation Routes: https://gis-txdot.opendata.arcgis.com/datasets/txdot-evacuation-routes/explore
- TxDOT Annual Average Daily Traffic (AADT): https://gis-txdot.opendata.arcgis.com/datasets/txdot-aadt-annuals-2017/explore
- District ITS Devices Map: https://its.txdot.gov/its/

Texas Permanent Count Station, Evacuation Routes, and AADT are GIS-based data sets, while the ITS Devices Map is a web-based data source.

2.6. Summary

This chapter identifies key findings from a comprehensive review of relevant literature. Both traditional and emerging ITS technologies for collecting real-time traffic data and monitoring traffic conditions during a disaster event were assessed. An ITS comprises a sensing system, a communication system, roadside units, a traffic signal control system, and a notification system. State transportation-related agencies, including TxDOT, operate and maintain ITS devices, such as vehicle sensors and video surveillance, for gathering real-time traffic information. Traffic management centers commonly use inductive loop detectors and CCTV cameras for vehicle counting and traffic monitoring during emergency evacuations. These technologies, however, can be costly to deploy and maintain and are susceptible to weather conditions. More sophisticated real-time traffic monitoring strategies for dealing with limited available resources and increasing network size are being pursued by many state agencies.

The literature review also identified the information needs for both public agencies and the public in times of evacuation. This analysis is useful as it allows CTR to determine the specific needs for traffic monitoring systems and the information gaps that traffic monitoring can help to address during hurricane evacuations.

Studies have determined how cell phone data, GPS-based probes, UAS, and connected vehicles may be used in traffic management operations during hurricane and other disaster evacuations to aid decision-making. Given the limitations of traffic monitoring equipment in terms of capturing the current traffic condition in its entirety, simulation models are necessary to estimate traffic flow based on the data obtained.

Chapter 3. Collect and Synthesize Stakeholder Information

3.1. Introduction

The primary goal of this chapter was to expand on the findings of the literature review by surveying evacuation stakeholders to gather further data regarding the current implementation and observed shortcomings of the real-time traffic monitoring system in Texas during past hurricane events. The researchers sought to determine the general perceptions of the existing systems, common issues with the systems during evacuations, and potential improvements for future implementation. The specific stakeholder groups that were targeted to participate in these efforts are as follows:

- Members of the general public who reside in Texas and have participated in past hurricane evacuation events,
- Employees of the Texas Department of Public Safety (DPS) who have worked to assist evacuation efforts during past hurricane evacuation events, and
- Employees of the Texas Department of Transportation (TxDOT) who work with real-time traffic monitoring devices and were employed during past hurricane evacuations.

The following sections detail the specific stakeholder groups targeted for involvement, methods, and results of this analysis. The primary focus of this chapter concerns the outreach and data collection of the general public survey, while a mention of outreach activities with DPS and TxDOT is provided in brief.

3.2. Participating Stakeholders

To fully determine the stakeholder perceptions regarding real-time traffic monitoring during hurricane evacuation events, efforts were made to include all relevant parties. Governance authorities, such as the public agencies responsible for implementing and operating the traffic monitoring devices, and end users, such as the public agencies and populations that use the data from the devices during actual evacuation events, were targeted for participation to obtain a broader understanding of the issue. The primary stakeholder groups that participated in these outreach efforts were members of the general public, DPS employees, and TxDOT employees.

3.2.1. Members of the General Public

Members of the Texas public who reside in coastal areas or locations prone to evacuation events were sought for study participation. As individuals who live in regions exposed to hurricanes are the primary participants in mass evacuation events in Texas, understanding their experiences was an important part of the stakeholder outreach process. Determining the end-user perceptions regarding the level of existing real-time traffic monitoring and potential improvements is crucial for identifying gaps in the services and areas to be targeted for future investment or network expansion. Therefore, considerable efforts were undertaken to achieve a representative sample of common hurricane evacuation experiences.

3.2.2. Texas Department of Public Safety

As a branch of the Texas state government, DPS is responsible for regulating driving in the state of Texas via the administration of driver's licenses. DPS is also responsible for the enforcement of laws and regulations. Within its scope, DPS is responsible for protecting Texans from extreme weather events such as major floods, wildfires, and hurricanes. DPS also seeks to reduce fatal vehicle crashes, offers air and boat patrol and rescue operations, and participates in major highway safety operations, among other responsibilities (Texas Department of Public Safety, 2021). Through these directives, DPS plays an active role in hurricane evacuations and rescue efforts. Therefore, understanding the real-time traffic monitoring data implementation level among active DPS employees who respond to severe weather events is a necessary action for fully articulating the depth and necessity of system improvement.

3.2.3. Texas Department of Transportation

TxDOT operates and maintains infrastructure devices used for the collection of real-time traffic monitoring data. Permanent count stations are present throughout the state and continuously collect volume, classification, speed, and weight data of the vehicles traveling past the sensors. In addition to traffic count data, TxDOT also maintains a system of cameras to monitor the conditions and location of roadway incidents on Texas highways. Other devices such as passive Bluetooth counters are present in some TxDOT districts as well. To better understand how TxDOT operates and maintains these devices, especially during times of natural disaster disruptions or evacuations, it is necessary to determine the operational capability of the current real-time traffic monitoring devices in Texas and gain input from employees tasked with the operation of these devices.

3.3. General Public Survey

3.3.1. Design and Data Collection

An online survey was developed using the Qualtrics platform to determine general sentiments toward the current real-time traffic information systems deployed in hurricane evacuations in Texas. The survey was constructed with the intention that the questions would be easy to respond to and the topics would be as concise and understandable as possible, with an emphasis on the role of real-time traffic information systems in hurricane evacuations. Therefore, the number of questions was kept to a minimum and the primary response style was multiple choice or multiple selection questions. The main questions desired to be answered by the survey were:

1. Did evacuees use real-time traffic data to assist route and destination selection during past evacuations?
2. Which platforms were most commonly used to access real-time information?
3. What issues did evacuees encounter while using the real-time data?
4. What suggestions do evacuees have to improve the real-time traffic information services?

With these main points in mind, the survey was created with four parts and a total of 32 possible questions. The first part of the survey included a brief introduction of the project and a consent page where respondents agreed to participate in the survey. A link to the one-page project summary sheet was also included in case participants wanted to know more details about the project. The project summary sheet may be found in Appendix A. Then, a question was presented asking if the respondent had previously participated in a hurricane evacuation in Texas. Those who responded "Yes" were taken to the full survey. A "No" response brought the respondent to a different set of survey questions that asked for the reasons why the individual did not evacuate and if improved traffic monitoring capabilities would have altered their decision not to evacuate. The survey also collected demographic information from all respondents to help understand the evacuee's behaviors during an evacuation. Since survey takers may not wish to respond to demographic questions, these questions were optional and written such that values were represented within a range. The complete set of survey questions may be found in Appendix B, and it was published using Qualtrics on July 21, 2022.

To receive sufficient survey results and increase the response rate for analysis, the researchers contacted officials at Texas DPS and met in a virtual meeting on April 7, 2022, to request email addresses of Texas drivers residing in the state to use in survey distribution. A data agreement was constructed between DPS and UT/CTR to allow for the transfer of the requested email addresses in a valid and legal manner. The data agreement was signed on August 4, 2022, and more than 13 million email addresses of drivers residing throughout the state of Texas were received and downloaded on September 6, 2022. Unfortunately, no home county or date information was provided, so it was not possible to selectively distribute the survey to residents in coastal counties or residents who were present in Texas during past major hurricane events, such as Harvey in 2017 or Rita in 2005. The researchers checked the email addresses format and removed invalid records. The email distributions started on September 20, 2022. During the period of September 20, 2022, to October 4, 2022, a total number of 1,482,538 email invitations were sent out; however, 337,935 of them bounced back and did not reach the recipient's inbox. Therefore, 1,144,603 effective email invitations were sent out.

The research team also contacted the TxDOT communications department to advertise the survey on official TxDOT social media sites. Upon the advisement of members of the TxDOT Social Media team, it was determined that the survey would likely get the most interaction if it were posted on Nextdoor, as the platform has a very responsive user base. A short blurb and project poster was posted on Nextdoor on August 30, 2022, with a link to the online Qualtrics survey. The social media post can be found in Appendix C. This method of distribution allowed for followers of official TxDOT social media accounts to encounter the survey and opt to participate at a low financial cost to the researchers and TxDOT.

3.3.2. Survey Participants

The web-based survey distributed to Texas residents between August 30, 2022, and February 22, 2023, received 1,510 valid responses. Among the 1,510 observations, 889 respondents (58.9%) reported having previous hurricane evacuation experience. The remaining 41.1% indicated no previous evacuation experience either because they chose not to evacuate based on personal decisions or they never received any evacuation orders (e.g., they reside in hurricane-free areas).

Figures 3.1 and 3.2 show respondent locations and evacuation rates by county. The seven counties with the most responses have been presented separately: Harris County, Galveston County, Fort Bend County, Brazoria County, Jefferson County, Montgomery County, and Nueces County. Notably, Harris County, where Houston is located, has the highest percentage of respondents at around 40%, and an evacuation rate exceeding 70%. In the Houston metro area, Galveston, Fort Bend, Brazoria, and Montgomery Counties display an evacuation rate of over 55%. Moving beyond the Houston area, Jefferson County and Nueces County contain the cities of Beaumont and Corpus Christi, and have evacuation rates of 94.3% and 75.6%, respectively. Regarding other coastal counties, the overall evacuation rate averages around 62.1%. In addition, the evacuation rate is 14.3% for non-coastal counties because residents may move or visit the coastal area during the hurricane season.

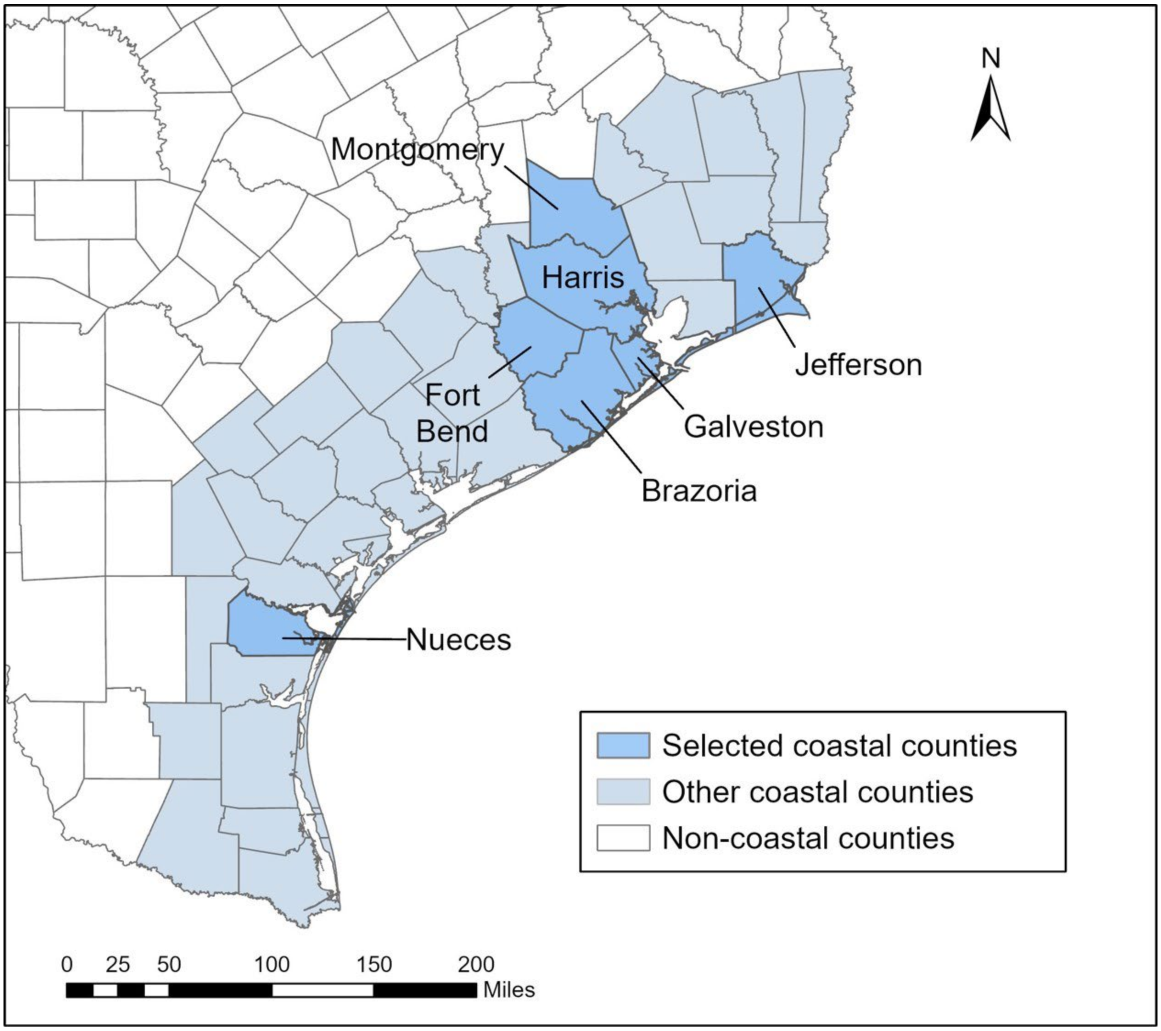


Figure 3.1: Geographic distribution of respondents across Texas counties

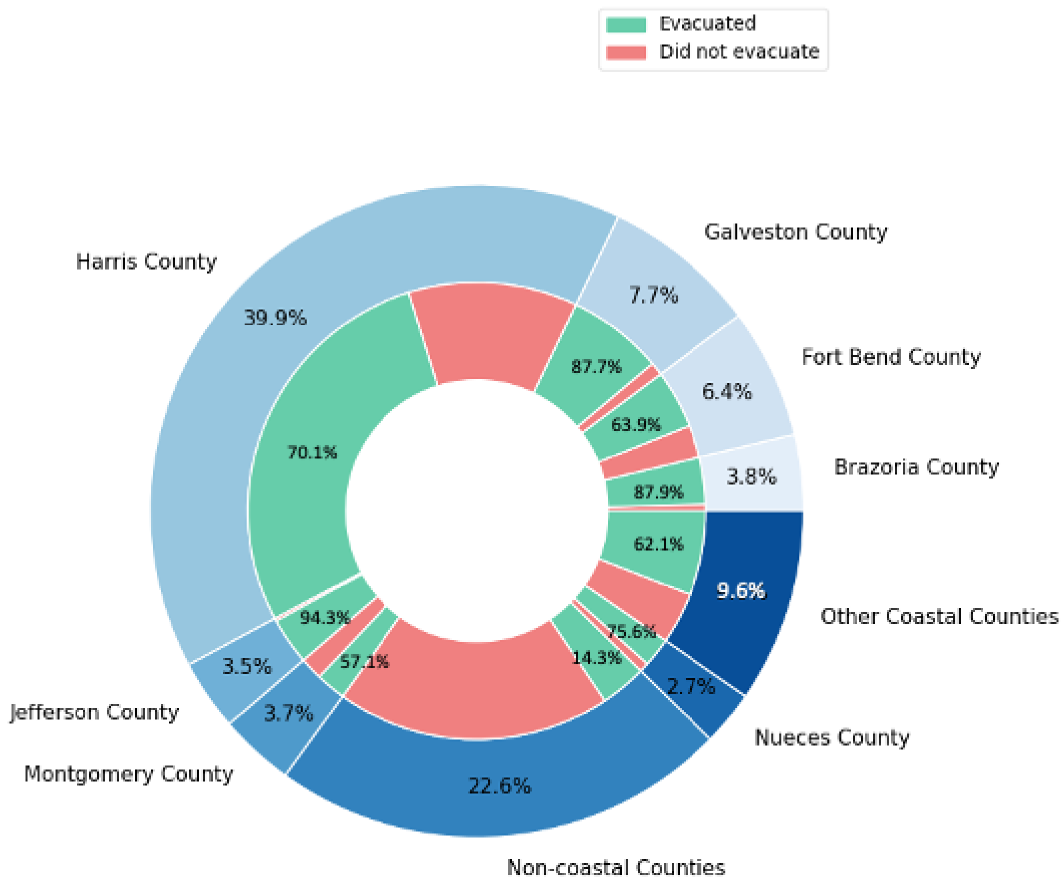


Figure 3.2: Survey respondent locations and evacuation rates by county

For participants who experienced a past hurricane evacuation, it was found that most respondents had participated in Hurricane Rita, with the second most evacuated storm being Hurricane Ike, followed by Hurricane Harvey. Several additional storms comprise the other results. Figure 3.3 shows the distribution of the storms in which respondents most experienced evacuations. Respondents were asked to select all past hurricanes from which they evacuated. Common text responses for "Other (please specify)" included hurricanes which occurred further in the past, such as Hurricanes Carla (1961), Beulah (1967), Allen (1980), and Alicia (1983).

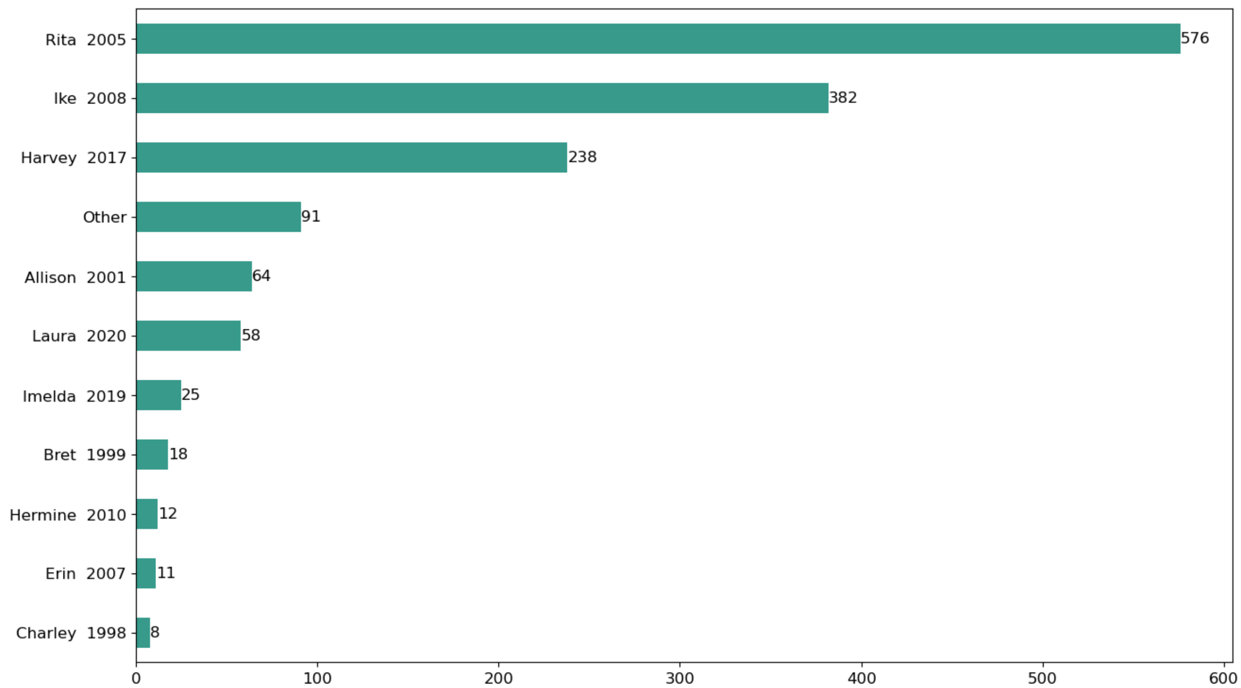


Figure 3.3: Survey responses for hurricane evacuation events experienced

Before being presented with questions regarding their experiences with hurricane evacuation traffic monitoring devices, respondents were asked a series of demographic questions. These demographics are presented in the following paragraphs and Figures 3.4 to 3.8, with results presented for both respondents who indicated that they evacuated during a past hurricane and those who indicated that they did not.

Figure 3.4 shows the reported age of the respondents at the time of their most-recently experienced hurricane. For both individuals who evacuated and those who did not, the most common responses were the 45-54 and 55-64 age ranges.

Respondent gender was also requested, as males and females are known to display differing amounts of risk-acceptance in behavior, and this may play a role in evacuation decisions. As shown from Figure 3.5, a higher percentage of man reported not evacuating compared to women, and more women reported evacuating than men. Results for the numbers of non-binary and individuals who preferred not to respond were consistent between the two groups.

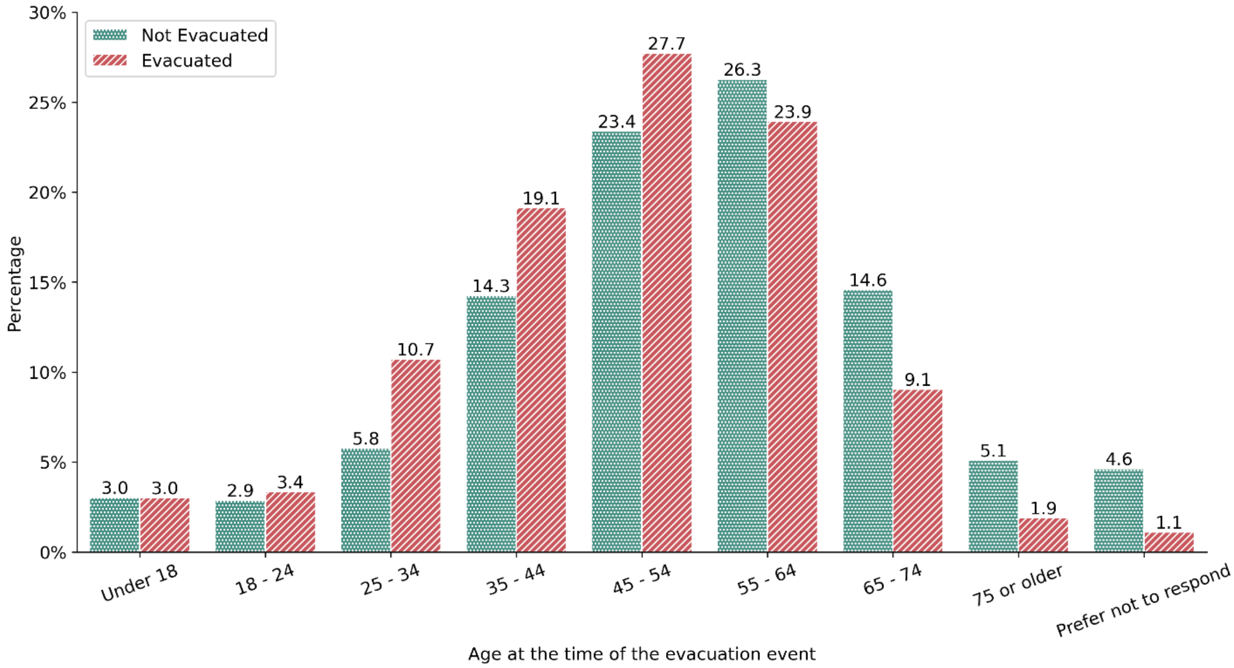


Figure 3.4: Respondent distributions for reported age at time of most-recently experienced hurricane, by evacuees and non-evacuees

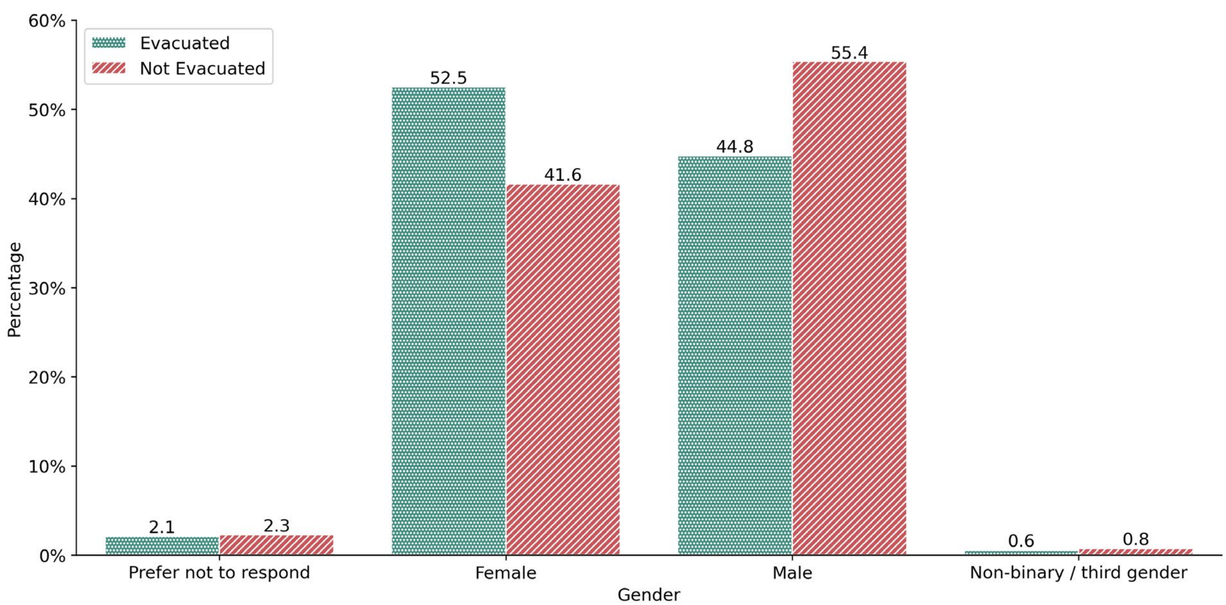


Figure 3.5: Reported respondent genders, by evacuees and non-evacuees

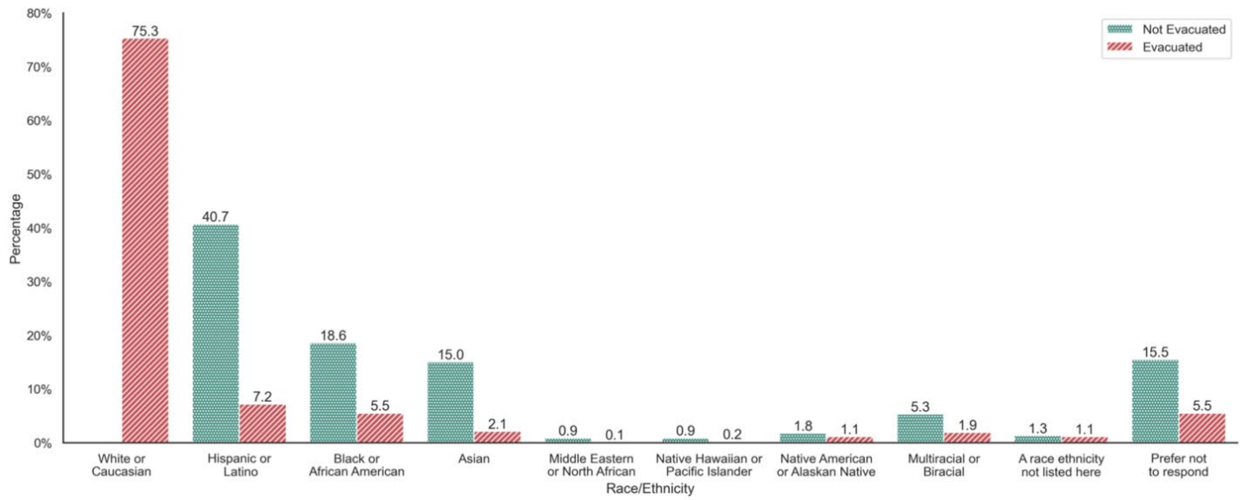


Figure 3.6: Reported respondent racial demographics, by evacuees and non-evacuees

The racial demographics of the respondents were also requested to better understand how different ethnic groups may respond to hurricane evacuation orders. Figure 3.6 shows the recorded racial breakdown of the respondents. Most respondents in both groups identified as “White,” followed by “Hispanic” and “African American” respondents. Amongst those who reported not evacuating, Hispanic-identifying individuals comprised a larger percentage of respondents who did not evacuate compared to the percentage who reportedly evacuated. This may reflect underlying inequalities regarding the ability of certain demographics to evacuate during times of disaster.

Respondents’ annual household income is shown in Figure 3.7. Around 20% of respondents in both groups preferred not to provide income information. Most individuals fell in the range of \$50,000-\$99,999 and \$100,000-\$199,000. This is roughly representative of middle-class households being the most represented in these results.

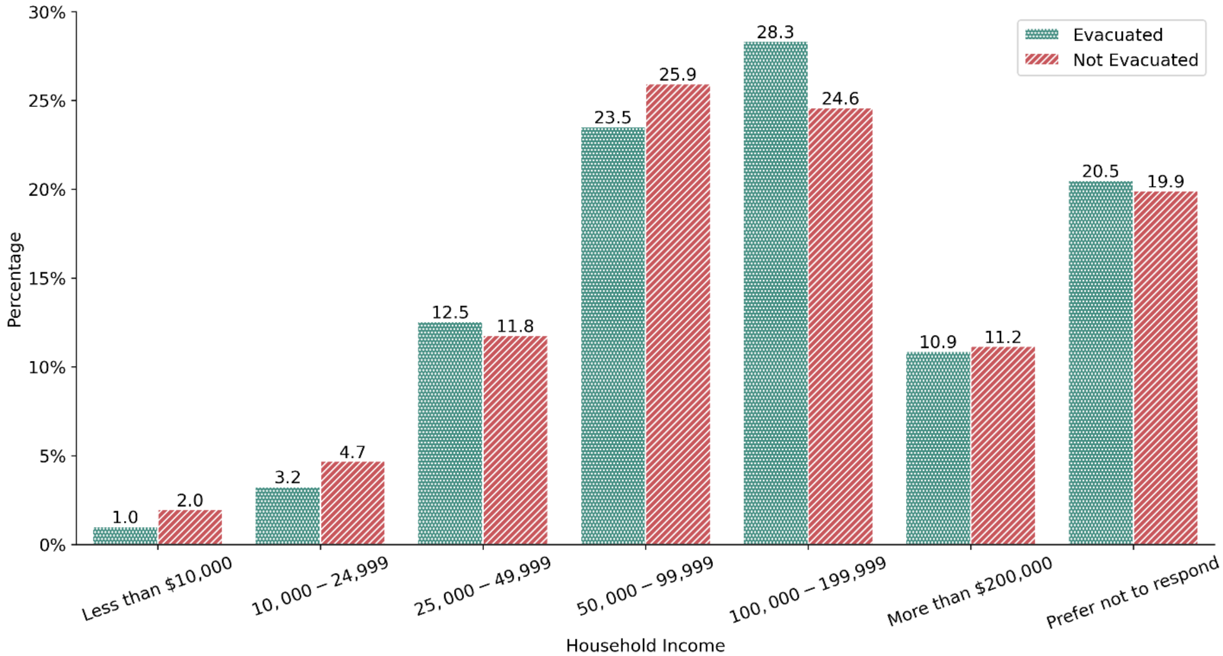


Figure 3.7: Reported respondent household incomes, by evacuees and non-evacuees

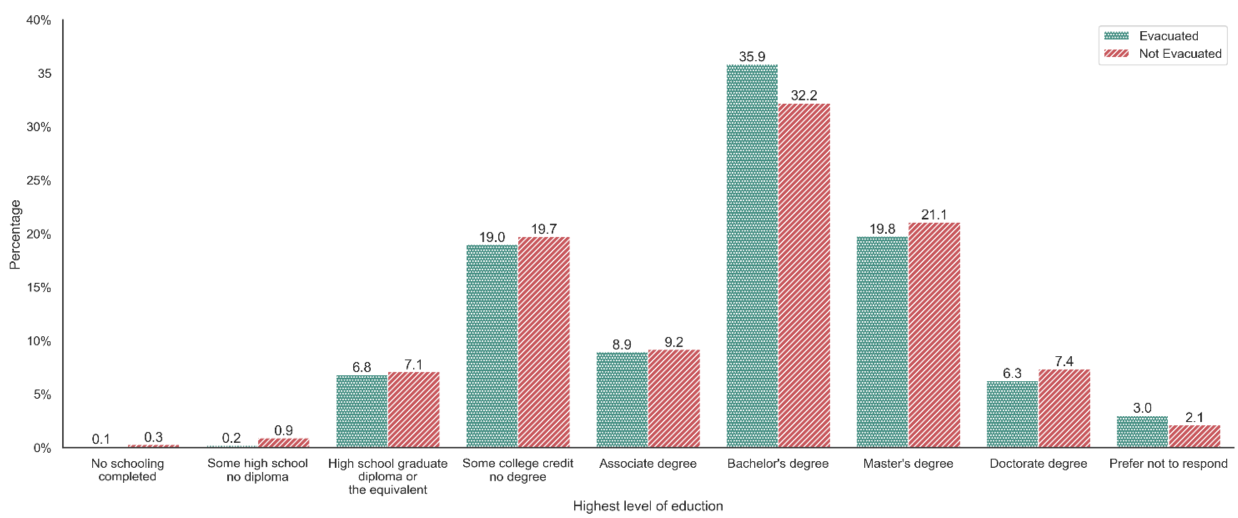


Figure 3.8: Reported respondent's highest level of education

Respondents' maximum education levels are shown in Figure 3.8. Results are consistent between those who opted to evacuate and those who did not. Over 30% of respondents have a bachelor's degree, around 20% have some college credit but no degree or master's degree, and this is followed by an associate's degree, which comprises around 9% of the sample. Other education options make up the remainder of the sample at a lower proportion.

3.3.3. Results and Discussion

After inquiring about respondent demographics, the questions shifted to determine evacuee behavior and issues encountered during past evacuations. Figures 3.9 to 3.20 analyze the behavior of evacuees who used real-time traffic data in previous evacuation events. For questions which gave respondents the opportunity to select multiple options, the results do not sum to 100%. Each bar represents the percentage or frequency of respondents choosing a particular option.

3.3.3.1. Evacuation Results

Figure 3.9 shows the departure period of evacuees before the hurricane landfall. The number of responses varies as some storms had more evacuees than others due to the location of the storm impact and the size of the population affected. For most hurricanes, evacuees reported leaving 12-24 hours in advance of the hurricane landfall. In severe storms, such as Hurricanes Rita and Ike, respondents indicated that they evacuated 24-36 hours in advance. This indicates that evacuees are more cautious and leave earlier for severe storms.

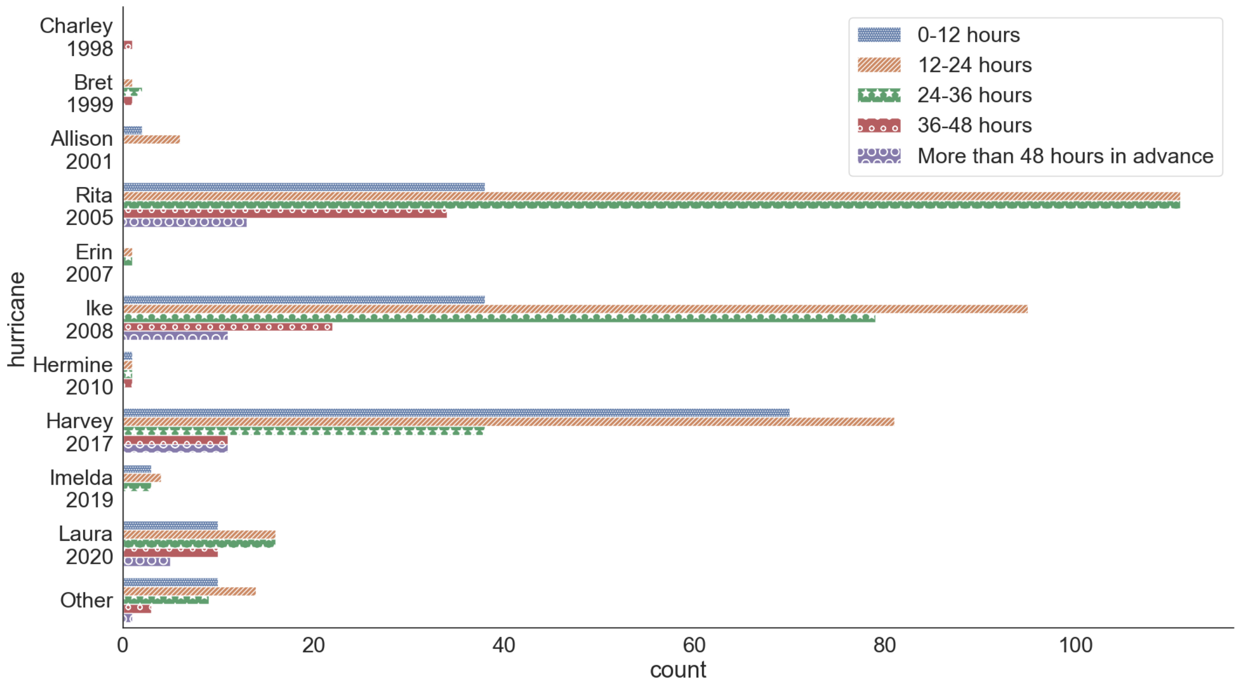


Figure 3.9: Reported evacuee departure times by hurricane event

Figure 3.10 shows the travel distance for evacuees to reach safety zones. While results vary by storm, common travel distance categories are 101-200 and 201-300 miles. It is important for agencies to note the potential destinations and evacuation travel distances during evacuation.

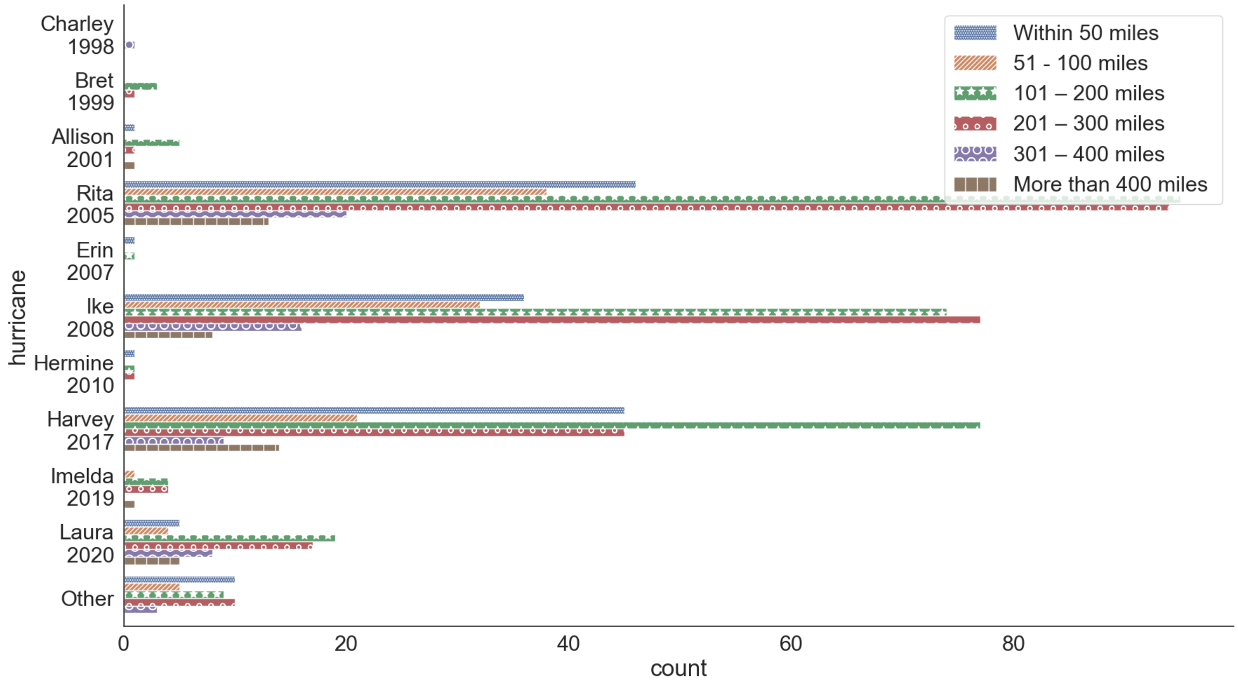


Figure 3.10: Reported evacuation distances travelled by hurricane event

Respondents were asked about the issues that they encountered during the evacuation. This is a multi-choice question, and all the selected issues would be recorded. The results shown in Figure 3.11 indicate that traffic congestion was the most commonly occurring issue during past Texas hurricane evacuations with 73% respondents chosen, followed by gas shortages (45%), road closures (25%), and road rage/other driver's behavior (19%).

Figure 3.12 shows the platforms that were most frequently used to gather information during an evacuation. Respondents predominantly used radio (30%) and mobile navigation applications (26%), followed by TV sources (18%). 11% of respondents used DriveTexas, the official TxDOT website for distributing real-time travel information in Texas, and 9% used DMS located along their evacuation route. Other responses included talking with TxDOT employees, calling TxDOT phone numbers, and other platforms.

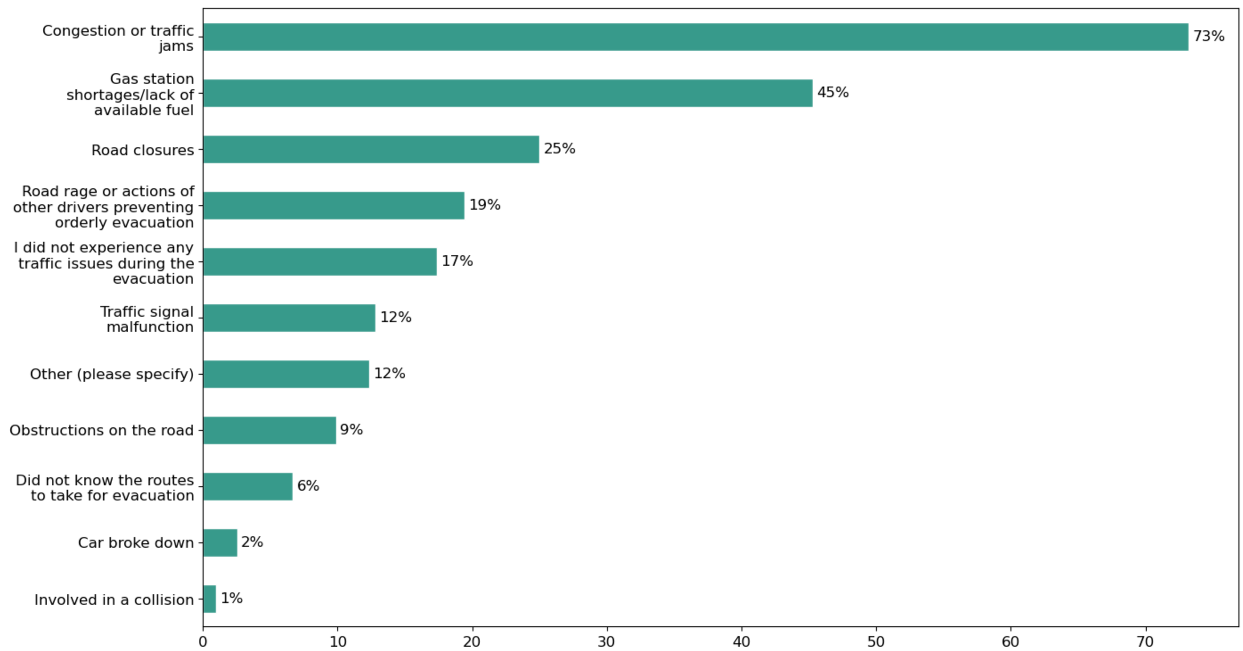


Figure 3.11: Common issues encountered by evacuees during past Texas hurricane evacuations

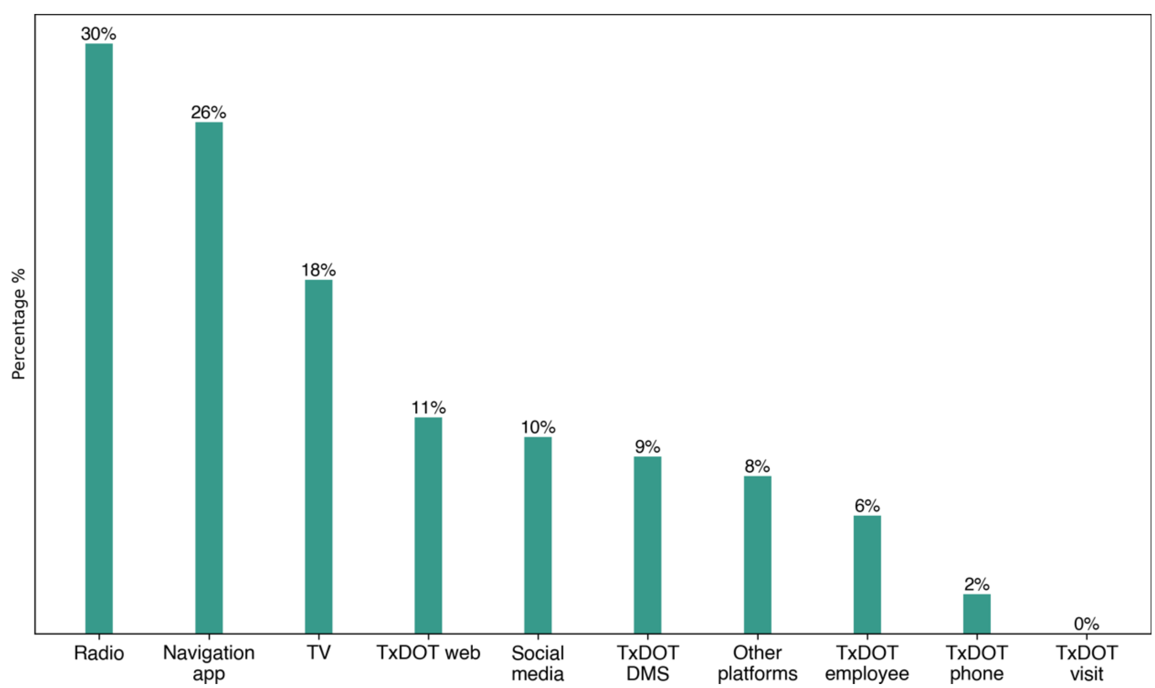


Figure 3.12: Utilization of real-time traffic data platforms during past Texas evacuations

After examining the common platforms that evacuees used for accessing real-time traffic data during an evacuation, understanding *why* they chose these platforms can provide insights to better serve evacuees for future events. Based on Figure 3.13, evacuees were inclined to select a service that was available, easy to use, and accessible during an evacuation. Familiarity, accuracy, and the information source are also important contributing factors to evacuees' selection. The cost of a service does not appear to be significant compared to other reasons.

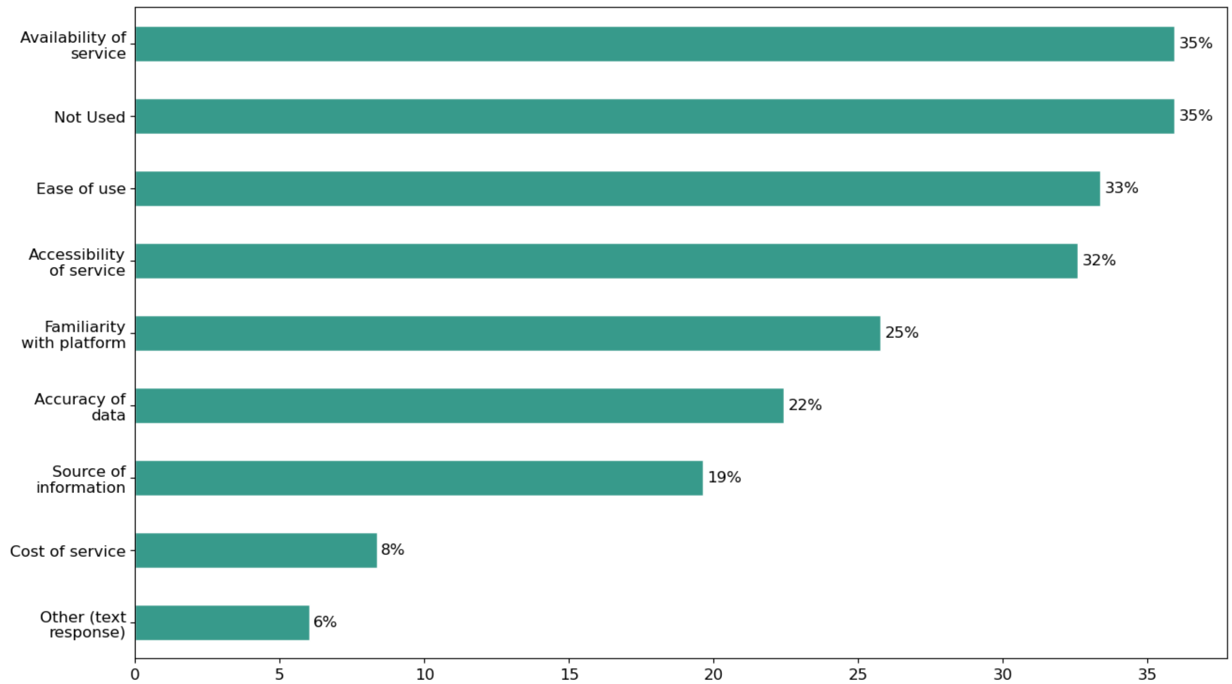


Figure 3.13: Reasons for selecting real-time traffic data platforms for use during evacuation

Figure 3.14 summarizes evacuee usage of real-time data during the evacuation process. Over one-third of participants used real-time data to help select initial evacuation routes, while a quarter of participants used real-time data during the evacuation to adjust routes or monitor evacuation progress. 17-18% of respondents mentioned that they used real-time platforms to select a departure time or choose a destination. These results indicate that evacuees are more likely to use real-time data to aid with route selection and mid-journey re-routing, rather than determining their destination or departure time. This suggests that evacuees may use real-time data to observe congestion levels and roadway incidents to select more efficient and reliable routes while departure times and destinations are likely influenced by other attributes. For example, evacuation destinations may be predetermined if a household has arrangements to stay with family members or friends.

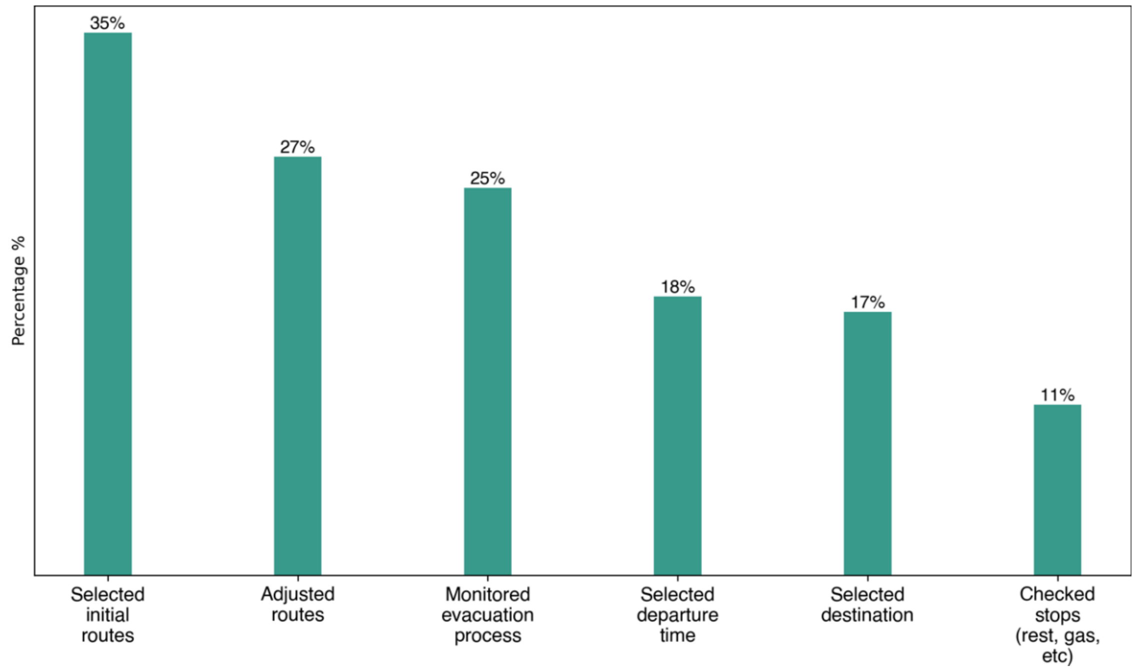


Figure 3.14: Evacuee motivations for using real-time traffic information

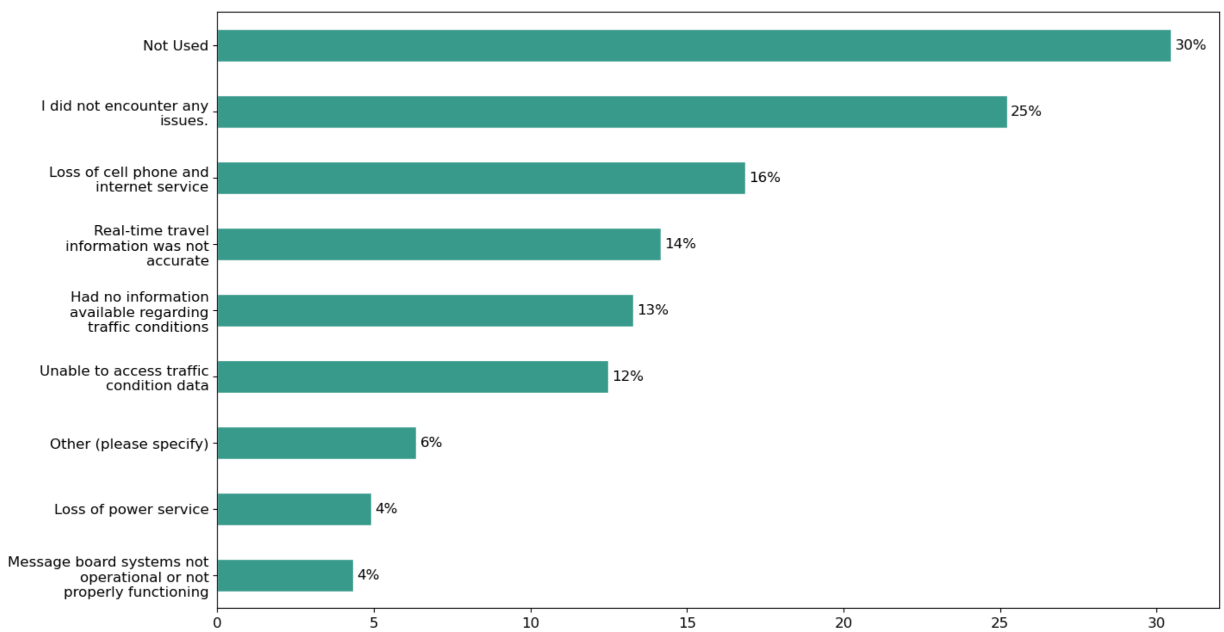


Figure 3.15: Issues encountered with the reliability or accuracy of the real-time traffic monitoring systems during the evacuation

For respondents who used real-time traffic data, around 25% said they did not encounter any issues regarding the reliability or accuracy of the systems as shown in Figure 3.15. It was approximately evenly distributed among individuals who encountered lost cell phone or internet service, inaccurate real-time travel information, or were unable to access traffic condition information. It was less common for people to experience inoperative or dysfunctional message board systems or a loss of power services.

Since most respondents evacuated during hurricanes that occurred before 2006, it was frequently mentioned that there were not many services available, or they were unreliable at the time of the evacuation. Cell phones and internet connectivity were not as widespread as now, so real-time traffic data was not widely available and accessible. Most of the evacuees were unable to receive real-time traffic updates due to service availability. Some of the respondents explained in the "Others (please specify)" field that they mostly relied on radios, news channels, and phone calls with family members and friends who lived in a safe area to acquire such information.

However, these services had their own limitations. For example, people mentioned that radio service was only available along major roads and was unreliable because of the storm. Therefore, availability and accessibility were two important factors of selecting a platform from their point of view. With the advancement of technology, more services have become available, and people are able to choose between a variety of services based on their familiarity with a platform, data accuracy, and the source of the information.

3.3.3.2. Evacuee Recommendations

Survey participants were asked if the real-time traffic monitoring system was sufficient to provide the data needed to support their decision-making during evacuations. 61.6% of participants thought that the current system was sufficient, while 38.4% of participants did not think it was sufficient. Following this question, participants were asked about the most important factor they would like to see addressed to improve the current real-time traffic monitoring system to make future evacuations better. The text responses for this question can be summarized and organized into three groups:

- Emergency Planning: which requires the government to develop a thorough evacuation plan and routes, better communicate information to the public, and organize emergency management responses during an evacuation process.
- Traffic Operations: which requires state agencies to install adequate devices on evacuation routes, ensure routes are clear to use, and ensure infrastructure devices are well maintained and functioning.
- Traffic Information: which involves providing more detailed and accurate data to the public and improving the methods of delivering such information.

Most residents in Texas would like to have more accurate traffic data from provided services to improve the existing evacuation real-time monitoring system, followed by providing educational resources to increase awareness of existing resources and how to use them.

In one question, respondents were asked to select the factors that they would most like to see improved. These responses were compared to the question asking the users' motivations for selecting specific data platforms. Figure 3.16 shows that more than one-third of respondents indicated that accessibility (35%), ease of use (33%), and availability of the service (32%) influenced their selection of services. Participants also heavily identified these aspects as areas requiring improvement. Around half of all respondents wanted enhanced data accuracy and indicated that they would like help to become familiar with the platforms.

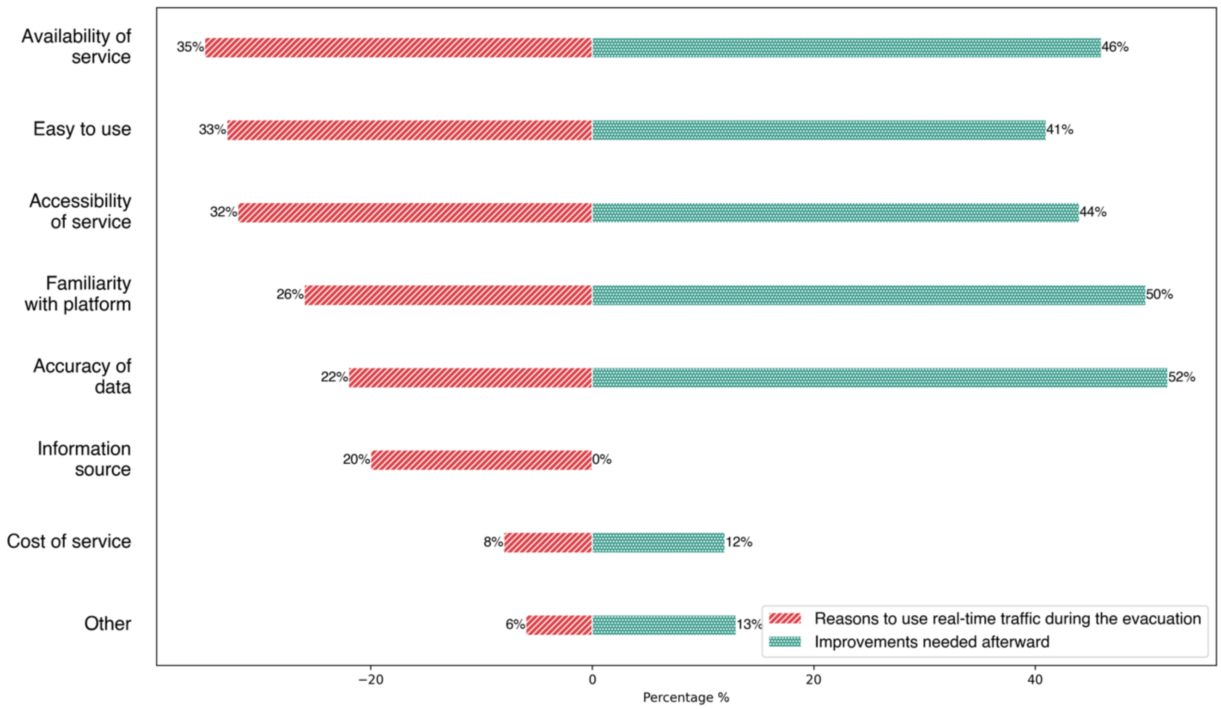


Figure 3.16: Motivations for using real-time traffic data platforms and desired improvements

3.3.3.3. Comparison with Post-Evacuation Return Results

The survey also asked respondents about their experiences with real-time traffic information when they were returning to their residence after the storm threat passed. As shown in Figure 3.17, most of the evacuees indicated that the post-storm real-time traffic data quality was the same compared to the initial evacuation for every hurricane. The number of people who rated the service better was significantly higher for Hurricane Rita, Hurricane Ike, Hurricane Harvey, and Hurricane Laura.

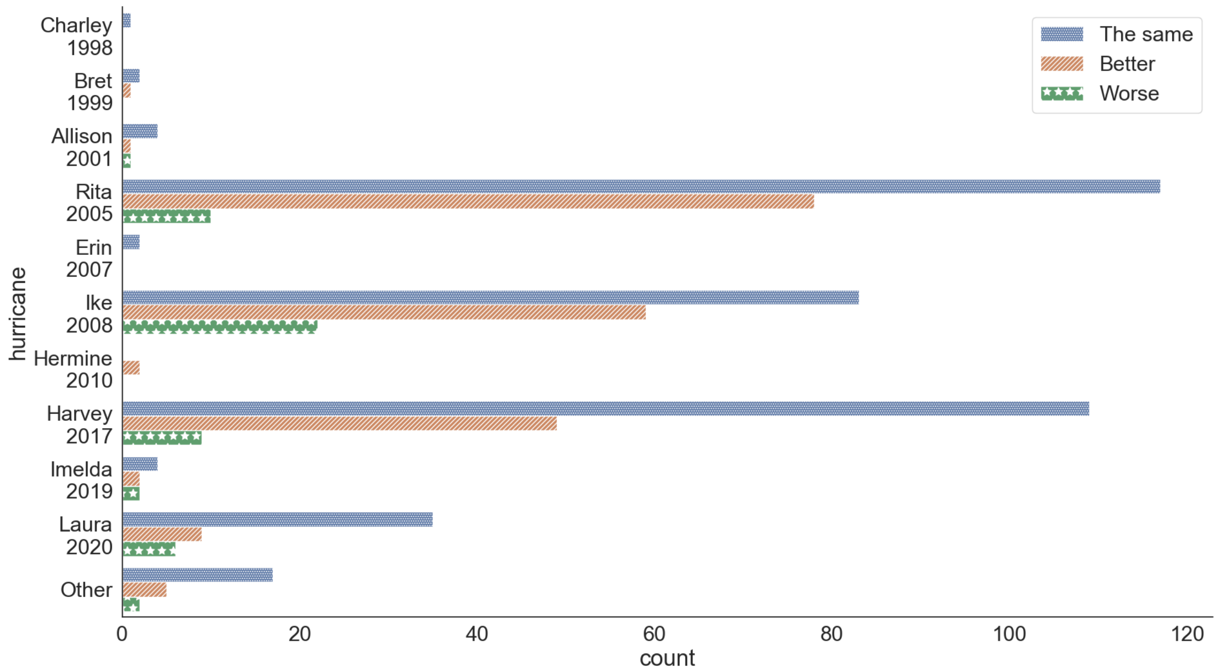


Figure 3.17: Data quality comparison between initial evacuation and return

Comparisons were drawn between factors that affected the initial evacuation as well as the post-evacuation return to the impacted area. Figure 3.18 shows the issues encountered during the evacuation and return. Approximately 25% of respondents reported no issues when evacuating; this percentage increased to 46% for the return. The main challenges during the evacuation were loss of phone or Internet service (18%), and inaccuracy (16%), unavailability (15%), and inaccessibility (14%) of real-time information. For the return trip, the focus shifted to concerns about loss of power service (17%), less information available about travel conditions (17%), and phone or Internet connectivity issues (15%).

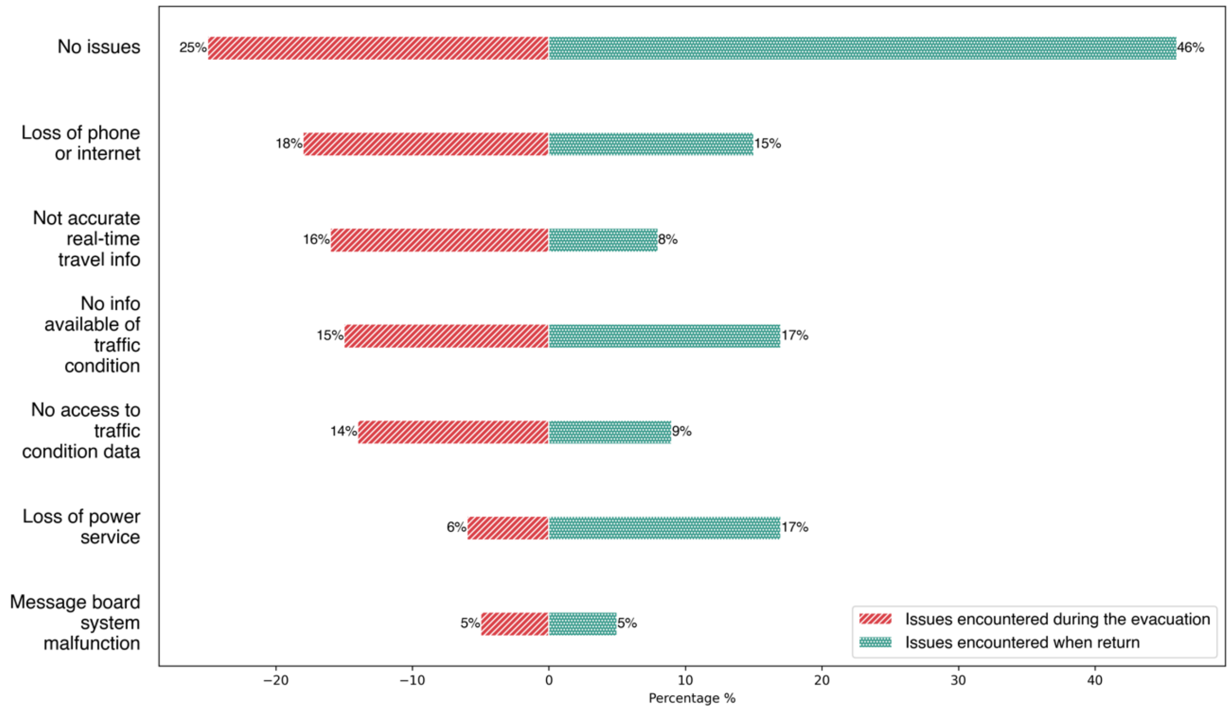


Figure 3.18: Challenges with real-time traffic data during evacuation and return

3.3.3.4. Non-Evacuee Responses

A different set of questions was given to participants who did not evacuate from hurricane events so that the reasons for individuals not evacuating could be understood. From Figure 3.19, around 38% of participants did not receive a mandatory evacuation order, and a similar number of participants believed it was safe to not evacuate and that they could handle the situation. As smart phones were not widely available during some past hurricane events, many people may not have had access to information announcing an evacuation order. If improved traffic monitoring data were accessible, about half of the participants who did not receive an evacuation order responded that they would evacuate, while only about 30% of those who believed it was safe would change their decision and evacuate. Many participants responded that they specifically did not live in an area that needed an evacuation.

The participants who did not evacuate in past events were also asked about service improvements that may increase the likelihood for them to evacuate. Figure 3.20 shows that non-evacuees care more about the availability, accessibility, and ease of use of existing services, with percentages over 30%. They also pay attention to the familiarity of the platform and the accuracy of the data, but not that much to the cost of service. During an evacuation event, there is intense demand for better service quality, and evacuees are less concerned about any potential costs of the services. Enhancing service availability and quality can grow the general public's confidence in evacuation safety and efficiency so that more people will be encouraged to evacuate in future hurricanes.

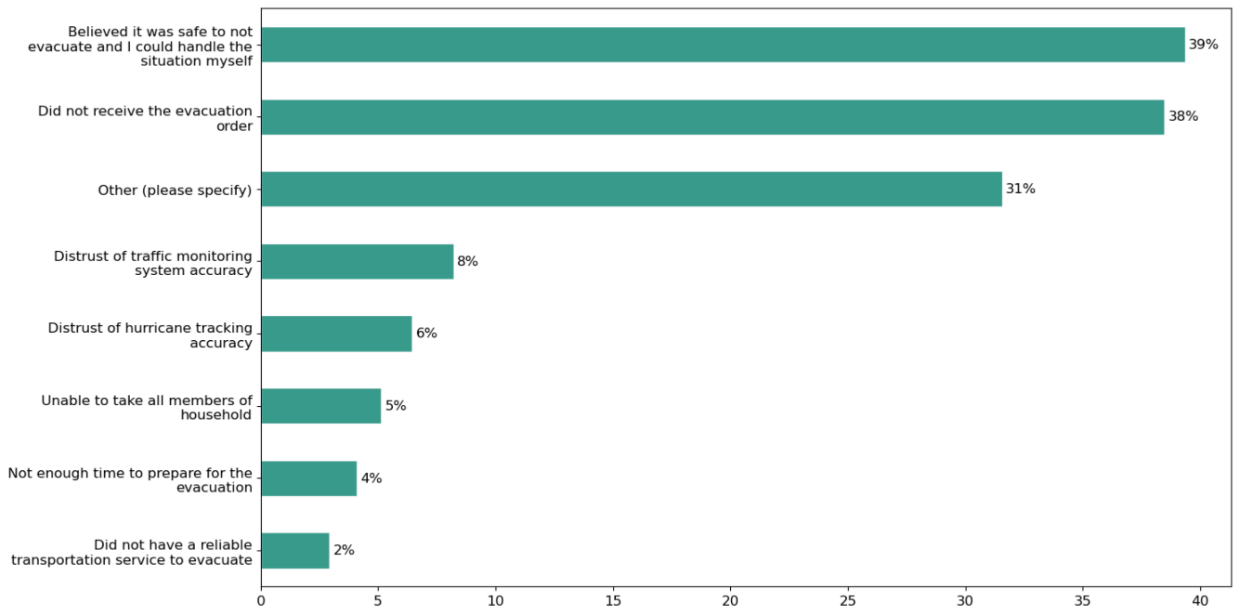


Figure 3.19: Reasons for not evacuating from hurricane events

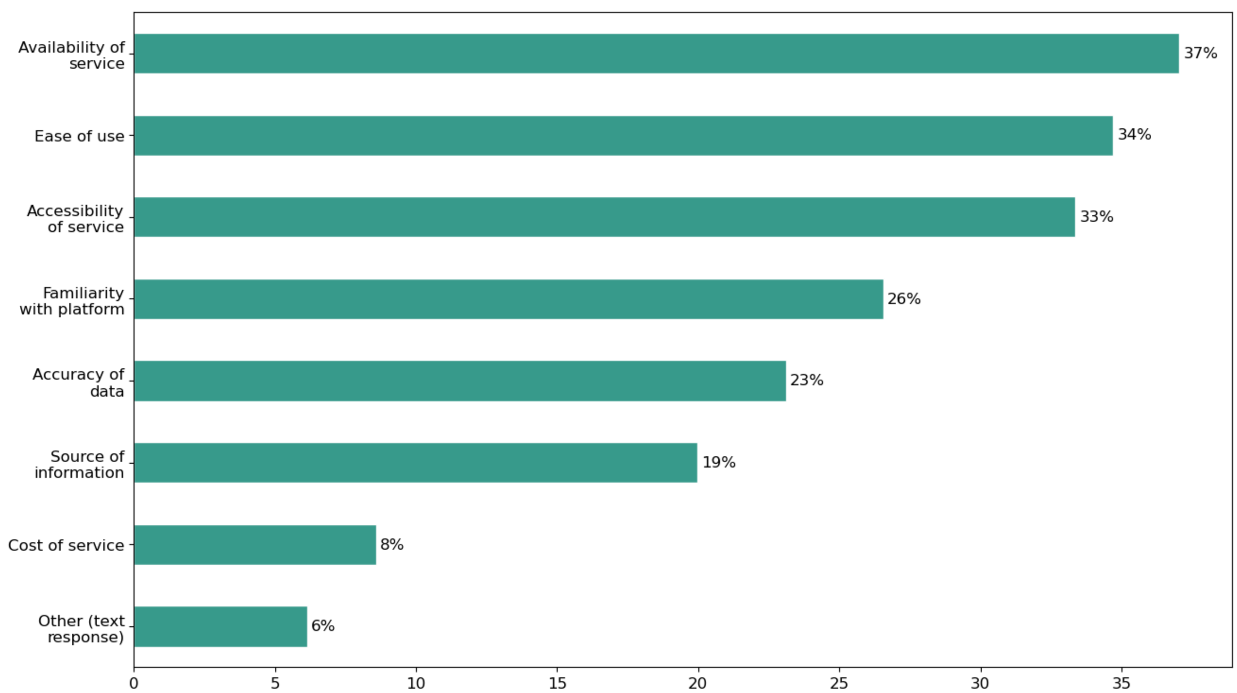


Figure 3.20: Service improvements that may encourage more people to evacuate

3.3.3.5. Additional Comments

In addition to the survey responses, individuals who follow the TxDOT Nextdoor account were engaged with the survey post. There were over 188 comments under the post, some of which were valuable to the research. Many commenters shared their experience with Hurricane Rita. Many mentioned that it was not a smooth evacuation, and it took over 10 hours to get to a safe destination. During the evacuation, there were also issues of congestion, flooded roads, and gas scarcity. Because of these issues, many individuals decided not to evacuate for any future evacuations, as they now think that evacuations are riskier than staying at home and riding out the storm. A few comments mentioned that traffic was better during voluntary evacuations. Individuals also commented that they were concerned about future hurricane evacuations as more electric vehicles on Texas roads may lead to issues if there are not enough EV charging stations installed along evacuation routes.

3.3.4. Survey Results Logistic Modeling

While a simple analysis of the survey results by response frequency helps us understand the types of respondents and the common issues faced, more insight into the specific types of information, platforms used, and issues encountered by evacuees may be obtained by using more sophisticated statistical methods. To enhance the significance of the findings acquired through the extensive survey techniques undertaken, logistic regression methods were used to further analyze and assess the data.

Understanding the utilization of real-time traffic monitoring system data is important for policymakers, traffic engineers, and emergency management staff to plan and manage evacuations as travel behavior during evacuations is markedly different than that under normal conditions. While many papers have discussed evacuee and non-evacuee behavior in hurricane-prone areas of the United States (Bian et al., 2022; Jiang, 2023; S. Wong et al., 2018; S. D. Wong et al., 2020), a limited number of studies have investigated the utilization of real-time traffic information, the motivations for its use, and the challenges encountered (DeYoung et al., 2016; Roy et al., 2022). This study focuses on understanding the utilization of real-time traffic data platforms during hurricane evacuations and the subsequent return, in past hurricane events in Texas, based on a survey conducted between August 2022 and February 2023. We further investigate households relying on real-time traffic information platforms by incorporating socioeconomic data and evacuation behavior of evacuees. After removing incomplete responses from the 889 valid responses from evacuees, the final evacuation dataset has 651 respondents who had past evacuation experience in Texas. Tables 3.1-3.3 present summary statistics of the dependent variables, socioeconomic variables, and evacuation behavior variables, respectively.

3.3.4.1. Response Variables

Table 3.1 shows the response variables in this study, which are treated as binary variables. We ran models to observe the impact of real-time data during an evacuation and post-event return and to examine differences among various data platforms. The binary response variables indicate usage of specific data platforms: navigation apps, social media, TV, radio, and official TxDOT information sources. We considered how platforms may be used for complementary purposes for disseminating information during the evacuation (Lindell et al., 2007).

Table 3.1 – Binary Response Variable Descriptions

Response Variables		Descriptions	Frequency
Total sample (N = 651)		Utilization of real-time traffic platforms during the evacuation	337 (51.77%)
		Utilization of real-time traffic platforms post evacuation (return)	215 (33.03%)
Evacuees using any real-time traffic platform (N = 337)	Navigation apps	Navigation apps including Google Maps, Waze, Apple Maps, etc.	179 (53.12%)
	Social media	Social media apps include Twitter, Facebook, etc.	66 (19.58%)
	TV	TV platform represents TV traffic or other weather channels.	102 (30.27%)
	Radio	Radio.	182 (54.01%)
	TxDOT info	TxDOT platforms such as the DriveTexas website, roadside DMS, in-person visit to a TxDOT Travel Information Center, phone calls to official resources such as TxDOT TIC and 511 system, law enforcement or TxDOT employees located along the evacuation route.	121 (35.91%)

Comments: Each frequency represents the count of respondents who selected this particular option, and the percentage is calculated by dividing the number of respondents by the total number of respondents. Choices were not mutually exclusive.

3.3.4.2. Explanatory Variables

Table 3.2 shows socioeconomic and demographic variables used in this model. All variables are binary except household (HH) size, which has six categories (i.e., 1, 2, 3, 4, 5, and 5+). Since ethnicity, age, HH income, and education influence evacuation likelihood (Bowser & Cutter, 2015; Gladwin et al., 2001; Huang et al., 2016), these variables are also included in this paper to better understand the real-time data platforms evacuees use and shed light on equity issues regarding access to these platforms. Drivers and non-drivers may use different information during an evacuation (and return), and household size may play a role, as large households may have more young or elderly members requiring care. The "multiple vehicles" variable is to identify different information patterns among one household, as they travel in multiple vehicles and may want to communicate en route.

Table 3.3 shows selected evacuation behavior explanatory variables. All variables are binary except the number of evacuations previously experienced. Characteristics such as departure time, evacuation distance, mode choice, and destination shelter type are included in the model based on past literature (Lindell et al., 2011). Previous evacuation experience may also influence a household's actions while evacuating and returning (Dow & Cutter, 2000; Thompson et al., 2017). We included a variable for evacuation experience prior to 2010 due to advancements in communication technologies (e.g., smart phones) in recent years (Dong et al., 2013).

Table 3.2 – Summary Statistics of Socioeconomic Explanatory Variables

	Total Sample		Real-time traffic data utilization	
Variables	**Mean**	**Std.Dev.**	**Mean**	**Std.Dev.**
Number of observations	**651**		**337**	
Driver	0.94	0.24	0.95	0.21
HH size	3.12	1.40	3.27	1.40
White (ethnicity)	0.78	0.41	0.76	0.43
Female	0.53	0.50	0.54	0.50
Age groups				
< 25	0.06	0.24	0.06	0.23
25-44	0.31	0.46	0.32	0.47
45-54 (base)	0.29	0.45	0.32	0.47
55-74	0.32	0.47	0.29	0.45
> 74	0.02	0.13	0.01	0.11
HH income				
< $25,000	0.05	0.22	0.06	0.24
$25,000 - $49,999	0.15	0.36	0.14	0.35
$50,000 - $99,999 (base)	0.29	0.46	0.30	0.46
$100,000 - $199,999	0.36	0.48	0.36	0.48
> $200,000	0.14	0.35	0.13	0.34
Education				
High school or less	0.28	0.45	0.27	0.45
Associate degree	0.10	0.30	0.10	0.30
Bachelor's degree (base)	0.37	0.48	0.41	0.49
Graduate degree	0.26	0.44	0.22	0.41
HH type (Owner)	0.79	0.41	0.79	0.41
Multiple vehicle	0.35	0.48	0.37	0.48

We included three variables related to the most common issues encountered during evacuation and return including congestion, gas station shortages, and road closures. In addition, we also included variables related to real-time traffic data usage: variables about the evacuee's purpose for using the real-time data, and the reasons or motivations behind their choice of selected real-time data platforms. Notably, the binary variable indicating the usage of the real-time traffic data during the evacuation is only included in the post-evacuation return model.

Table 3.3 – Summary Statistics of Evacuation Explanatory Variables

	Total Sample		Real-time traffic data utilization	
Variables	**Mean**	**Std.Dev.**	**Mean**	**Std.Dev.**
Number of observations	**651**		**337**	
Departure time (before hurricane lands)				
0-12 hour	0.20	0.40	0.20	0.40
12-24 hour	0.36	0.48	0.38	0.49

24-36 hour	0.30	0.46	0.28	0.45
36-48 hour	0.09	0.29	0.10	0.30
more than 48 hours (base)	0.04	0.20	0.05	0.22
Distance travelled to evacuate destination				
Within 50 miles (base)	0.17	0.37	0.14	0.34
51-100 miles	0.11	0.32	0.09	0.29
101-200 miles	0.33	0.47	0.37	0.48
more than 200 miles	0.39	0.49	0.40	0.49
Number of evacuations	1.64	1.01	1.72	1.01
Whether evacuated before 2010	0.82	0.38	0.80	0.40
Issues during evacuation				
Congestion	0.77	0.42	0.80	0.40
Gas stations shortages	0.48	0.50	0.50	0.50
Road closures	0.26	0.44	0.29	0.45
Shelter type				
friend or family (base)	0.61	0.49	0.61	0.49
hotel	0.21	0.41	0.24	0.43
other shelter	0.18	0.39	0.15	0.36
Mode choice				
Sedan (base)	0.25	0.43	0.23	0.42
SUV	0.44	0.50	0.45	0.50
Pickup truck	0.19	0.39	0.19	0.40
Other transport mode	0.12	0.32	0.12	0.33
Use of real-time traffic data during evacuation*	0.52	0.50	--	--
Purpose of using real-time data				
Selected departure time	--	--	0.31	0.46
Selected initial routes	--	--	0.66	0.47
Selected destination	--	--	0.29	0.45
Adjusted route or destination during evacuation	--	--	0.50	0.50
Monitored evacuation process	--	--	0.50	0.50
Checked the location and availability of gas stations, rest stops.	--	--	0.19	0.39
Motivations using real-time traffic platforms				
Accessibility of service	--	--	0.61	0.49
Ease of use	--	--	0.65	0.48
Availability of service	--	--	0.65	0.48
Accuracy of data	--	--	0.44	0.50
Cost of service	--	--	0.17	0.38
Familiarity with platform	--	--	0.50	0.50
Source of information	--	--	0.37	0.48
Other motivations	--	--	0.05	0.21

*: this variable is only used in the post-evacuation return model.

3.3.4.3. Methodology

We used binary logistic regression to analyze the survey results. This section presents the model structure and interpretation of the parameters (Harrell, 2015).

Model Structure

The logistic model investigates how a set of predictor variables $\boldsymbol{X}$ determines the response binary variable Y. Y is either 0 or 1, and $\boldsymbol{X}$ denotes the vector of predictors $\{X_1, X_2, \ldots, X_k\}$. Then, the statistical model can be expressed as Equation 3-1:

$$Prob\{Y\} = P\{Y = 1|\boldsymbol{X}\} = [1 + exp(-\boldsymbol{X\beta})]^{-1} \quad (3\text{-}1)$$

In this study, the response variable Y represents whether real-time traffic information platforms are adopted (during evacuation or post evacuation), or whether a specific real-time traffic platform is used (navigation app, social media, TV, radio, official sources from TxDOT). The vector of predictors $\boldsymbol{X}$ is composed of socioeconomic variables listed in Table 3.2 (e.g., ethnicity, age, education), and evacuation-related variables presented in Table 3.3 (e.g., number of evacuations, departure time, distance travelled). The regression parameters β are computed using maximum likelihood estimation.

Multicollinearity occurs in regression models if there is a correlation among independent variables, which affects the interpretation of regression results. Multicollinearity can be measured by the variance inflation factor (VIF); as a general rule, a VIF less than 5 means that predictor correlation will not negatively impact the analysis.

Parameter Interpretation

To interpret the results of logistic regression models, the odds ratio is introduced to determine the effect of a predictor variable on the outcome variable. The logistic regression model can be rewritten as Equation 3-2:

$$logit\{Y = 1|\, \boldsymbol{X}\} = logit(P) = log[p/(1-p)] = \boldsymbol{X\beta} \quad (3\text{-}2)$$

$\frac{p}{1-p}$ is the odds ratio of an individual evacuating (the ratio of probabilities that an individual will and will not evacuate). The model can be considered as a linear regression model in the logarithmic odds ratio. For the jth parameter in $\boldsymbol{\beta}$, the parameter β_j represents the change in the logarithmic odds ratio for every unit change in the corresponding predictor variable X_j, assuming X_j has no interaction with other factors and other factors are constant.

3.3.4.4. Model Results

Logit models were estimated to examine the impact of socioeconomic and evacuation variables. Results are summarized in Tables 3.4 and 3.5. Table 3.4 shows results for respondents who used real-time traffic data during their evacuation and return. Table 3.5 shows evacuee use preferences for different platforms. The results are reported as odds ratios: a value greater than 1 indicates a higher likelihood of using the platform than not. The VIF values for the explanatory variables in the models were less than 5, indicating that there is no significant multicollinearity among explanatory variables. The data was processed using Python, and the models were implemented in Stata 15.1.

Table 3.4 shows model results analyzing the utilization of real-time traffic platforms during the evacuation and return. An additional household member increases the odds of utilizing real-time traffic data by 1.176*. This suggests that a larger household size tends to increase the possibility of using these platforms during an evacuation, which is consistent with the results of Jiang (Jiang, 2023). Respondents less than 25 years old are less likely to utilize real-time information compared to those in the 45-54 age group. It could be explained that while younger people may rely more on technology, teenagers may often travel with parents or seniors during an evacuation, and in such cases, evacuation information is typically accessed by seniors at home.

Interestingly, household income does not signify a preference for using real-time traffic data. The analysis also reveals that households with a high school education or lower, as well as those with a graduate degree, are less likely to use these platforms.

Regarding evacuation behavior, households planning to depart 24-36 hours before storm landfall are less inclined to use real-time information compared to those leaving more than 48 hours in advance. This finding may suggest that “cautious” households likely to evacuate well ahead of the forecasted storm arrival are willing to use more real-time resources to aid with planning.

Households traveling 101-200 miles to their evacuation destination are more likely to rely on real-time traffic data. This suggests that individuals in this distance category would benefit more from using real-time information, whereas shorter-distance travelers are more familiar with the local roadway network and require less navigational aid. For those who travel longer than 200 miles during an evacuation, they may depart early to encounter less congestion, reducing their reliance on real-time traffic data.

For each additional prior evacuation experienced by a household, there is a 1.272* greater likelihood for using real-time traffic data. Although Wong et al. found that past hurricane experiences lowered the evacuation rates (S. D. Wong et al., 2020), it may reflect that past evacuation experiences would enhance the usage of traffic information sources for future evacuations. However, households with evacuation experience before 2010 demonstrate a lower tendency to use real-time traffic monitoring device data with a factor of 0.492**. This may be because emerging technologies such as smart phones are not widely spread.

For the post-evacuation return, two variables emerge as significant: ethnicity (white households are less likely to use real-time traffic data) and whether the household used such platforms during the evacuation process. If the household utilized information for evacuation, there is a strong likelihood for them to use it during their return, with an odds factor of 9.063***.

Table 3.4 – Logit Models for Real-time Traffic Information Platform Utilization

	Utilization of real-time traffic information platforms	
Variables	**During evacuation**	**Post-evacuation (return)**
Number of observations	N = 651	
Driver	--	--
HH size	1.176*	--
White	--	0.578*
Female	--	--
Age groups (base: 45-54)		
< 25	0.437*	--
25-44	--	--
55-74	--	--
> 74	--	--
HH income (base: $50,000 - $99,999)		
< $25,000	--	--
$25,000 - $49,999	--	--
$100,000 - $199,999	--	--
> $200,000	--	--
Education (base: Bachelor's degree)		
High school or less	0.610*	--
Associate degree	--	--
Graduate degree	0.520**	--
HH type (Owner)	--	--
Multiple vehicle	--	--
Departure time (base: more than 48 hours)		
0-12 hour	--	--
12-24 hour	--	--
24-36 hour	0.404*	--
36-48 hour	--	--
Distance travelled to evacuate destination (base: <= 50 miles)		
51-100 miles	--	--
101-200 miles	1.909*	--
more than 200 miles	--	--
Number of evacuations	1.272*	--
Whether evacuated before year 2010	0.492**	--
Issues during evacuation		
Congestion	--	--
Gas stations shortages	--	--
Road closures	--	--
Shelter type (base: friend or family)		
hotel	--	--
other shelter	--	--
Mode choice (base: Sedan)		

SUV	--	--
Pickup truck	--	--
Other transport mode	--	--
Use of real-time traffic data during evacuation	--	9.063***

Comments: 1) Results are odds ratios. 2) *, **, and *** indicate statistical significance at levels 0.1, 0.05, and 0.01, respectively. 3) HH represents household.

To explore distinctions among different platforms, we estimated five additional models summarized in Table 3.5. These models respectively focused on navigation apps, social media, TV, radio, and official sources (including the DriveTexas website, TxDOT roadside DMS, in-person visits or phone calls to a TxDOT Travel Information Center, the 511 system, and law enforcement or TxDOT employees located along the evacuation route).

The respondent's status as a driver does not significantly impact the platforms accessed. However, the presence of an additional household member has a positive association with using radio, with an odds ratio of 1.265**, perhaps because additional passengers in the evacuating vehicle not occupied with driving are available to help search for radio channels in the vehicle during the evacuation.

No age variable demonstrates a significant influence on platform usage, except for those of age 55-74, who are less likely to use TxDOT information platforms (odds ratio 0.457**). Regarding household income, households with income exceeding $200,000 are more likely to use navigation apps (odds ratio 2.298*). This finding aligns with the observation that higher income individuals usually undertake jobs accompanied by information communication technology, which gives them more chance to access information (Garrote Sanchez et al., 2021). In terms of education, those with a high school diploma or less and associate degree households show a higher likelihood of using social media for obtaining evacuation traffic information compared to households with a bachelor's degree. Conversely, respondents with a graduate degree are less likely to rely on social media, showing a divide between certain education levels and their perceived trustworthiness of different data platforms.

Time of departure time does not exhibit significant influence on the choice of data platforms. However, the distance to the destination does impact preference for specific platforms. Individuals traveling more than 50 miles show a clear preference for navigation apps, with odds ratios of 2.971*, 2.721**, and 2.324** for the travel distance categories of 51-100 miles, 101-200 miles, and >200 miles, respectively. This indicates that evacuees traveling greater distances benefit more from using navigation apps with real-time traffic layers than evacuees who remain within 50 miles of their origin during an evacuation. Additionally, as the distance increases, there is a reduced reliance on navigation apps, resulting in lower odds ratios, which suggests that individuals tend to depart early to encounter less congestion.

Households with more prior evacuation experience prefer navigation apps and social media platforms (odds ratios 1.766*** and 1.518**), while households with evacuation experience prior to 2010 are more likely to use radio and TV (odds ratios 2.362* and 3.952***). This aligns with existing literature (Dow & Cutter, 2000; Robinson & Khattak, 2011). As households gain more experience, they may become more familiar with real-time updates provided by navigation apps and social media platforms. It should be noted that households with evacuation experience before 2010 are limited to data platforms, and they may develop habits and preferences for traditional information sources such as radio and TV.

Regarding the challenges encountered during evacuations, respondents who experienced congestion during an evacuation tend to use radio as a source of traffic information (odds ratio 2.223**). This is likely because radio was a common in-vehicle data source in 2005 when the severely congested Hurricane Rita evacuation occurred.

Regarding the purpose of using specific platforms, TV and radio are used more for selecting departure time, while social media platforms are favored for destination selection. This may be because televisions are used primarily for checking departure times through local news shows (Ye et al., 2010), rather than for making mid-route decisions during the evacuation. Conversely, evacuees may access social media platforms to gain up-to-date, qualitative information from posts or comments about destination feasibility. Additionally, households rely on a combination of social media, radio, and TxDOT platforms to make route adjustments and monitor evacuation progress. Radio is a convenient in-vehicle resource during the evacuation, and social media could provide extra information regarding evacuation conditions along the route.

Among navigation app users, platform familiarity (odds ratio 3.606***) is highly valued, followed by platform ease of use (odds ratio 1.734*). Similarly, social media users prioritize platform familiarity and information credibility (odds ratios 4.303*** and 1.924*). TV users prioritize service accessibility (1.989**), and similar findings were reported by Ye et al. (2010). On the other hand, radio users prioritize service availability (2.770***), which was identified as the most common source of traffic information during evacuations (DeYoung et al., 2016; Dow & Cutter, 2000; Robinson & Khattak, 2011). Finally, users of TxDOT information platforms pay particular attention to data accuracy (2.069**).

Table 3.5 – Logit models for different real-time traffic platforms

	Navigation app	Social Media	TV	Radio	TxDOT info
Number of Observations			N = 337		
Driver	--	--	--	--	--
HH size	--	--	--	1.265**	--
White	--	--	--	--	--
Female	--	--	--	--	--
Age groups (base: 45-54)					
< 25	--	--	--	--	--

25-44	--	--	--	--	--
55-74	--	--	--	--	0.457**
> 74	--	--	--	--	--
HH income (base: $50,000 - $99,999)					
< $25,000	--	--	--	--	--
$25,000 - $49,999	--	--	--	--	--
$100,000 - $199,999	--	--	--	--	--
> $200,000	2.298*	--	--	--	--
Education (base: Bachelor's degree)					
High school or less	--	2.700**	--	--	--
Associate degree	--	4.639***	--	--	2.924**
Graduate degree	--	0.267*	--	--	--
HH type (Owner)	--	--	--	--	--
Multiple vehicle	--	--	1.791*	--	--
Departure time (base: more than 48 hours)					
0-12 hour	--	--	--	--	--
12-24 hour	--	--	--	--	--
24-36 hour	--	--	--	--	--
36-48 hour	--	--	--	--	--
Distance travelled to evacuate destination (base: <= 50 miles)					
51-100 miles	2.971*	--	--	0.310*	--
101-200 miles	2.721**	--	--	--	--
more than 200 miles	2.324*	--	0.458*	--	--
Number of evacuations	1.766***	1.518**	--	--	--
Whether evacuated before year 2010	--	--	2.362*	3.952***	--
Issues during evacuation					
Congestion	--	0.384*	--	2.223**	--
Gas stations shortages	--	--	--	--	--
Road closures	--	--	--	--	--
Shelter type (base: friend or family)					
hotel	--	0.407*	--	--	--
other shelter	--	--	--	--	--
Mode choice (base: Sedan)					
SUV	--	--	--	2.549**	--
Pickup truck	--	--	--	--	--
Other transport mode	--	--	--	--	--
Purpose of using real-time data					
Selected departure time	0.279***	--	2.945***	2.312**	--
Selected initial routes	--	--	--	--	--
Selected destination	--	2.201*	--	--	--
Adjusted route or destination during evacuation	--	--	--	--	1.710*
Monitored evacuation process	--	2.425**	--	1.966**	--

Checked the location and availability of gas stations, rest stops, etc.	--	--	--	--	--
Motivations using real-time traffic platforms					
Accessibility of service	--	--	1.989**	--	--
Ease of use	1.734*	--	--	0.531*	--
Availability of service	--	--	--	2.770***	--
Accuracy of data	--	0.397**	--	--	2.069**
Cost of service	--	--	--	--	--
Familiarity with platform	3.606***	4.303***	--	--	0.389***
Source of information	0.548*	1.924*	2.040**	2.303***	1.873**
Other motivations	0.250*	--	--	--	--
Constant	-1.05	-1.05	-1.786	-2.693*	-1.036

Comments: 1) Results are odds ratios. 2) *, **, and *** indicate statistical significance at levels 0.1, 0.05, and 0.01, respectively. 3) HH represents household.

3.4. Texas Department of Public Safety Outreach Efforts

Activities were completed to obtain input from DPS employees. Research team members met with a panel of DPS employees at a virtual meeting on April 7, 2022, to discuss the applicability of the research project to DPS operations and to ask questions regarding DPS use of real-time traffic monitoring data during evacuation events. During the meeting, a DPS captain from the Highway Safety Operations Center shared insights on how DPS uses real-time traffic information during an evacuation.

From the virtual call with DPS officials, the researchers were able to learn about the real-time methods that are used to assist in evacuations. DPS uses an internal ESRI-based mapping system called TXMAP that overlays with data from Google, Waze, and other public sources, such as the traffic information from TxDOT's Drive Texas website, and weather information from NOAA. Field sources are also used to accumulate additional traffic data. These are the main real-time methods that have been used for pre-event unit placement, disaster response during the event, and post-disaster recovery. Patrol officers can use their mobile devices or computers to access TXMAP in the field to make "real time" decisions at a front-line point level.

3.5. Texas Department of Transportation Outreach Efforts

Extensive work was undertaken to collect data on ITS devices, hurricane operations, and past lessons learned from TxDOT employees. Virtual calls with members of the PMC, online workshops, and email correspondence were performed to acquire both qualitative, anecdotal data and quantitative data on ITS device assets. These efforts led to extensive amounts of data being collected, and a more complete discussion of these TxDOT outreach activities is provided in Chapters 5 and 6.

3.6. Summary

This chapter summarizes efforts to collect data from stakeholders who have experienced a past hurricane evacuation in Texas to understand current perceptions, common issues, and potential improvements of the real-time traffic monitoring systems. The research team selected three stakeholder groups, including members of the general public, DPS employees, and TxDOT employees. A survey was created using the Qualtrics platform to obtain input from members of the public. Survey questions were designed to learn how members of the public interacted with real-time traffic monitoring systems during past hurricane evacuations. The survey was distributed to emails accounts obtained through a Texas DPS database and a post on the TxDOT Nextdoor social media account.

A total of 1510 responses were received for the public survey and about 59% respondents participated in at least one hurricane evacuation in the past in Texas. Respondent demographics were well distributed but are weighted toward the user characteristics of Nextdoor. The respondents tend to be white, middle-class homeowners, with tertiary-level education.

The use of various real-time traffic information platforms and the challenges and motivations associated with their usage were analyzed. It was found that evacuees predominately rely on radio and navigation apps, and that these data platforms are more commonly used for selecting routes, both initially and re-routing mid-evacuation. The choice to use these platforms depends on service availability, ease of use, and accessibility. Two areas of improvement were identified: enhancing the accuracy of real-time data and providing educational resources to increase user awareness of the available platforms. Ensuring uninterrupted phone or internet service, increasing the availability of traffic data, and providing continuous power service during evacuations are also important.

We also investigated socioeconomic and behavioral differences in the utilization of real-time traffic platforms during evacuations and return. We found that households with more members, longer evacuation travel distances, and a history of multiple evacuations are more inclined to use real-time data platforms. Respondents under the age of 25, those with a graduate degree or a high school education or lower, and those who evacuated before 2010 are less likely to use real-time traffic information platforms.

To gain a deeper understanding of each traffic information platform, we estimated additional models for navigation apps, social media, TV, radio, and TxDOT platforms. We found that respondents who evacuated prior to 2010 were more likely to rely on radio and TV for traffic updates, showing how technological advances may impact preferences since smart phones were not popular before 2010. Conversely, respondents with more past evacuation experience tend to use navigation apps and social media apps for obtaining traffic information. Furthermore, users of official information sources highly value data accuracy, while TV users prioritize the accessibility of the information, and radio users place an emphasis on the availability of the service.

These findings provide valuable insights for researchers and policymakers regarding emergency evacuation preparedness in Texas. By understanding the patterns and preferences of evacuees in accessing and using real-time traffic information, stakeholders can make informed decisions about the best ways to improve the effectiveness and efficiency of disaster response operations and better understand the benefits of expanding or upgrading traffic monitoring devices in the state.

A potential limitation of our findings is self-selection bias in the sample demographics. Particularly, white females from high-income households were overrepresented in the data, which may be due to the platforms used for survey distribution (Nextdoor and email). Future research should investigate similar questions among a more diverse sample to improve the understanding of this topic.

Chapter 4. Develop Recommendations for Monitoring System Expansion

4.1. Introduction

The objective of this chapter is to identify locations for evacuation traffic monitoring device system revision and expansion in urban and rural Texas areas. To accomplish this, the project team conducted a hurricane evacuation study (HES) using network analysis and simulation techniques in the coastal regions of the state. Network simulation takes the physical road network and abstracts its components into links and nodes, where links represent roadways and nodes represent travel origins, destinations, or interchanges where vehicles may transfer from one link to another. The HES is designed to represent real-world hurricane evacuation characteristics to determine the traffic demand, flow, and congestion in the Texas evacuation network. The results of this simulation are used to determine which nodes and links experience the most congestion and may potentially benefit the most from the addition of new real-time traffic monitoring devices such as CCTV cameras.

Traffic monitoring devices can aid evacuation efficiency and safety by providing evacuees and officials with real-time information on traffic conditions, route options, and incident detection. This allows users to select more efficient travel routes with fewer delays and allows officials to recognize incidents such as crashes, stalled vehicles, and blocked travel lanes more quickly. Therefore, determining the best locations for the placement of traffic monitoring devices on Texas roadways is necessary to optimize the potential benefits of these devices in evacuation events.

To conduct the HES, researchers performed two case studies to understand the evacuation conditions and potential impact of traffic monitoring devices in coastal Texas roadways. The following sections of this chapter detail the methodology, results, and recommendations for traffic monitoring device system expansion in the Texas evacuation network.

4.2. Methodology

4.2.1. Overview

The evacuation simulation process consists of three main components, as shown in Figure 4.1. First, the network model must be constructed. This means creating a computer model of hypothetical links and nodes that accurately represent the actual evacuation network. Second, the demand for each county must be estimated for the different storm scenarios. Finally, the outputs from the previous two steps are used as inputs in the simulation analysis, and the results of the simulations inform the researchers' recommendations for the traffic monitoring system expansion.

To simulate hurricane evacuations along the Texas Gulf Coast, two case studies of regions that have been frequently impacted by hurricanes in the past were selected to convey the impacts on the road network in different geographies. The first (Case Study 1) represents a hypothetical hurricane striking the Houston-Galveston area, with a total of 11 counties experiencing some amount of evacuation. This simulates a cyclonic storm event striking the eastern portion of the Texas coast, such as hurricanes Laura (2020), Ike (2008), and Rita (2005), among others. The second (Case Study 2) represents a cyclonic event striking further south along the Texas coast near Corpus Christi. This is similar to past events such as hurricanes Harvey (2017) and Celia (1970).

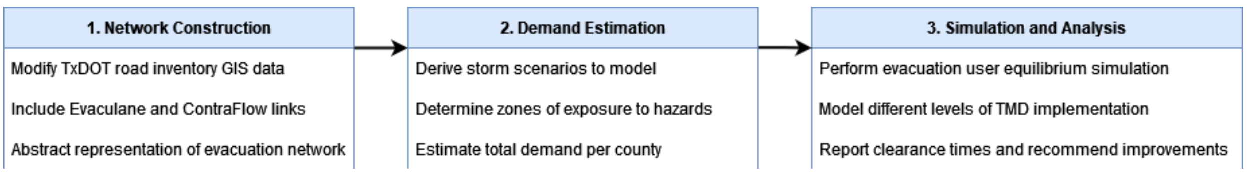


Figure 4.1: Framework for HES simulation

To select the counties from which people would evacuate, a standard storm width must be determined. Literature indicates that storm sizes vary widely but that cyclones in the northern hemisphere typically have longer eastern tails than western tails. A past study found that for "average" cyclones, "hurricane-force winds extend forward and to the right about 50 to 100 km from the eye and 25 to 50 km to the left" (Keim et al., 2007). Figure 4.2 shows hurricane profiles assumed in this study, which quantified the occurrence and distribution of hurricanes in the US from 1901 to 2005.

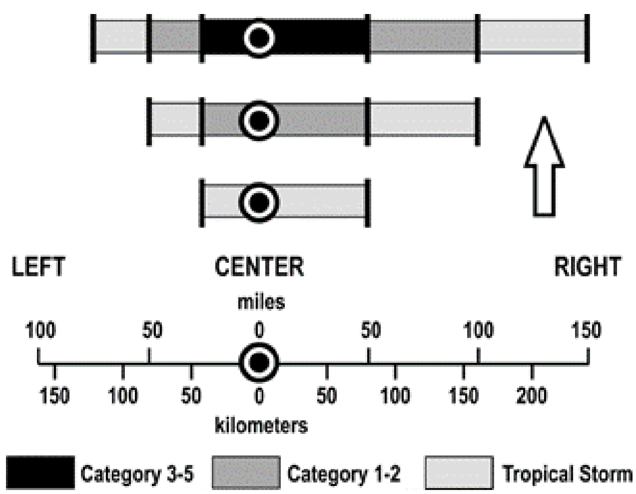
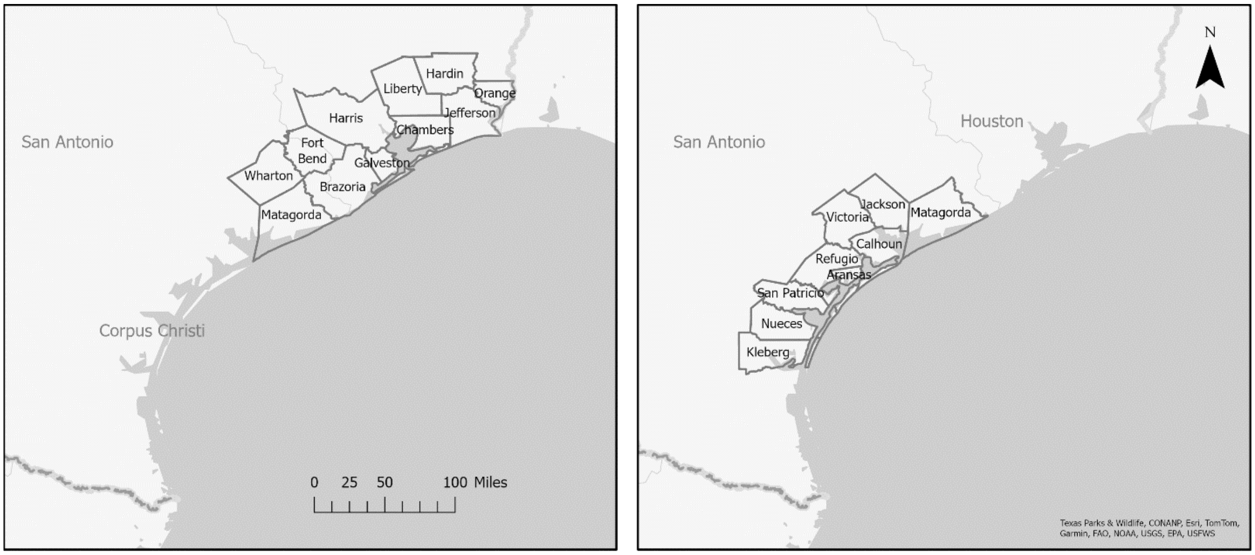


Figure 4.2: Kiem et al. (2007) model of typical cyclonic storm widths by severity

Based on this information, a "typical storm width" of approximately 150 miles (100 miles to the right and 50 miles to the left of an assumed storm center track) was used to determine the counties that would be impacted by such a storm for each case study. It was assumed that these counties are the only ones from which people would be evacuating. Case Study 1 contains eleven counties: Matagorda, Wharton, Brazoria, Fort Bend, Galveston, Harris, Chambers, Liberty, Hardin, Jefferson, and Orange, while Case Study 2 contains nine counties: Kleberg, Nueces, San Patricio, Aransas, Refugio, Calhoun, Victoria, Jackson, and Matagorda. Figure 4.3 shows the locations of the study area counties for both case studies.



a) Case Study 1 *b) Case Study 2*

Figure 4.3: Study locations for HES

To accomplish the tasks necessary to model the evacuation network, the project team employed a variety of data sources that provided the desired information. A summary of the data sources used in the simulation are shown in Table 4.1.

Table 4.1 – Summary of data sources for network simulation

Dataset	**Description**	**Source**	**Type**
TxDOT Roadway Inventory	Complete linework and attribute information for Texas roadways	Texas Department of Transportation	GIS layer
SLOSH Storm Surge Extent Estimates	Estimated inundation extents for storm surge flooding for various hurricane intensities	National Oceanic and Atmospheric Administration	GIS layer
County and census tract boundaries	Map linework for Texas counties and census tracts	US Census Bureau	GIS layer
Tract level census data	Population counts from 2020 census at tract level	US Census Bureau	Data tables
TxDOT Evacuation Routes	Statewide Texas hurricane evacuation routes, contraflow, and Evaculanes	Texas Department of Transportation	GIS layer

4.2.2. Network Structure Construction

The simulation network model was constructed from the evacuation route network defined by TxDOT, which largely covers the coastal Texas region that may be impacted by hurricane events.

In this study, it is assumed that all evacuees use the major evacuation routes to reach their destinations.

Figure 4.4 shows the final network with toll roads and centroid connectors.

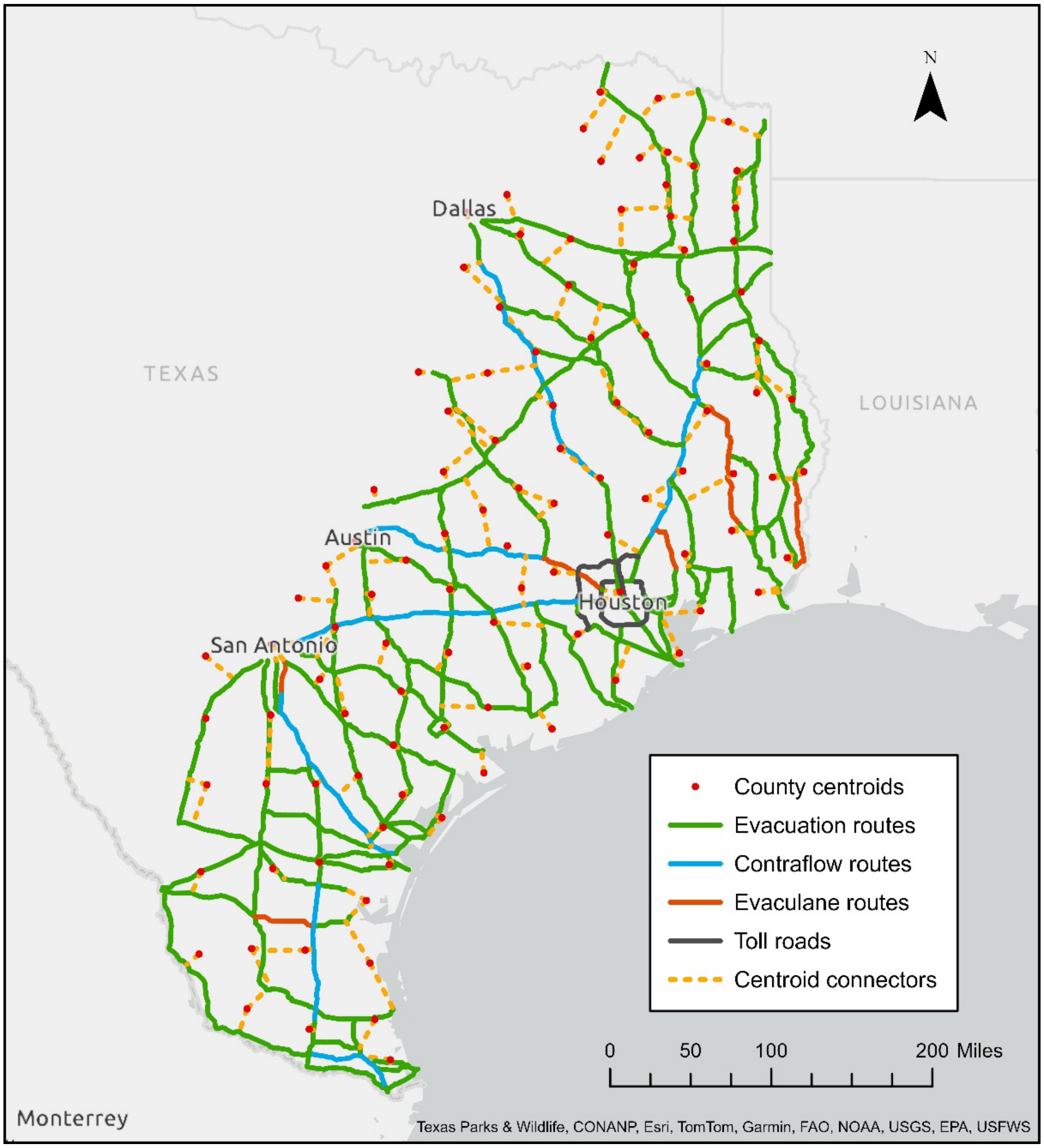


Figure 4.4: Evacuation network map

During Hurricane Laura, Texas Governor Greg Abbott ordered that all tolls along TxDOT's portion of SH99/Grand Parkway in the Houston area be temporarily waived (Office of the Texas Governor, 2020). Harris County Judge Lina Hidalgo also granted free passage for travelers on Harris County Tollway (Harris County Toll Road Authority, 2020). Therefore, this study assumes that the Sam Houston Tollway, SH99/Grand Parkway, and Hardy Toll Road are free to the public during an evacuation, and these toll roads are included in the base network model. Since in emergencies, transportation agencies may undertake actions such as reversing opposing travel lanes for evacuation, a practice known as “contraflow,” and opening roadway shoulders to create an additional travel lane, known as “Evaculanes,” a second network was developed to model the potential outcomes of such capacity-increasing emergency response activities. Contraflow roads were modeled such that all travel lanes were shifted to the evacuation outbound direction, and the Evaculane routes were modeled as an additional lane in the evacuation outbound direction.

For both cases, the evacuation route network was simplified and modeled in standard GIS software. The links represent roadways, and the nodes represent intersections or simplified interchanges. The evacuation process was modeled as evacuees traveling from origin nodes that were impacted by the hurricane to “safe” destination nodes. The origin nodes of the evacuation were assumed to be at the geometric centroid of counties that are within a 20-mile radius of a major evacuation route. These origins were then connected to the network perpendicularly through the two closest roadway links, creating a hypothetical “centroid connector” link. Centroid connectors model the lower functional classification roadways that evacuees use to travel to the modeled major evacuation routes. Centroid connectors were modeled with an infinite capacity and free flow speeds sufficient to connect evacuees to the network in a single simulation timestep.

Evacuees’ destinations were represented by a single “safe” hypothetical sink node. All the vehicles reaching the western boundary of the network would be sent to this node and assumed to reach safety. Under this formulation, evacuees were routed to safety and not to specific locations. While this assumption may reduce simulation accuracy, it also greatly reduces the data preprocessing and the computational requirements from a modeling perspective. The survey results collected in Task 3 showed that the top five most-common destinations for actual evacuees were: 1) Harris County (Houston), 2) Dallas County (Dallas), 3) Travis County (Austin), 4) Bexar County (San Antonio), and 5) Brazos County (College Station). Most of these metro areas are located along the I-35 corridor, and therefore the nodes for these counties were directly connected to the “safe” sink node as a vehicle reaching one of these locations is considered to have reached “safety.” As a note, Harris County was the most common response for the destination from the public survey, which may represent individuals who drove from an at-risk area along the coast to a safe location in the north or western region of the Houston area.

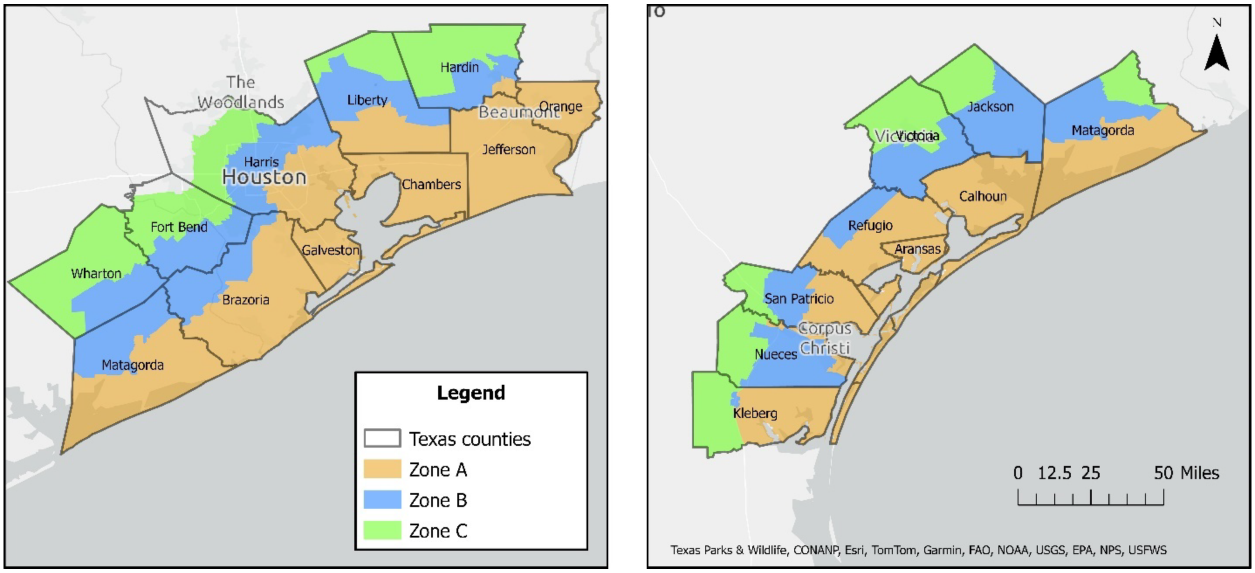
Simulating routing behavior of evacuation traffic requires an estimate of link capacity and travel time. The lane number and speed limit attributes of the evacuation routes were obtained from the TxDOT roadway inventory GIS layer attributes, and the capacity assumptions used by Boyles (2013) were adopted, namely: 1) roadway capacity is 2,000 vehicles per hour per lane; 2) jam density is 240 vehicles per lane per mile; and 3) free flow speed is equal to the posted speed limit. For simplification purposes, the network construction assumed a uniform number of lanes and a consistent speed limit for all road segments in a single continuous corridor; the specific numbers adopted were based on the number of lanes and speed limit that made up the greatest proportion of the corridor.

4.2.3. Demand Formulation

During a hurricane event, not all residents of an impacted region will evacuate. Residents in parts of the region most exposed to hazardous wind or water conditions are the most vulnerable to hurricane hazard impacts and are more likely to evacuate. Researchers employ a variety of methods to accurately estimate the number of people or, more precisely, the number of vehicles that will be evacuating in a storm event.

To estimate the number of vehicles evacuating at a county-level resolution, the project team derived risk zones. The risk zones have varying amounts of potential exposure to storm surge from tropical storm or hurricane events. Zone A has the highest exposure and represents locations closest to the coast and potential flooding; Zone B has the second-highest exposure and represents areas that are not immediately on the coast but may still experience damages from the hurricane event; and Zone C represents the locations that are furthest from the expected impact zones and only exposed to minor damages, and therefore fewer of its residents will evacuate.

Storm surge was used as the primary hazard mode for predicting evacuation volumes. While wind events may be damaging, the most hazardous aspect of a cyclone event is storm surge, which involves a massive uplift of water due to pressure and wind from the cyclone. Storm surges can be very dangerous, resulting in severe flooding that can lead to property destruction, injuries, and fatalities. Many variables play a role in a given event's storm surge height such as wind speed, air pressure, depth of the sea floor, tide level, and more. Therefore, the storm intensity, commonly measured using the Saffir-Simpson Hurricane Wind Scale, which uses "Categories" to convey storm severity using only the observed sustained wind speed of a storm, is not directly included in the modeling. Instead, the risk zones were estimated using high-tide storm surge flooding extents for a Category 1 storm. GIS raster data from the NOAA storm surge viewer tool was used to assign risk zones to each census tract within the impacted counties for both case studies. Each census tract within the counties of interest was assigned a risk zone (A, B, C, or None, as described above) representing differing storm surge severity and evacuation rates. This overall approach is similar to that employed by previous HES projects, such as the Texas Coastal Bend Hurricane Evacuation Study (Peacock et al., 2020). Figure 4.5 shows the final risk zones that were used for estimating the evacuation demand per county for each case study.



a) Case Study 1 *b) Case Study 2*

Figure 4.5: Map of evacuation risk zones

Next, the total demand per county was estimated using data from the 2020 US census. This data was merged with the geographic risk zone data, such that the resulting datasets contained both population counts per census tract and information on which risk zone each census tract was assigned to (United States Census Bureau, 2022a, 2022b). This gave the total population per county residing in each risk zone.

For estimation of the fraction of each risk zone population that would evacuate, existing literature and the general public survey results were consulted. A plethora of post-evacuation survey studies exist detailing the origins of evacuees and the fraction of each county that evacuated for a given hurricane. These studies indicate that the percentage of a county that evacuates varies greatly depending on the storm and the location of the county relative to the coast and center of the storm track. Existing literature for Texas (Bierling et al., 2020) and Louisiana (Gottumukkala et al., 2011) indicates that in locations closest to the coast and the eye of the storm (i.e., risk zone A), around 75–100% of the population evacuates in advance of a storm. In areas that border these locations but are not as close to the storm eye (i.e., risk zone B), around 60–74% of the population evacuates. Finally, the impacted regions that are farthest from the storm track and coast (i.e., risk zone C) see around 40–59% of the population evacuate.

In the 2021 Coastal Bend Hurricane Evacuation Study (Mullins III et al., 2020), the base demand case scenario assumed that 75% of the population in Zone A evacuated, 51% of the population in Zone B evacuated, and 40% of the population in Zone C evacuated. This study also assessed other scenarios where higher rates of evacuation were assumed—90%, 66%, and 55% for zones A, B, and C, respectively—and another scenario where 100% of the population evacuated for all three zones in each county.

The researchers analyzed the general public's responses to the query, "Zip code of residence at time of hurricane event," from the Qualtrics survey conducted in Task 3 for both people who evacuated and who did not evacuate and compared them with the previously mentioned results from the literature. The zip codes were converted to county locations, and the percentage of people who evacuated and did not evacuate was calculated for each county from the responses received. These results are rough estimates that represent the total fraction of each county that evacuated for all past hurricanes, not for any specific event. Table 4.2 summarizes the fraction of the population that evacuated for the seven most reported counties of residence from the Qualtrics survey, out of 1,796 valid survey responses. The results appear to be consistent with those found in the literature, with over 80% of respondents from the most exposed coastal counties reporting that they evacuated, and 60–70% of respondents from other coastal counties reporting evacuating.

Table 4.2 – Percent of each county that evacuated, based on survey results

County	% of total responses	% of population evacuated	% of population not evacuated
Harris	38.9	70.8	29.2
Galveston	7.8	86.4	13.6
Fort Bend	6.6	63.9	36.1
Brazoria	4.0	85.9	14.1
Montgomery	3.7	61.8	38.2
Jefferson	3.3	96.6	3.4
Nueces	2.6	72.9	27.1

Therefore, to account for both existing literature and this study's survey results, the research team assumed that 75% of households within Zone A, 60% of households within Zone B, and 50% of households within Zone C would evacuate for this HES.

Existing literature shows that in past Texas and Louisiana hurricane evacuations, 1.25–1.75 vehicles per household were used depending on the storm event (Maghelal et al., 2017; Lindell et al., 2013; Wu et al., 2013). In the general public Qualtrics survey, respondents from households with less than 5 members who evacuated with only one vehicle (620 responses of 1,796) reported 2.7 people in that vehicle, on average. When assuming that households who reported using "more than one vehicle" to evacuate used exactly two cars, the average number of vehicles used for evacuating was approximately 1.36 per household, with the true value being slightly higher. Therefore, when accounting for the values found in the literature and the Qualtrics survey, it was assumed that each household would use 1.5 vehicles to evacuate for this HES simulation. The total county-level demand for Case Study 1 is shown in Table 4.3 and for Case Study 2 in Table 4.4.

Table 4.3 – Total county-level demand for Case Study 1

#	County	# vehicles evacuating
1	Brazoria	147,151
2	Chambers	18,314
3	Fort Bend	168,643
4	Galveston	167,093
5	Hardin	22,014
6	Harris	1,527,455
7	Jefferson	122,565
8	Liberty	30,498
9	Matagorda	19,881
10	Orange	42,618
11	Wharton	13,900

Table 4.4 – Total county-level demand for Case Study 2

#	County	# vehicles evacuating
1	Aransas	23,336
2	Calhoun	17,859
3	Jackson	9,703
4	Kleberg	11,448
5	Matagorda	18,611
6	Nueces	155,362
7	Refugio	9,285
8	San Patricio	29,441
9	Victoria	41,218

The final component of the demand estimation is to determine a profile for departure time. Existing literature, including the Coastal Bend Hurricane Evacuation Study (Bierling et al., 2020), provides survey results for evacuees' reported departure times during past hurricanes. Figure 4.6 shows the departure times from this report. Figure 4.7 shows the cumulative evacuation fraction over time for Hurricane Mathew (Pham et al., 2020).

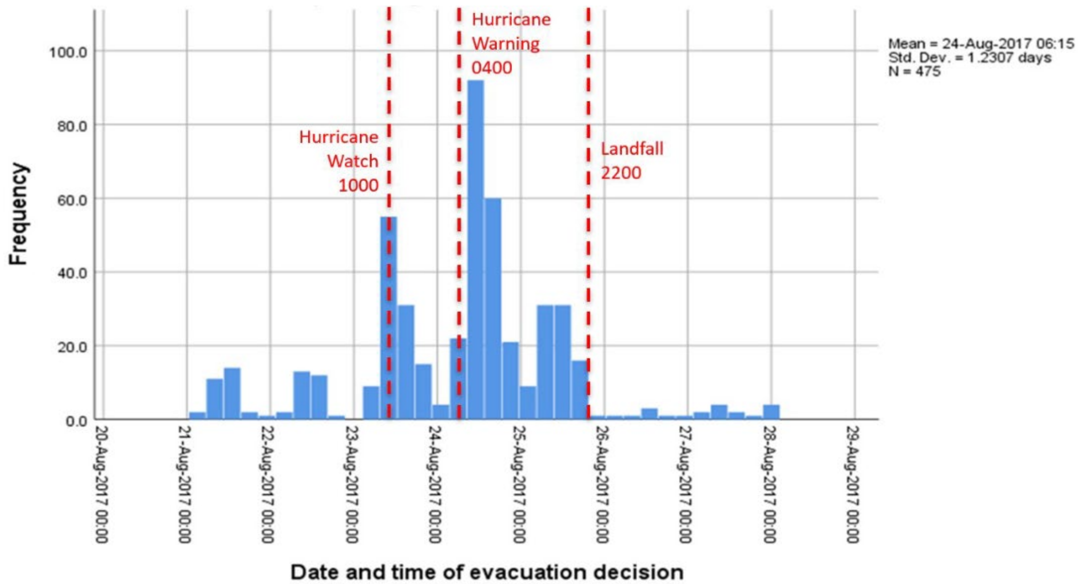


Figure 4.6: Bierling et al. (2020) reported evacuation departure times for Hurricane Harvey

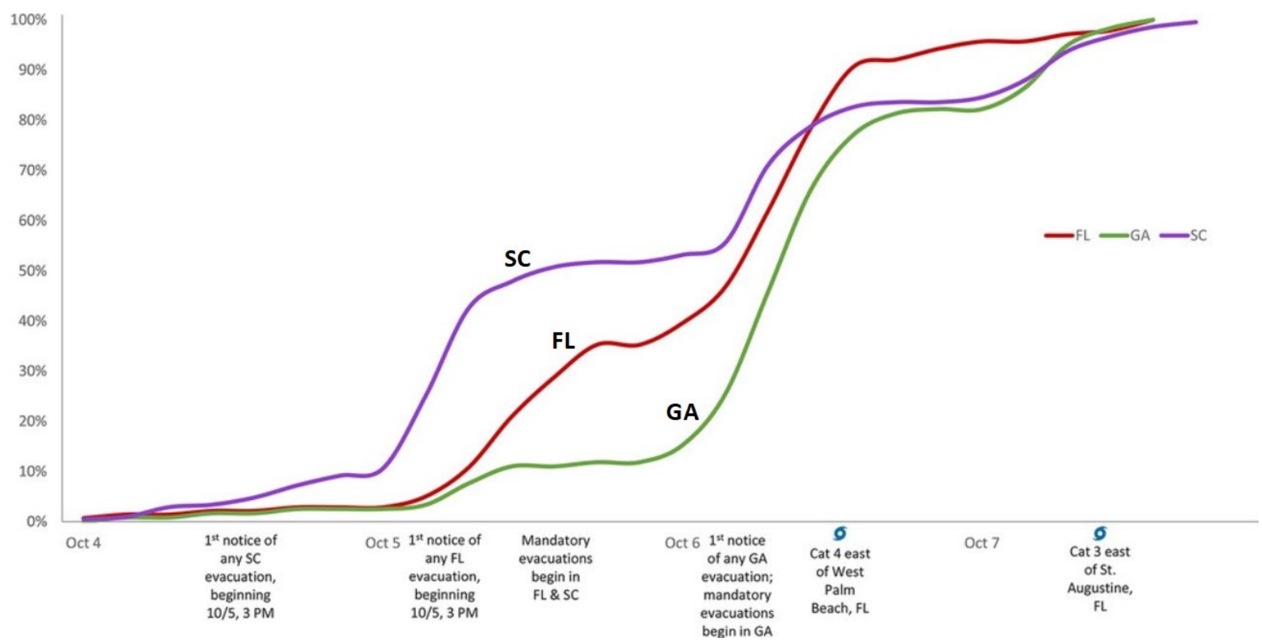


Figure 4.7: Pham et al. (2020) cumulative evacuation fraction over time for Hurricane Mathew in FL, GA, and SC

During Hurricane Harvey, most residents left over a three-day period as shown in Figure 4.6. Also, most evacuees left during daylight hours, with the daily peak occurring between 8 am and 12 pm. The distributions then taper in the afternoon hours, and departures are at their lowest point at night. Figure 4.7 indicates that evacuees in different states had different responses to the storm as it arrived, and the exact track of the hurricane became clearer. For example, evacuees in South Carolina and Georgia departed in three distinct days, while evacuees in Florida appear to have departed in two large portions. Evacuations in South Carolina occurred in the most regular manner in three roughly evenly spaced groups, in contrast to Georgia, where few individuals left three days before storm arrival, the majority left in the second day before arrival, and the remaining individuals departed the day immediately preceding landfall.

The Qualtrics survey responses from Task 3 to the question, “How soon prior to the forecast arrival of the hurricane did you evacuate?” for each hurricane is summarized in Figure 4.8. For nearly all storms, the most frequent response is that evacuees departed 12–24 hours in advance of the storm arrival, followed by 24–36 hours in advance.

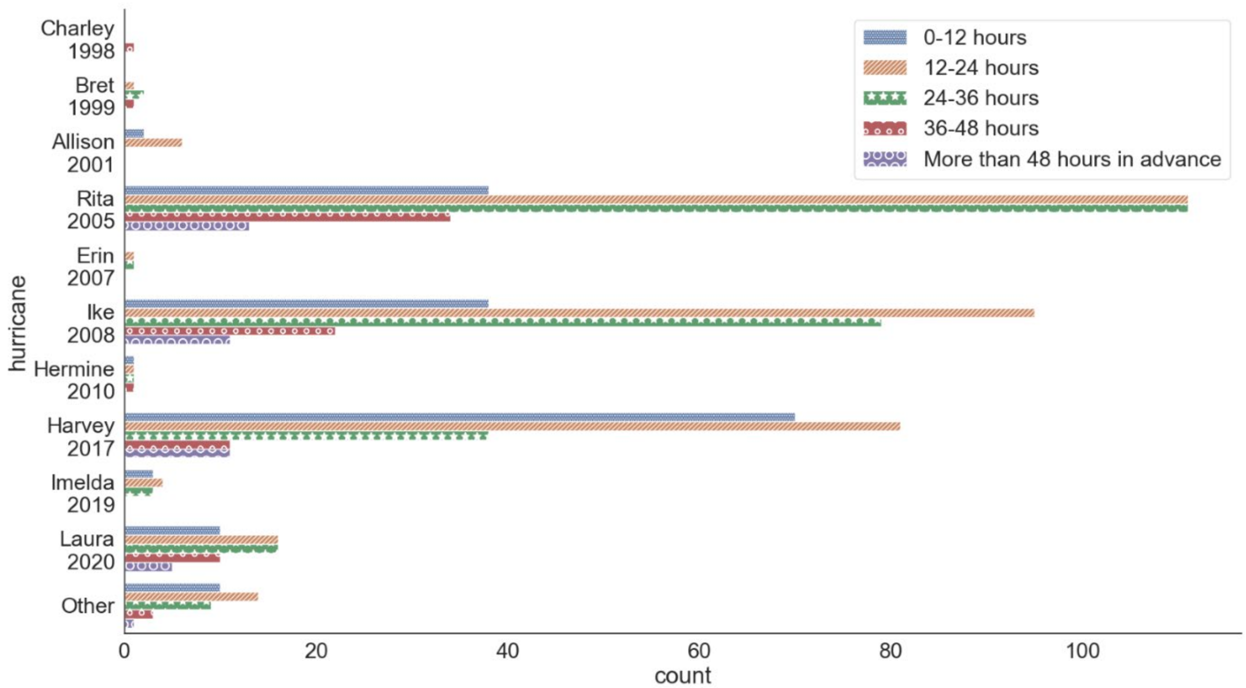
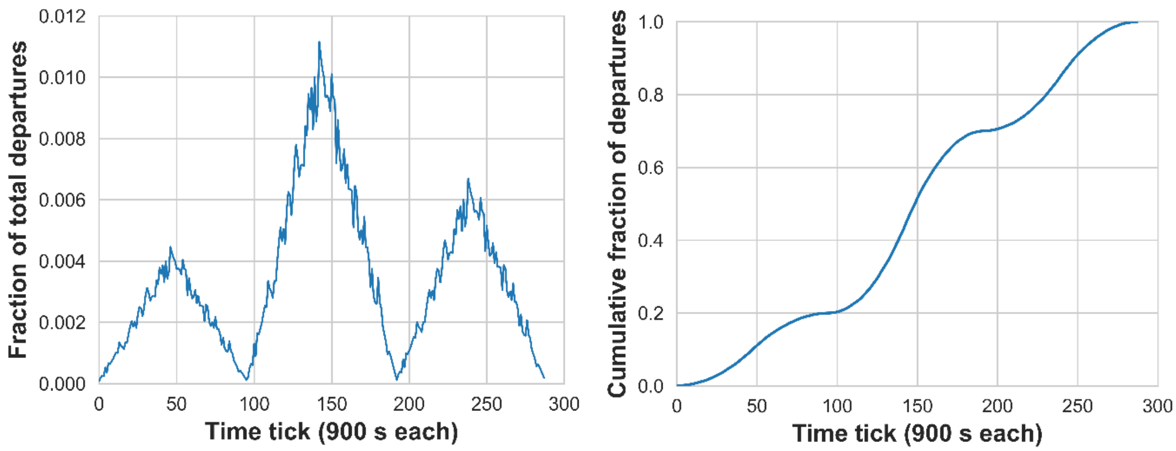


Figure 4.8: Reported evacuee departure time by hurricane from survey results

From these findings, it was assumed that the evacuation in the HES would occur over three consecutive days. Most individuals will depart during daylight hours, with the peak departure time occurring at 12 pm (noon). A triangular distribution was used for each day to randomly sample the number of evacuees at 15-minute intervals. Based on a review of literature, the researchers assumed that 20% of evacuating households leave three days before landfall, 50% evacuate two days before landfall, and the remaining 30% evacuate on the final day before landfall. This results in three distinct triangular distribution samples, with values at 15-minute tick intervals, representing evacuees’ departure times. An example of the departure time profile employed in the HES is shown in Figure 4.9.



a) Incremental profile *b) Cumulative fraction*

Figure 4.9: 72-hour demand profile, with departures occurring in 15-minute intervals

The origins of the evacuation demand are given by the respective node IDs within the network model for the impacted counties in each case study, and the destinations of all evacuating vehicles are the safety sink node. The final product of the demand formulation is a trip table for each case study giving the number of vehicles per origin county in a 15-minute departure interval, represented by the current tick count of the simulation. Table 4.5 and Table 4.6 show samples of the final demand files for each case study, respectively.

Table 4.5 – Case Study 1 final demand estimate sample

#	Origin	Destination	Departure Time	Demand
1	546	sink	1	24
2	546	sink	2	44
3	546	sink	3	50
4	546	sink	4	68
5	546	sink	5	50
...	...	...	...	...
3164	429	sink	284	8
3165	429	sink	285	8
3166	429	sink	286	8
3167	429	sink	287	3
3168	429	sink	288	3

Table 4.6 – Case Study 2 final demand estimate sample

#	Origin	Destination	Departure Time	Demand
1	546	sink	1	2
2	546	sink	2	2
3	546	sink	3	3
4	546	sink	4	8
5	546	sink	5	7
...	...	...	...	...
2588	456	sink	284	19
2589	456	sink	285	26
2590	456	sink	286	26
2591	456	sink	287	17
2592	456	sink	288	5

4.2.4. Simulation Approach – Max-flow Min-cut Algorithm

The max-flow min-cut theorem is a fundamental concept in network flow analysis. This theorem determines the maximum flow that can be sent through a network using the known capacities on each link. It has two dual perspectives: a flow perspective and a cut perspective which provide the same answer. Maximum flow refers to the maximum flow that could be sent between a source and a sink node in the network, subject to the capacity constraints on the links between nodes and mass balance constraints at all nodes. Minimum cut, on the other hand, refers to the minimum capacity of links that must be cut to separate the source node and the sink node (Ahuja, Magnanti, & Orlin, 1988). These links that make up the minimum cut are "critical" in that any added capacity to these links will reduce the total evacuation time. Conversely, any reductions in capacity on these critical links (either from traffic incidents or sub-optimal routing decisions) will increase the total time needed for all vehicles to evacuate. The mathematical formulation for the theorem is as follows.

Maximize v

Subject to

$$\sum_{\{j:(i,j)\in A\}} x_{ij} - \sum_{\{j:(j,i)\in A\}} x_{ji} = \begin{cases} v & for\ i = s \\ 0 & for\ all\ i \in N - \{s\ and\ t\} \\ -v & for\ i = t \end{cases}$$

$$0 \le x_{ij} \le u_{ij} \qquad for\ each\ (i,j) \in A$$

We refer to a vector $x = \{x_{ij}\}$ satisfying the formulation above as a flow and corresponding value of the scalar variable v as the value of the flow. There are assumptions that the maximum flow problem follows:

- Assumption 1: The network is directed.

- Assumption 2: All capacities are nonnegative integers.
- Assumption 3: The network does not contain a directed path from node s to node t composed only of infinite capacity links.

These assumptions are generally acceptable for traffic networks as all links have positive and finite capacities and are modeled as directed links. One of the benefits of the maximum flow methodology is that the results are easy to interpret. In the final solution, there will be a subset of links flowing at capacity. These links are "critical" in the sense that any disruption on these links will delay the overall evacuation time. This means that these links are important to monitor to ensure that they are always flowing at capacity.

Unfortunately, the maximum flow methodology has the major drawback that the solution is found between a single origin node and destination node. Multiple destination nodes can be connected to a single super sink without negatively affecting solution quality. However, the same is not necessarily true for the origins, as there are specific demand proportions that come from each county. Allowing flow to move between counties could cause large deviations from the true flow solution. To relax this constraint, we modified the fixed time maximum flow algorithm to be used in a discretized set of time-steps using a queueing model. To do this, we set the capacity of the link between the super source and each origin as the number of vehicles wanting to leave at that timestep. We then ran maximum flow for that timestep (15-minute increments) and updated the vehicles wanting to travel. In this way, we could track vehicles at each origin through a set of timesteps to maintain the consistency between demand and flow from each origin.

Another concern with maximum flow is that it represents a best-case scenario for vehicles leaving the network. We call this the system optimal case since as much flow is leaving as is possible. However, individual vehicles may not take the best route to leave the network if they think a different route might have a lower travel time. To account for this, we ran static traffic assignment (user equilibrium) to find the number of vehicles that would attempt to leave using each route. This is the most common routing approach used in practice where every individual attempts to minimize their own travel time. The flows at user equilibrium could then be used as upper bounds on flows using the max-flow methodology to restrict the capacity to routes that people actually want to take. Note that max-flow still needs to be run to get the flows in each 15-minute increment since static traffic assignment does not obey capacity constraints. This user equilibrium solution must take at least as long to evacuate all the vehicles, so it is non-optimal. This suggests that routing vehicles onto the correct paths is vital to ensuring a rapid evacuation.

Finally, a major benefit of the maximum flow methodology is that it can be run quickly. This allows us to investigate the impact of crashes and other traffic incidents such as vehicle abandonment. Survey results suggested that these were common issues during past evacuations, so the effects of these incidents are investigated further using Monte Carlo simulation (HCM 2010; Collins et al., 2013; Fonseca et al., 2013). Incidents were generated from two cases: collisions, and abandoned/disabled vehicles (Li et al., 2018). These incidents were defined by a start time, a duration, and a capacity drop (Ji et al., 2014). The incidents were generated using a Poisson process with a rate of 2 collisions per million vehicle miles traveled (VMT) and 10 disabled/abandoned vehicles per million VMT (Zhang et al., 2012). The duration was generated from a normal distribution with a mean of 0.67 hours for both cases and a variance of 16.13 and 16.25 for crashes and abandonments respectively (Ji et al., 2014). Finally, the collision capacity loss was taken from a Beta distribution with $\alpha = 4.05907$ and $\beta = 6.83057$. The disabled/abandoned vehicle incidents had alpha equals 5.19123 and beta equals 2.22481 (Chin et al., 2004; Qin & Smith, 2001; Yazici et al., 2015).

Incidents were generated according to these distributions, and the capacities were updated for the respective time periods on each link. To incorporate the impact of monitoring devices, the duration of incidents was reduced by 80% for the monitoring case. In addition, instead of collisions per VMT, collisions per possible VMT was used by substituting roadway capacity for flow. This overestimates the number of collisions on low flow links, but such collisions do not affect the simulation since a reduction in capacity would not affect a very low flow.

4.3. Results

Four scenarios were implemented for each case study, namely, user equilibrium (UE) and system optimal (SO) in combination with a base network or a network equipped with monitoring devices. Two networks were used: the base network and an expanded network which includes contraflow lanes, toll roads, and capacity expansions for shoulder running (Evaculane treatments). The max flow/min cut approach was employed for each scenario, and Monte Carlo simulations were conducted 100 times to obtain the most precise results. The study considered two types of incidents, namely collisions and disabled vehicles. Our study assumed that the implementation of monitoring devices would lead to an 80% reduction in clearance time. Though it is a strong assumption, it represents a best possible scenario for improvements using ITS. From Figure 4.10, the study concluded that all evacuee vehicles were able to reach shelters within 120 hours (or five days) for Case Study 1 on the base network. The system optimal situation for the network with monitoring devices has a smaller cumulative delay compared to the base network. While in the UE scenario, there was no significant difference between the networks with or without monitoring devices, and the delay accumulated during the evacuation remained approximately the same.

The results from Case Study 2, shown in Figure 4.11, demonstrate significantly lower delays compared to Case Study 1. Although the system optimal case has slightly higher delays between hours 30-50 of the evacuation, these delays do not affect the overall evacuation time since there is plenty of capacity later in the day. Similarly, the incidents during the evacuation do not have a significant impact, as all vehicles are still able to leave the network within the planned three-day window.

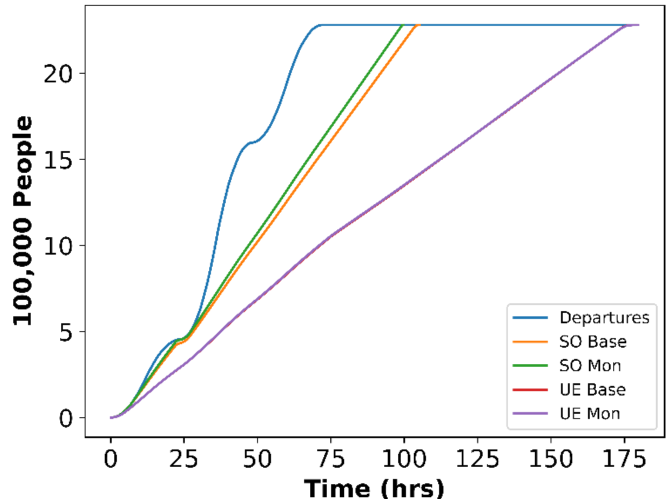


Figure 4.10: Cumulative number of vehicles arriving at safe nodes, Base Network, Case Study 1

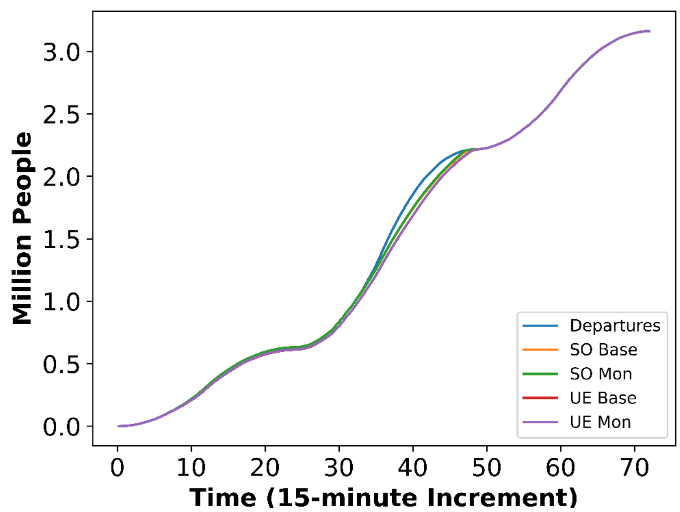


Figure 4.11: Cumulative number of vehicles arriving at safe nodes, Base Network, Case Study 2

The bar chart in Figure 4.12 depicts the important findings for Case Study 1. The results indicate that although the average moving time for user equilibrium scenarios is marginally lower than that of system optimal scenarios, the latter demonstrate significantly lower average delay and overall travel time (summation of average moving and average delay). However, the biggest impact on the evacuation time is the routing behavior. We can see from Figure 4.12 that the UE solution reduces moving time for vehicles. This reduction comes at the expense of very long delays that slow the entire evacuation by about three days. This is a major concern for evacuees, as the survey found that the earliest evacuees leave only three days before landfall.

The results of Case Study 2, presented in Figure 4.13, indicate significantly lower average moving times and delay when compared to Case Study 1. This discrepancy can be attributed to the differences in the geographical regions considered. Furthermore, the overall average total time for system optimal is slightly lower than the user equilibrium, and the base network and monitoring network are approximately the same.

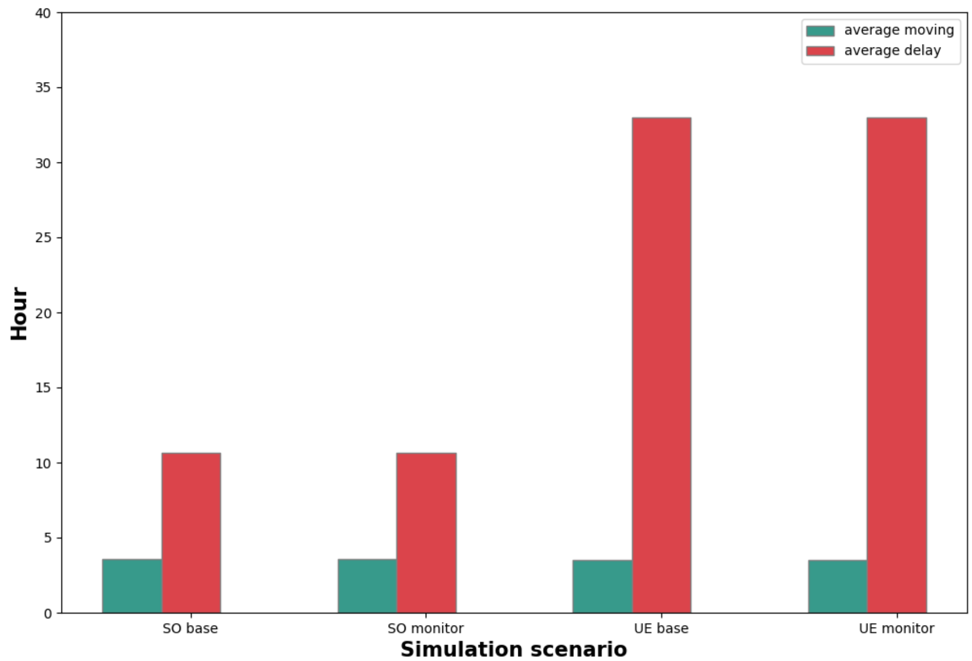


Figure 4.12: Average moving and average delay (unit: hour) in SO and UE scenarios, Base Network, Case Study 1

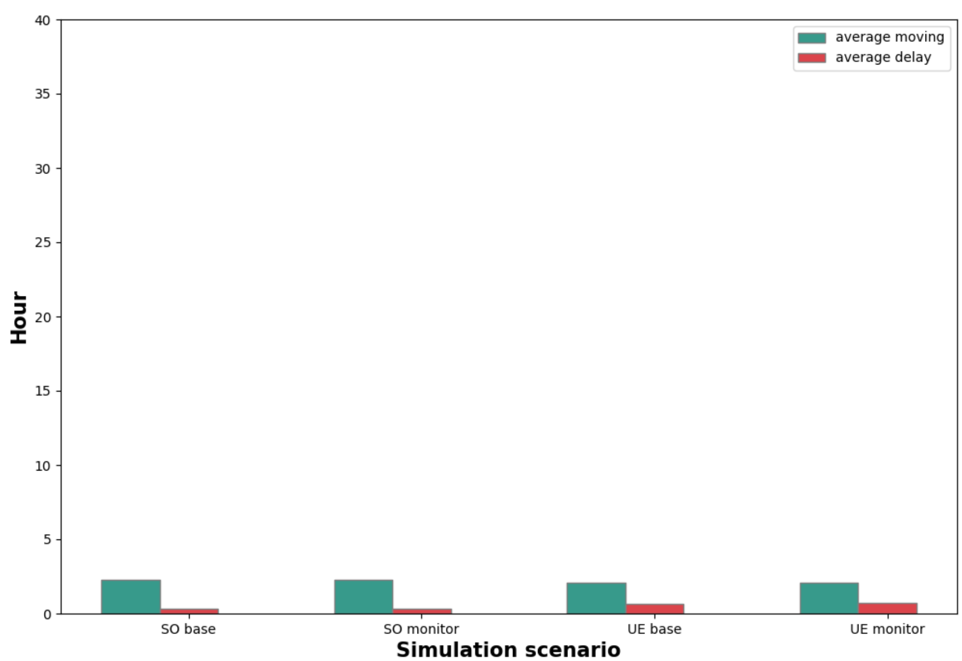


Figure 4.13: Average moving and average delay (unit: hour) in SO and UE scenarios, Base Network, Case Study 2

Finally, Figures 4.14 and 4.15 show the results of both scenarios on the additional network which also includes toll roads, contra-flow lanes, and capacity expansions for shoulder running. The additional capacity provided by these treatments is effective in reducing the total evacuation time in Case Study 1. There are still substantial delays for all scenarios, but the total evacuation time for the UE evacuations is reduced by almost 75 hours. In addition, the SO monitoring case takes less than 79 hours for all vehicles to evacuate, only seven hours behind the three-day evacuation target. Case Study 2 shows very similar results to those in the base network. This is not unexpected since the evacuation already proceeded with few delays, and there are fewer infrastructure differences between the base and additional networks in that part of the state.

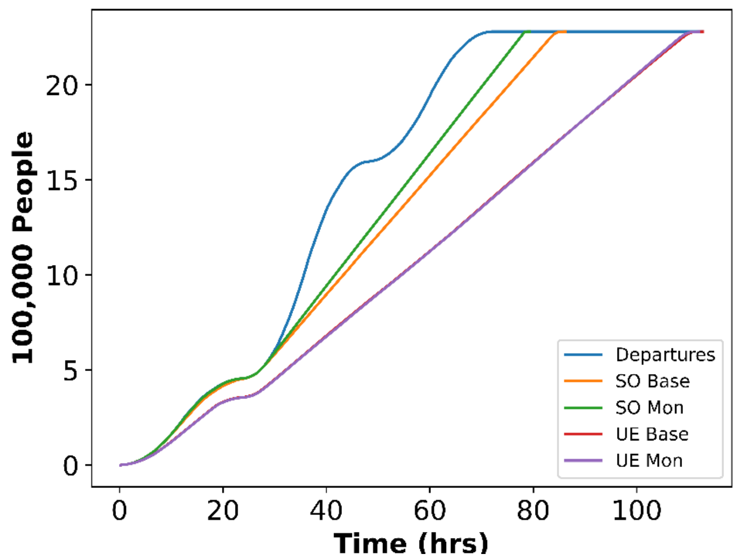


Figure 4.14: Cumulative number of vehicles arriving at safe nodes, Additional Network, Case Study 1

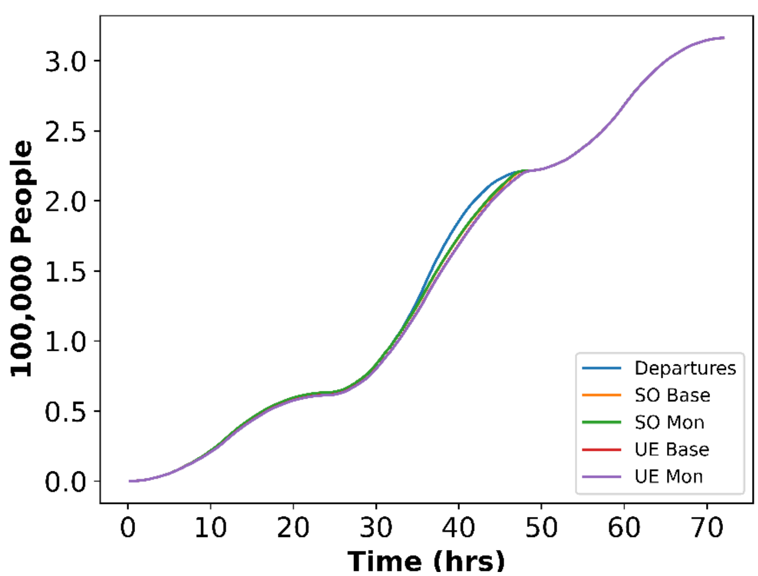


Figure 4.15: Cumulative number of vehicles arriving at safe nodes, Additional Network, Case Study 2

4.4. Recommendations for System Expansion

From the simulation results, the researchers identified critical links for potential TMD system expansion. By providing accurate, real-time information on traffic congestion levels and traffic incidents, traffic monitoring devices (TMD) can inform residents as to the best choices to make during their evacuations. Figure 4.16 shows TMD locations acquired from the TxDOT Houston District.

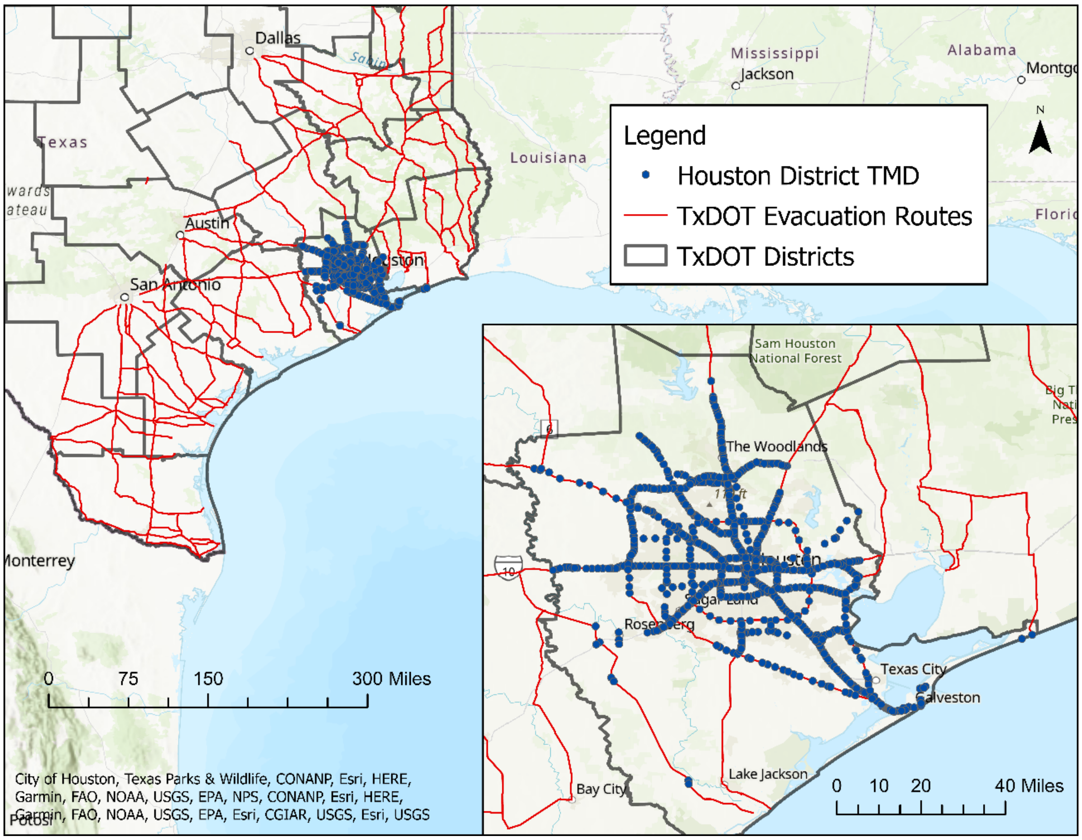
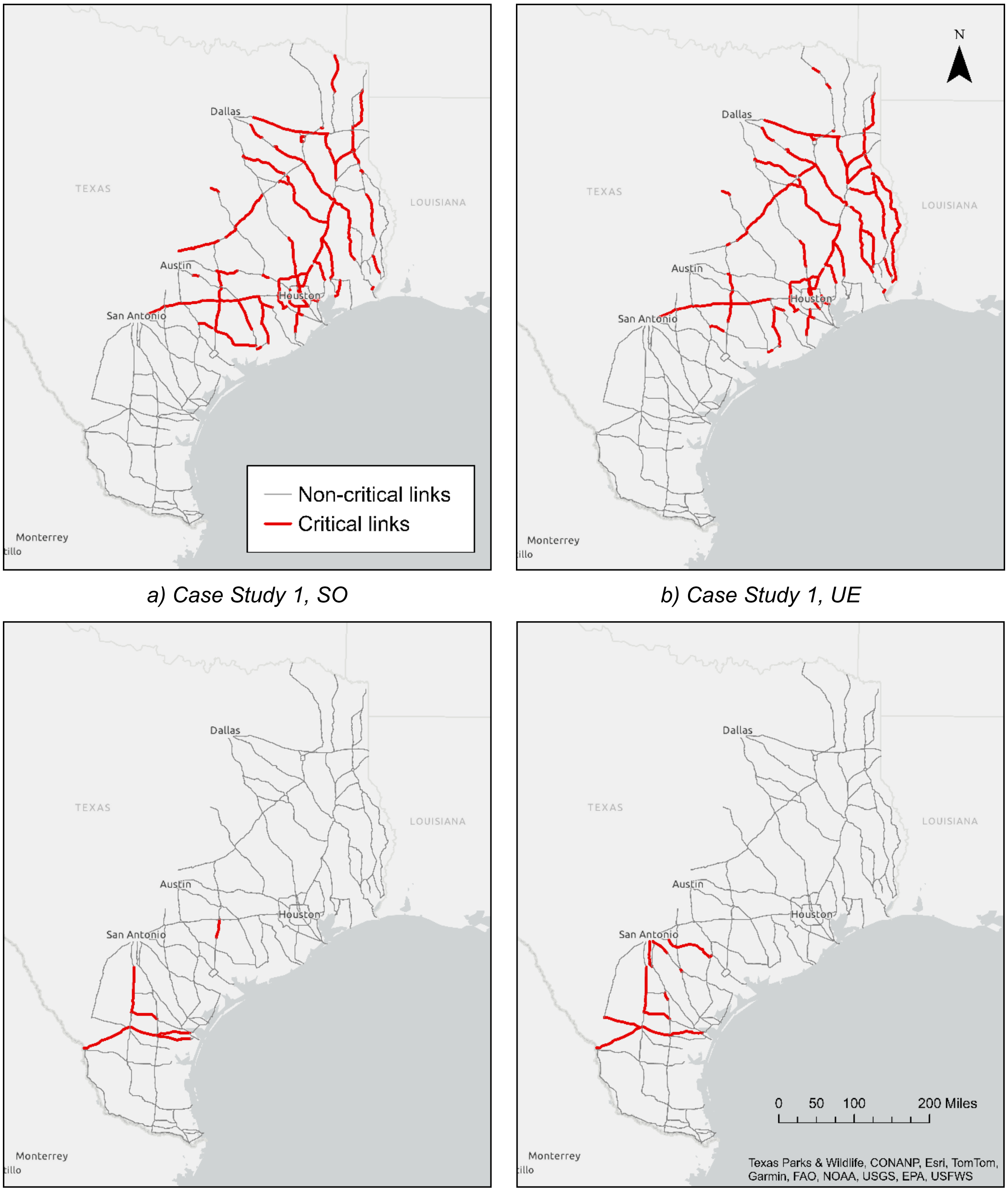


Figure 4.16: Existing TxDOT Houston District TMD locations

The results indicate that even though the clearance time for the network under monitoring conditions is 80% better than the base network, the accumulated delay does not change significantly. Moreover, the system optimal scenario has much lower delay compared to user equilibrium, indicating that the monitoring devices should guide the evacuees to use system optimal routes. To achieve this, we recommend using ITS devices, such as dynamic message signs (DMS) and road weather information systems (RWIS), as well as freeway infrastructure, such as contraflow/Evaculane treatments, to provide routing suggestions under a system optimal situation.

Furthermore, the study highlights the critical links in both networks under monitoring condition, which are links that have reached maximum flow. Improving these links can help increase the overall flow in the network. Figure 4.17 shows these critical links in red for each Case Study scenario.

It is important to focus on improving the critical links to enhance the overall flow in the network and guide evacuees to use system optimal routes to reduce the delay. By implementing traffic monitoring and ITS systems on the critical links, the network's overall performance can be enhanced, and the evacuation process can be made more efficient.



a) Case Study 1, SO *b) Case Study 1, UE*

c) Case Study 2, SO *d) Case Study 2, UE*

Figure 4.17: Map of critical links

4.5. Summary

This report summarizes the methods and findings of the HES process employed to determine critical links as locations for ITS expansion. First, a network model was constructed to portray the coastal Texas evacuation routes as links and nodes. This network then allowed researchers to simulate hypothetical evacuation events to observe the behavior of vehicles on the roadways. The demand for two independent evacuation case studies, one in the Houston-Galveston region and one in the Corpus Christi region, was estimated by first determining risk zones for areas exposed to hurricane storm surge hazards. Census data was used to estimate the number of households per risk zone that would evacuate, and these values were converted into a final number of vehicles evacuating per county. Finally, a time profile was applied to obtain the evacuation demand profile in 15-minute intervals.

The network model and demand estimates were used to simulate evacuations on Texas roadways. A mesoscopic simulation and maximum flow approach with Monto Carlo simulation were implemented. The simulation results highlight links that play a critical role in increasing overall flow and reducing delay during an evacuation. These critical links are the roadways which should be prioritized for future ITS device expansion as this will most enhance network performance. Moreover, a system optimum approach rather than a user equilibrium situation can significantly reduce delay during evacuation. While this may not be fully attainable in practice, it is recommended to guide evacuees towards system optimal routes using data from ITS devices and real-time information on preferred routing to efficiently manage an evacuation.

Chapter 5. Develop Recommendations for Prioritizing Improvements

5.1. Introduction

This chapter presents a method to determine a priority schedule for the implementation of traffic monitoring system improvements. The recommended improvements may consist of upgrading or retrofitting existing devices to improve the quality or reliability of real-time travel time information for hurricane evacuees, or to install new devices on road corridors which do not currently have any to reduce gaps in the monitoring system coverage. To determine the criteria deemed most important for system improvement or expansion, feedback from relevant agency employees was used in conjunction with a common multi-criteria decision analysis method to determine preference weights for various goals and alternatives. A series of workshops were conducted to collect pairwise comparison rankings for the Analytical Hierarchy Process between each goal and factor from TxDOT employees. The results collected from staff participating in this study represent various impacted districts. This gives a good review of what is important to some TxDOT staff, but no TxDOT administration was included in the survey and the results do not reflect TxDOT as a whole.

The goal and factor weights were then used to rank a set of critical roadways identified from the network simulation in Chapter 4 to prioritize them for implementation, to demonstrate the effectiveness of the methodology. The results of this chapter may inform TxDOT as to the optimal strategy for device deployment intended to improve the determination and distribution of real-time travel times during hurricane evacuation events in Texas.

5.2. Selection of Multi-Criteria Decision Analysis Method

In this study, there are several factors that are assessed against several competing goals using both subjective qualitative data and quantitative values. A method is needed to select the preferred alternatives and rank them for prioritization. When selecting multiple alternatives against a set of numerous, competing goals, techniques referred to as multi-criteria decision analysis (MCDA) methods are commonly employed. MCDA offers the ability to simplify complex decisions involving many alternatives and decision factors. There are several techniques commonly used in MCDA problems, such as the Analytical Hierarchy Process (AHP), Analytical Network Process (ANP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), the Delphi method, and more (Zlaugotne et al., 2019). Distinctions between these methods are provided in Table 5.1.

Table 5.1 – Comparison of MCDA methods and uses

MCDA Method	Description	Use Case
Analytical Hierarchical Process (AHP)	Pairwise comparison on ratio scale with ranking scores as the output; consistency ratio used to check validity of responses (Saaty, 1988)	Choice, ranking, and sorting problems (Zlaugotne et al., 2019)
Analytical Network Process (ANP)	Generalized form of AHP structured as a network rather than a hierarchy; can analyze interdependent relationships among goals and factors (Kheybari et al., 2020)	Choice, ranking, and sorting problems (Kheybari et al., 2020)
Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)	Indifference and preference thresholds weights are used to calculate partial and complete pairwise outranking degrees; typically requires specialized software (Zlaugotne et al., 2019)	Choice, ranking, and description problems (Zlaugotne et al., 2019)
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Vector normalization used to determine alternatives that have the shortest distance from the positive-ideal solution to maximize benefit criteria; provides a cardinal ranking and does not require preferences to be independent (Behzadian et al., 2012)	Choice and ranking problems (Zlaugotne et al., 2019)
Delphi method	Multiple rounds of questionnaires completed, and results discussed by a panel of experts until a mutual agreement is reached in an interactive manner (Helmer, 1967)	Choice problems seeking group consensus (Helmer, 1967)

Each MCDA method has its own data requirements, some of which require the participation of many individuals and the coordination of multiple meetings (such as the Delphi process). For this study, it was desired to conduct an analysis that was straightforward, relatively easy to collect accurate input from experts, time efficient, and capable of producing quantitative results. Based on these needs and practical considerations, the AHP was selected as the MCDA tool for use in this study due to its simplicity and flexibility.

As AHP allows for alternatives to be ranked from most to least desirable, it can provide a priority ranking. It also allows for observations to be made as to the relative preference of one alternative over another, as the weights are determined using pairwise comparisons, meaning that insights into the magnitude of alternative preferences can be observed. AHP also applies a consistency ratio to ensure that rankings are valid, and that rankings are logical.

5.3. Overview of the Analytical Hierarchical Process

5.3.1. Use of AHP in Asset Management

AHP concepts have been applied to numerous medical (Sipahi & Timor, 2010), political (Vaidya & Kumar, 2006), operations management (Subramanian & Ramanathan, 2012), construction (Darko et al., 2019), and engineering fields, including the fields of transportation engineering and infrastructure asset management (Smith & Tighe, 2006). The method is commonly used to prioritize a set of alternatives, such as competing projects or alternative treatments for a single project, to determine the preferred option for implementation.

First introduced in the 1970s by Thomas Saaty (Saaty, 1988), AHP has been used in engineering management for decades and applied to many traditional civil asset management problems. It has been used to model steel bridge maintenance, repair, and rehabilitation (MR&R), and to develop a preferred remediation plan (Rashidi et al., 2017). AHP has also been used to prioritize pavement MR&R candidate projects while incorporating agency priorities in Texas (Porras-Alvarado et al., 2017) and to model the consequence-of-failure of wastewater pipe networks in Louisiana (Vladeanu & Matthews, 2019). Studies have extensively used AHP to analyze railroad operations such as the selection of maintenance activities (Nyström & Söderholm, 2010) and to assess the traffic safety risks of railroad infrastructure (Bureika et al., 2013). AHP has even been used to develop tools that agencies may use to measure the effectiveness of their level of asset management implementation (Cooksey et al., 2011), and some researchers have developed extensions of the AHP method to improve on its inherent shortcomings (Ikpong et al., 2021).

More recently, AHP has been used to assess contemporary issues in engineering design and management. It was used to demonstrate how community input may be incorporated into electric grid projects in Spain to account for the social impacts of infrastructure projects in decision-making (Álvarez et al., 2013). AHP has been employed to determine the priorities for planning green infrastructure projects (Monteiro et al., 2022), to prioritize transportation infrastructure projects with sustainability metrics (Oswald Beiler & Treat, 2015), and to measure road asset operations for achieving sustainability objectives (Gunarathna & Hassan, 2020).

Another benefit of AHP is its ability to be combined with other techniques for further analysis. In the engineering management research area, this is beneficial as many common methods may be employed with AHP. Examples include the use of fuzzy logic in conjunction with AHP to determine life cycle cost assessment risk for public-private partnership (PPP) projects (Li & Zou, 2008) and to incorporate public opinion into transportation project selection (Arslan, 2009).

AHP is widely applicable to many cases in civil engineering and asset management where alternative selection and prioritization among many competing factors are required.

5.3.2. Conceptual Framework of AHP

AHP allows for the pairwise comparison of alternatives on a ratio scale and can incorporate both quantitative and qualitative data (Farhan & Fwa, 2009; Porras-Alvarado et al., 2017; Zhang et al., 2004). It provides a logical and systematic approach to solving complex problems. The process involves four components: (a) defining a hierarchy, (b) prioritizing criteria through pairwise comparisons, (c) using these pairwise comparisons to determine a priority vector, and (d) checking for consistency in the pairwise comparisons.

The first step of AHP is to structure a hierarchy, which involves decomposition of the problem of interest into independent elements. The hierarchy is an abstraction of a system's structure, allowing for the study of functional interactions and impacts (Saaty, 1980, 1988). To structure a hierarchy for a specific problem, the elements or sub-problems must be identified and grouped into homogeneous sets, creating a hierarchical structure based on logical relationships (Saaty, 1980, 1988).

The second step is to collect pairwise comparison judgements for the previously defined hierarchy elements. Subject matter experts with domain knowledge are ideal candidates for completing the judgements. The pairwise comparisons are conducted between all elements at each hierarchy level with respect to each element ("criterion" for the current level) in the previous level. For example, pairwise comparisons for elements in Level 3 are repeated multiple times, with each set of judgements performed with respect to each Level 2 element. The pairwise comparison is conducted using a 1-9 scale to indicate the relative importance of one factor over the other, as recommended by Saaty (Saaty, 1980). A value of 1 indicates that the elements are of equal importance, while a value of 9 indicates that one element is of extreme importance over the other element, with intermediate values following a linear scale between these bounds. The results from the pairwise comparisons for each level are modeled as a positive reciprocal matrix **A** and represent the intensity of each expert's preference between each individual pair of elements.

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \tag{5-1}$$

where,

A = pairwise comparison matrix

n = the number of criteria or elements

a_{ij} = relative priority of i to j

The third step is to derive the priority vector w, which is a vector of "importance" weights for each of the elements in the comparison matrix **A**. This is typically done using the principal eigenvalue method (Saaty, 1980), where the principal eigenvector w is the eigenvector corresponding to the largest eigenvalue of **A**, λ_{max}.

$$\mathbf{A}w = \lambda_{max}w \tag{5-2}$$

The principal eigenvectors are normalized (noted as v) for all elements at each level with respect to each criterion. The overall priority for all elements is calculated using the priority vector of all criteria and all elements for each criterion.

$$v = \mathbf{X}v_0 \tag{5-3}$$

where,

v = the overall priority vector of all elements

X = the matrix of priority weights of the element with respect to each criterion in the upper level, i.e., X_{ij} is the relative weight of element i with respect to criterion j

v_0 = the priority vector of criteria in the upper level

Ideally, the expert judgements should be consistent such that:

$$a_{ik} = a_{ij} \cdot a_{jk} \tag{5-4}$$

However, as the input is restricted to integer values and objective expert judgements, there are often inconsistencies or self-contradictions in the initial pairwise comparison values. To reduce the presence of inconsistent judgements, input values are checked using the consistency ratio (CR), defined as follows:

$$CR = \frac{CI}{RI} \tag{5-5}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{5-6}$$

where CI is the consistency index and RI is the random consistency index. CI is computed based on the λ_{max}, which equals n when matrix **A** is consistent and greater than n when matrix **A** is inconsistent. RI is the average CI of many randomly generated n by n matrices. The matrix **A** is considered consistent if the CR ratio is smaller than a given threshold. The threshold of CR values is typically 0.1, but larger values up to 0.2 have also been used such that it is more practical for experts to complete a consistent set of judgements in a reasonable time.

5.4. Workshop Planning and Design

To collect the pairwise comparisons needed to derive the weights in the AHP method, an Excel-based spreadsheet tool was designed, and a series of virtual workshops were conducted with TxDOT employees. Figure 5.1 shows an overview of the workflow employed in this study.

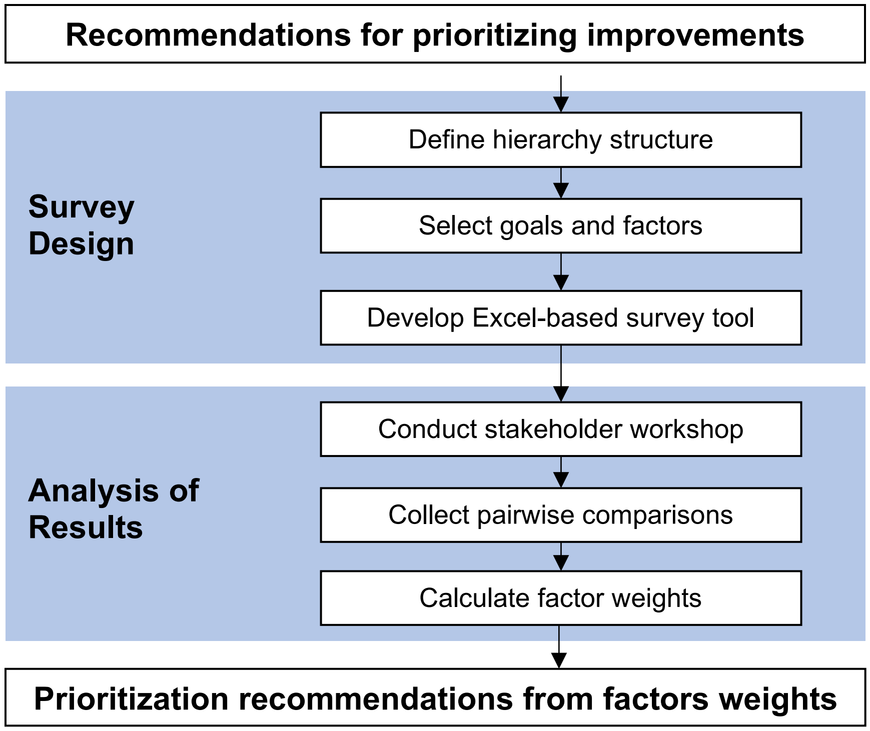


Figure 5.1: Prioritization development framework

The method consists of two main components: 1) design and development of the AHP survey tool and 2) collection and analysis of results. Finally, recommendations for factors that should be considered in the prioritization of TMDs for evacuations are formulated using the weights obtained from AHP. The first component designs the AHP framework, which decomposes the overarching primary objective of determining "recommendations for prioritizing TMD improvements" into a three-level hierarchy structure with selected Level 2 "goals" and Level 3 "factors." An Excel-based survey tool was developed to collect the pairwise comparisons needed for AHP from TxDOT subject matter experts. In the second component, the pairwise comparison results are used to calculate priority weights, and quantitative and qualitative analysis was performed to assess the results. Finally, recommendations for prioritizing TMD installations are synthesized from the analysis results.

An initial set of candidate goals and factors were identified by synthesizing existing reports developed by TxDOT (*Statewide Long-Range Transportation Plan 2035 Executive Summary*, 2011; *Texas Rural Transportation Plan 2035*, 2012; *Texas Transportation Plan 2040*, 2015). Eight candidate goals and ten factors were selected to be considered in Level 2 and Level 3, respectively. The complete list of candidate goals and factors and accompanying descriptions are presented in Table 5.2 and 5.3. To create an AHP tool that is less cumbersome and requires minimal time to complete, it was desired to reduce the total number of Level 2 goals to three or four, and the total number of Level 3 factors to five or six. To refine the Level 2 and Level 3 factors shown in Tables 5.2 and 5.3, a virtual call was held on April 13, 2023, with four PMC members. Discussions focused on finalizing the goals and factors to be included in the questionnaire and identifying individuals to attend the upcoming workshops. For both the Level 2 and Level 3 items, a description and definition for each option were provided to the attendees. Then, the TxDOT PMC members discussed which of the options were most relevant to evacuations based on their past experiences and professional opinions. Finally, the PMC members were polled to determine which of the Level 2 and 3 items were to be included in the final AHP questionnaire. The final Level 2 goals and Level 3 factors are indicated in Tables 5.2 and 5.3, respectively.

Table 5.2 – Level 2 goals considered for inclusion with selected goals as shown

No.	Description	Selected
1	**Enhance traffic safety during evacuation**: Enhance roadway safety by providing real-time incident detection to reduce the occurrence of collisions and improve first responder response times.	✓
2	**Improve mobility during evacuation:** Ensure evacuation routes remain open, available, and flowing for efficient evacuation.	✓
3	**Increase system resilience:** Maintain a robust, redundant, resourceful, and rapid transportation system during hurricane evacuations. Ensure system is able to adapt to changing conditions and overcome disruptions that may arise.	✓
4	**Promote user satisfaction:** Install devices that offer roadway users the best experience during hurricane evacuations.	
5	**Optimize multimodal connectivity:** Select devices that are able to provide information to facilitate communication between different transportation modes, such as cars and buses.	
6	**Improve existing monitoring system performance:** Improve the performance of the existing system by investing in new devices that will most increase performance metrics.	
7	**Preserve infrastructure network asset value:** Invest in maintenance actions or new alternatives that will best preserve or increase the valuation of the TMD system.	
8	**Support statewide transportation planning initiatives:** Select projects that best meet the statewide goals presented in long term transportation plans or other planning initiatives.	

Table 5.3 – Level 3 factors considered for inclusion with selected factors as shown

No.	Description	Selected
1	**Compatibility with existing devices:** If the new devices can be integrated with the data platforms, power systems, and IT systems used to operate existing devices.	✓
2	**Presence of existing devices:** The functionality and condition of existing devices along the corridor; if any gaps exist in the current system coverage.	✓
3	**Influence on traffic flow:** *Incident detection:* reduce incident durations and improve flow during evacuations, maintain reliable travel times. *Route choice:* provide drivers with information on alternate routes and travel time estimates.	✓
4	**Evacuation route status:** Official designation as an evacuation route, and treatments such as contraflow or Evaculane shoulder operations.	✓
5	**Access to critical facilities:** Roadway provides a route to a critical facility for evacuees, such as a shelter, gas station, hospital, etc.	✓
6	**Relative cost effectiveness of the new monitoring device:** *Cost:* device cost, cost of installation. *Benefits:* data quality, detection accuracy.	
7	**Access to high-density population residential areas:** If the road corridor provides access to densely populated urban or suburban areas.	
8	**Contribution/performance during normal (i.e., non-evacuation) periods:** Benefits offered by device during a non-evacuation period, such as daily traffic operations and incident detection on roads that are congested during regular AM/PM peak hours.	
9	**Presence of vulnerable users (equity for under-served areas):** Whether a route provides mobility to under-served or vulnerable communities, such as elderly, children, low-income, and minorities.	
10	**Use of the devices during post-hurricane return to impacted regions:** Whether the device can monitor one-way traffic or two-way traffic; incident detection and route adjustment for safe return.	

The final AHP hierarchical structure used in this study is shown in Figure 5.2, with Level 2 goals and Level 3 factors as selected by members of the TxDOT PMC.

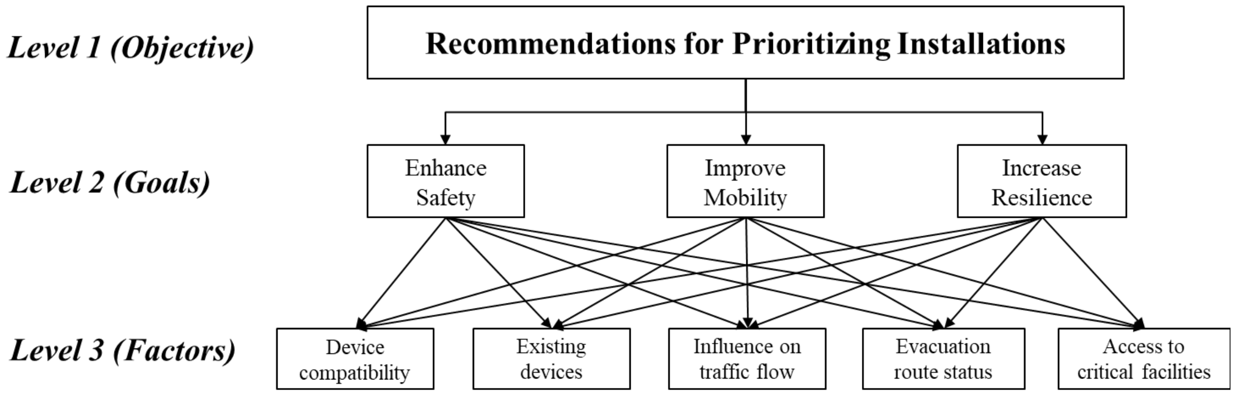


Figure 5.2: Objective, goals, and factors hierarchy selected for AHP tool

Once the final hierarchy was defined, an Excel-based tool was created so that workshop participants could easily input their pairwise comparisons. The ranking scale used in the tool is shown in Table 5.4. The tool was designed such that the consistency ratio and target threshold were immediately calculated and presented to the user, allowing for easy adjustment of rankings to ensure consistent comparisons. The tool was also coded such that the calculation of the positive reciprocal matrix and priority vector used to derive the final weights was completed, allowing the users to see their final ranking weights.

Table 5.4 – AHP tool numerical rating scale

Verbal Judgement of Preferences	Numerical Rating
Extremely preferred	9
Very strongly to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

To collect responses and obtain pairwise comparisons, a series of workshops were held with employees of TxDOT. The employees were selected due to their professional roles in traffic management and hurricane evacuation operations in coastal Texas regions, thereby serving as subject matter experts in the study.

The workshops were hosted virtually, with between three to five participants attending each two-hour long session. The workshops contained information on AHP concepts, a training tutorial on how to use the tool, and dedicated time for assistance with completing the tool. The workshops concluded with a brief discussion on the tool process and general topics related to real-time traffic monitoring device applications in evacuation events.

5.5. Workshop Results

A total of ten responses, in the form of completed AHP tool spreadsheets, were collected from June 20 to June 29, 2023. Figure 5.3 shows the locations of the workshop attendees by TxDOT district. Attendees were from four of the five Gulf Coast districts—Corpus Christi, Yoakum, Houston, and Beaumont—all of which regularly experience hurricane evacuations. Two additional attendees were from the Bryan District, which is located inland, but is responsible for implementing contraflow operations on Interstate Highway 45 when Houston experiences a major evacuation event, and so it was desired to obtain input from engineers in this district. In addition to the attendees shown on the map in Figure 5.3, there was also one attendee from the statewide Hydraulics Design Division as the researchers wanted to incorporate additional input from diverse perspectives within TxDOT.

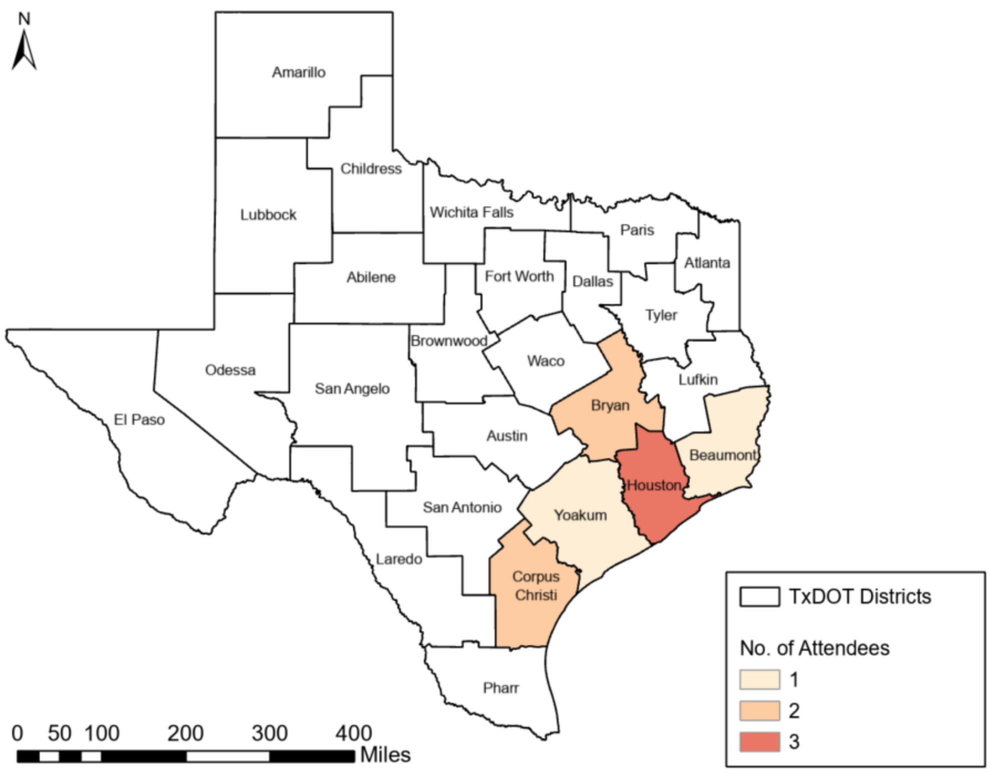


Figure 5.3: Locations of workshop attendees by TxDOT district

All 10 responses were valid with the consistency ratio checks meeting the desired thresholds in all cases. The pairwise comparisons were used to calculate weights for each Level 2 goal and Level 3 factor, and overall relative weights (ORW) were computed from all responses using Equations 5-2 and 5-3.

The overall results for the Level 2 goals are shown in Table 5.5 and Figure 5.4, with the values representing the mean of all responses from all expert participants. Among the three Level 2 goals, “Enhance Safety” was weighted to be the most important goal with a value of relative weight of 41.3, while “Improve Mobility” was close behind at 39.0, and “Increase Resilience” was less important with a value of 19.5. This does not imply that enhancing resilience is unimportant. It remains one of the top three goals; it simply has a slightly lower priority compared to enhancing safety and improving mobility.

Table 5.5 – AHP weight results for Level 2 goals

Goal	Description	Mean AHP Weight
Enhance traffic safety during evacuation	Enhance roadway safety by providing real-time incident detection to reduce the occurrence of collisions and improve first responder response times.	41.3
Improve mobility during evacuation	Ensure evacuation routes remain open, available, and flowing for efficient evacuation.	39.0
Increase system resilience	Maintain a robust, redundant, resourceful, and rapid transportation system during hurricane evacuations. Ensure system is able to adapt to changing conditions and overcome disruptions that may arise.	19.5

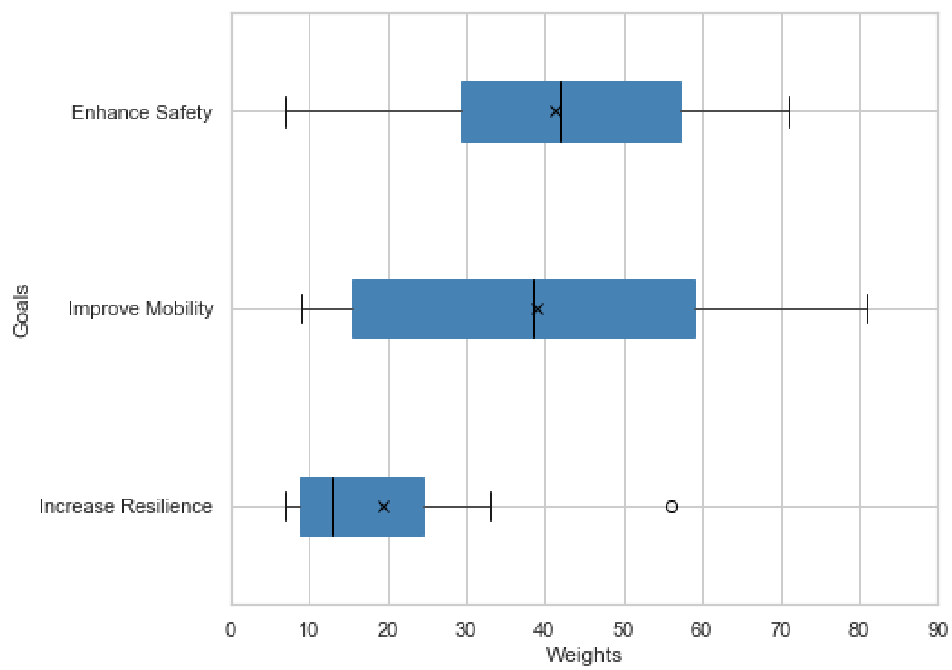


Figure 5.4: Box plot showing the spread of AHP weight results for Level 2 goals

The Level 2 results influence the final Level 3 rankings, as each pairwise comparison for Level 3 is performed under the context of each individual Level 2 goals, and the final Level 3 ORWs were computed using Equation 5-3. Table 5.6 and Figure 5.5 show the ORW for the Level 3 factors.

“Influence on traffic flow” was selected as the most important factor, with a normalized weight of 25.1. This indicates that the employees surveyed most value the ability of TMDs to maintain favorable traffic flow characteristics during the evacuation. By providing real-time information on congestion, travel times, and incidents, employees are better able to coordinate their efforts to ensure that limited resources are deployed where needed to best assist with the evacuation. Providing evacuees with accurate information on real-time traffic data ensures that they have all available information with which to select their route and make destination decisions.

The second ranked factor was “access to critical facilities.” This indicates that the employees surveyed value monitoring roadway corridors that provide access to facilities that provide critical services during hurricane evacuations, such as gas stations, electric vehicle charging stations, hospitals, and public shelters. By monitoring these roads, employees can ensure that access to these facilities is maintained, receive real time information regarding any interruptions, and react promptly to minimize the lost access.

The third ranked factor was “evacuation route status,” which refers to the status of the roadway as an evacuation route as well as its designation as a contraflow or Evaculane corridor. These treatments are deployed during evacuations to increase the roadway capacity, and targeting these segments for traffic monitoring devices may be a worthwhile strategy to ensure that the evacuation traffic treatments are implemented correctly, and traffic is flowing.

Finally, “presence of existing devices” and “compatibility with existing devices” were selected as the fourth and fifth factors, respectively. These factors, while still important, were ranked as the final two. While the surveyed employees valued ensuring that network coverage contains no gaps and that any new devices are compatible with existing infrastructure systems, these aspects pertain more to asset management resource allocation strategies and have less direct application to evacuations.

Table 5.6 – AHP weight results for Level 3 factors

Factor	Description	Mean AHP Weight
Influence on traffic flow	*Incident detection*: reduce incident durations and improve flow during evacuations, maintain reliable travel times. *Route choice*: provide drivers with information on alternate routes and travel time estimates.	25.1
Access to critical facilities	Roadway provides a route to a critical facility for evacuees, such as a shelter, gas station, hospital, etc.	22.5
Evacuation route status	Official designation as an evacuation route, and treatments such as Contraflow or Evaculane shoulder operations.	21.9
Presence of existing devices	The functionality and condition of existing devices along the corridor; if any gaps exist in the current system coverage.	16.1
Compatibility with existing devices	If the new devices can be integrated with the data platforms, power systems, and IT systems used to operate existing devices.	14.5

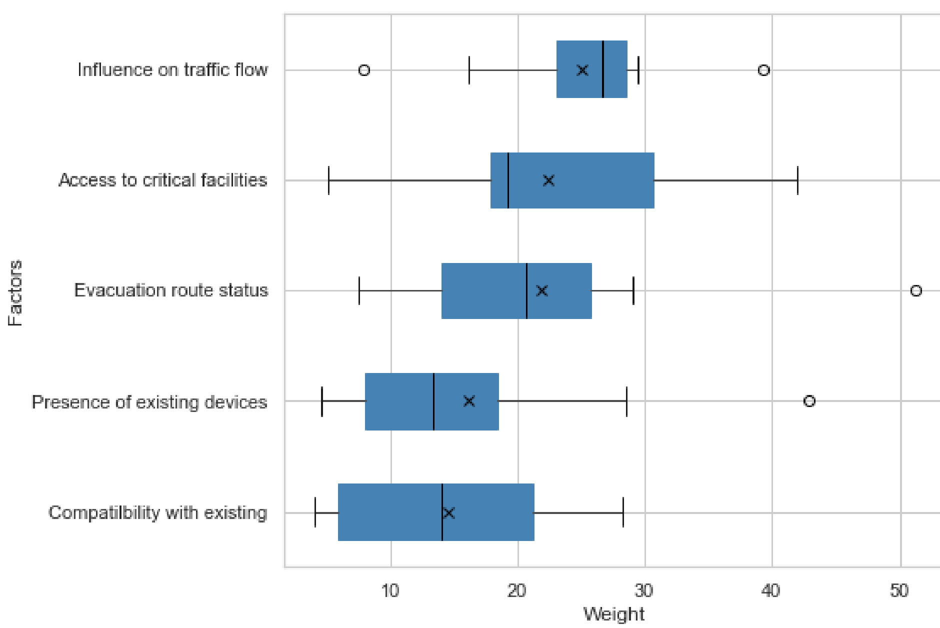


Figure 5.5: Box plot showing the spread of AHP weight results for Level 3 factors

5.6. Prioritization Case Study

While the AHP weights shed light on the preferred factors to be used for prioritizing traffic monitoring device improvements, the weights must be leveraged in an actual prioritization use case to demonstrate an application of the full procedure. By showing how the weights may be used to rank and prioritize a set of project alternatives, TxDOT may be able to incorporate these methods into their asset management practices in the future.

To apply these factors to a set of project alternatives, data attributes and variables that represent these factors are identified to create a data-driven priority rank for the projects, and the AHP weights are applied to create a weighted average for the attributes. For this prioritization, selected roadway links identified as "critical" within Chapter 4 are used as a set of candidate locations for new device deployments, leading to a set of project alternatives to be prioritized. The case study provides an overview of how the AHP results may be leveraged with additional data to prioritize ITS device deployments regarding their usefulness to hurricane evacuations.

5.6.1. Scoring Method

In civil asset management, utility functions are commonly used to incorporate the "usefulness" of an infrastructure asset into a valuation of the asset's cost (Bai et al., 2008). This study takes a similar approach, with the "utility" interpreted as the benefit that would be gained from additional traffic monitoring devices along a given roadway corridor. For example, a roadway with more critical facilities along its corridor would have a higher utility score as this location would benefit more from having additional ITS devices during a hurricane evacuation, thus enabling better real-time information to be known about the traffic conditions on the roads that provide access to these critical facilities. Utility functions provide a quantitative score by scaling a data attribute value to a specified range, with the score taking a desired shape. Common utility function shapes are exponential and sigmoidal, and utility functions may be increasing or decreasing (Porras-Alvarado et al., 2015). Exponential functions may represent decreasing or increasing data where an extreme value is less frequent and requires a greater or lesser score. Sigmoidal functions, which are S-shaped, are typically employed when data are centered around some value, and extreme values to the left or right of the center are desired to be scored higher or lower depending on the understanding of the system. Common functions and shapes of utility functions are shown in Equations 5-7 to 5-10 and Figure 5.6.

Exponential:

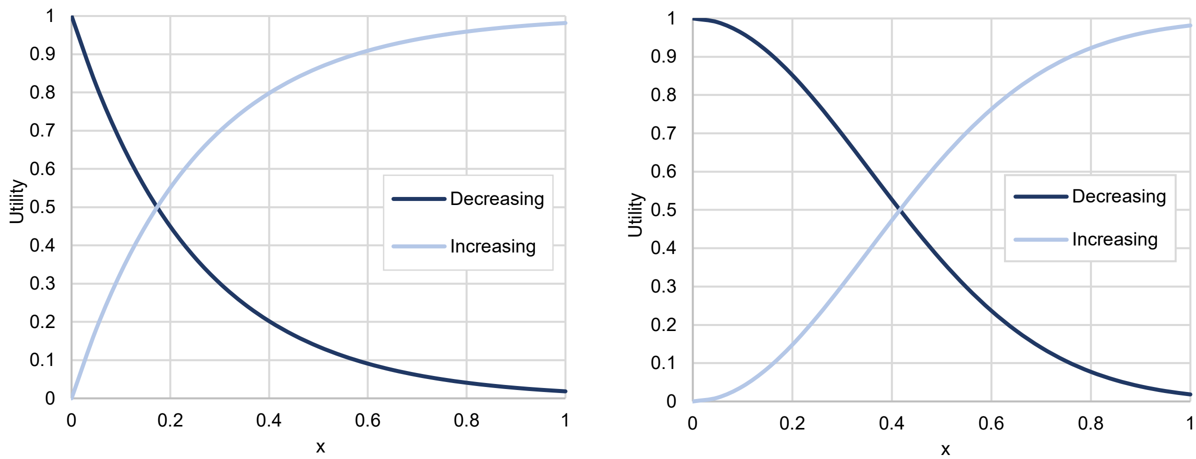
$$U(x) = be^{-ax} \quad b > 0, a > 0 \text{ (decreasing utility)} \tag{5-7}$$

$$U(x) = b(1 - e^{-ax}) \quad b > 0, a > 0 \text{ (increasing utility)} \tag{5-8}$$

Sigmoidal (S-shaped):

$$U(x) = be^{-ax^2} \quad b > 0, a > 0 \text{ (decreasing utility)} \tag{5-9}$$

$$U(x) = b\left(1 - e^{-ax^2}\right) \quad b > 0, a > 0 \text{ (increasing utility)} \tag{5-10}$$



a) Exponential *b) Sigmoidal*

Figure 5.6: Common utility function shapes, with b=1 and a=4 for all functions

The scoring method uses an amalgamation technique to combine the utility values of different factors into a final score representing the priority of each road segment for the installation of new traffic monitoring devices. For this application, a simple utility configuration where the five factors are organized in series is employed, shown in Equation 5-11.

$$P = k_{Cap}U_{Cap} + k_{Fac}U_{Fac} + k_{Eva}U_{Eva} + k_{Dev}U_{Dev} + k_{Com}U_{Com} \quad (5\text{-}11)$$

where,

P is the prioritization score for a roadway segment,

U_{Cap} is the utility score for the roadway capacity,

U_{Fac} is the utility score for the access to critical facilities,

U_{Eva} is the utility score for the evacuation route status,

U_{Dev} is the utility score for the presence of existing ITS devices,

U_{Com} is the utility score for the compatibility with existing devices,

and the k values are corresponding factors to increase the importance of each respective utility score. In this case, these are the final Level 3 weights obtained from AHP. In Equation 5-11, the variables are subject to the following constraints.

$$\sum_i k_i = 100 \quad (5\text{-}12)$$

$$U_i \in [0,1]\ \forall\ i = 1, \ldots, n \quad (5\text{-}13)$$

5.6.2. Case Study

To account for the factors that the AHP workshop participants selected as being most important, data attributes that best represent the factors were selected and a scoring system was devised. Table 5.7 shows the key indicators, performance measures, and utility functions used for the scoring method. Discrete variables, such as binary or categorical values, were directly assigned a score. Continuous variables were assigned scores derived from exponential utility functions. In practice, significant efforts are required to calibrate the utility functions such that they adequately represent the preferences of TxDOT and other stakeholders, and the utility values returned accurately represent the functions of the assets. For this scenario, utility functions are designed to demonstrate an application of the technique. For full implementation, significant efforts should be undertaken to ensure that the utility functions are calibrated to an acceptable level prior to the full implementation of this method (Porras-Alvarado et al., 2015; Stone, 2014).

The scoring system in Table 5.7 was used to assign a priority score to selected roadway segments using Equation 5-11. Data was collected from TxDOT, prior research, and public sources. The "influence on traffic flow" factor was represented by the product of the link capacity and the criticality ratio, which is the number of hours that the link was at capacity during the network simulation in Chapter 4, divided by the total number of hours of the simulation. This quantity gives insight into the number of vehicles that may be moved on a given link during an evacuation, as well as how congested the link may be throughout the evacuation process.

Table 5.7 – Indicators, Performance Measures, and Utility Functions for Case Study

Factor	**Indicators**	**Performance Measure**	**Scaling Performance Measure**
Influence on traffic flow	Roadway capacity, traffic dynamics	Product of link capacity and fraction of time at capacity (CR[1])	$U_{Cap} = 1.0(1 - e^{-0.0004\text{CR}})$
Access to critical facilities	Accessibility to facilities important during an evacuation	Per mile count of fueling stations and hospitals along route (FPM)	$U_{Fac} = 1.0(1 - e^{-0.5\text{FPM}})$
Evacuation route status	Official evacuation route designation	Evacuation route, Evaculane, or Contraflow treatment	U_{Eva} = 0.3 (evacuation route) = 0.5 (Evaculane) = 0.7 (Contraflow) = 0.9 (both Evaculane and Contraflow)
Presence of existing devices	Devices located along road corridor	Per mile ITS device spacing (DPM)	$U_{Dev} = 1.0(e^{-0.5\text{DPM}})$
Compatibility with existing devices	Device power supply and IT platform	Proposed devices use necessary power and IT platforms	$U_{Com} = 0.5$

[1] $CR = C_i \times \frac{t_{c,i}}{T}$, where C_i is the capacity of link i (vph), $t_{c,i}$ is the amount of time (hours) at which link i was at capacity during the simulation, and T is the total simulation runtime (hours)

The “access to critical facilities” factor was represented by the number of critical facilities located along the roadway corridor, such that evacuees could use the specific link to access these facilities if needed during the evacuation process. For this study, critical facilities were defined as fueling stations (both gas stations and electric vehicle charging stations) and hospitals. Location data for these facilities was accessed through the open source OpenStreetMap via the Overpass API with the overpass turbo frontend (OpenStreetMap contributors, 2017). Then, a two-mile buffer was used to count the number of features near each of the critical links in the network, and this count was divided by the link length (in miles) to get the number of facilities per mile.

The “evacuation route status” variable is represented by the designation of a given road segment as a standard evacuation route, Evaculane, Contraflow, or both Evaculane and Contraflow. This data was accessed through the TxDOT GIS data portal and TxDOT official evacuation maps (Texas Department of Transportation, n.d.-a). Note that the network simulation in Chapter 4 was performed on a road network made entirely of links that are in the evacuation network. Therefore, all links in this scoring are part of the base evacuation network at a minimum.

The “presence of existing devices” factor was represented by the number of devices per mile along the critical network links. While the researchers do not have access to the device location data needed to completely perform this analysis, a manual count was performed on the TxDOT ITS device GIS web map to determine the counts of sensing devices and DMS boards along selected roadway corridors for this case study (Texas Department of Transportation, n.d.-b).

Finally, a value of 0.5 was assumed for all road corridors for the “compatibility with existing devices” variable, as the detailed data needed to represent this attribute was not available to the researchers. Data on the types of power supply (electric voltage, amperage, etc.) and IT systems (wireless/fiber optic connectivity, software platforms, etc.) of existing devices and new proposed devices is needed to fully articulate this factor as a quantitative variable in this scoring method.

As the purpose of this case study is to illustrate the application of the scoring method, five road corridors were selected to perform the scoring process and prioritize the selected roads for potential ITS device improvements. The five selected corridors are shown as orange links in Figure 5.7.

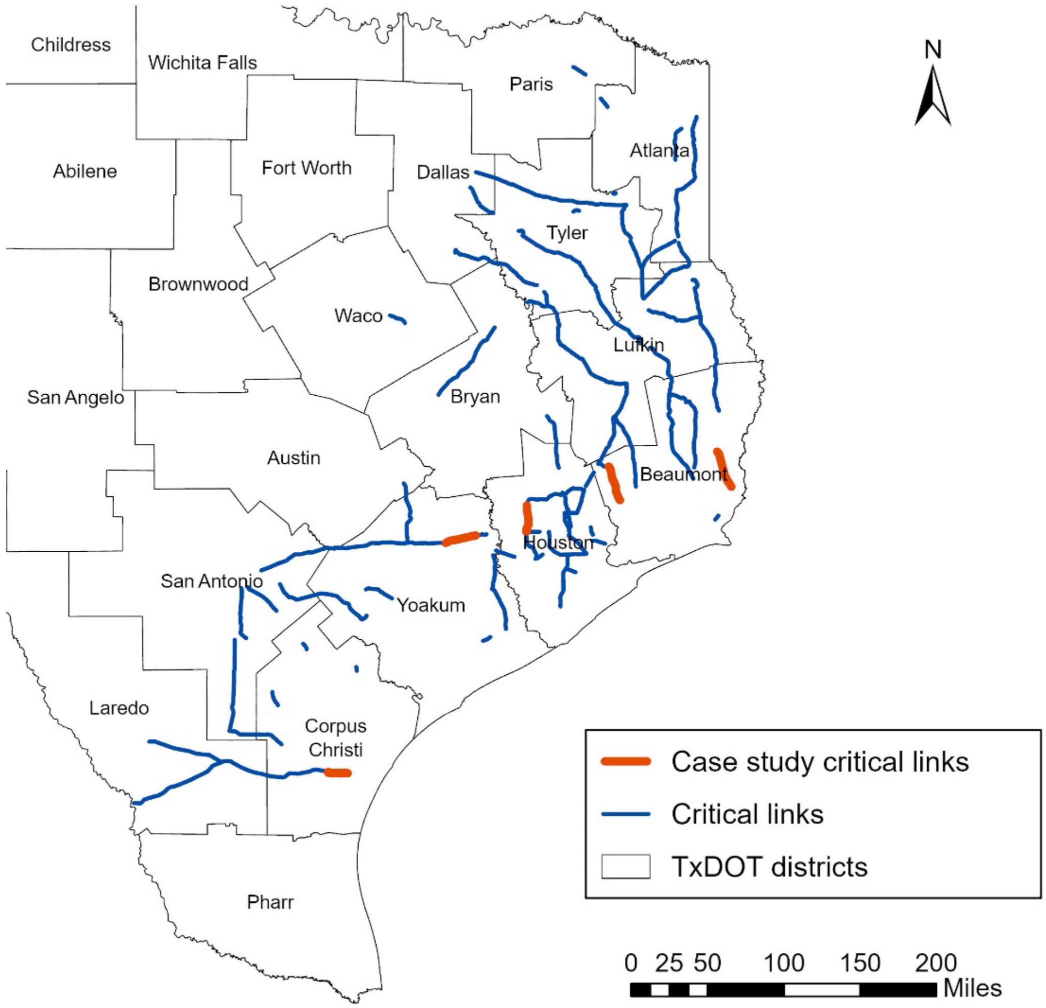


Figure 5.7: Map of critical links and links selected for case study

In all, the simulation from Chapter 4 found that 146 links were critical, or at maximum capacity for a nonzero amount of time during the network simulation. The five links for which the case study was performed were selected due to their proximity to the coast, where evacuations are more likely, and their dispersion across the network. An emphasis was placed on selecting roads which do not currently have any devices, roads which are designated as Evaculane or contraflow corridors, and roads which are located in urban or rural areas to have a diverse set of links for which to perform the analysis. The characteristics of the selected road segments are shown in Table 5.8.

Table 5.8 – Case study profiles

Route	**1**	**2**	**3**	**4**	**5**
Roadway name	SH 99	SH 44	IH 10	SH 321	SH 62
Network link	(89, 350)	(131, 224)	(45, 575)	(8, 9)	(331, 366)
Location	IH 10 to US 290	IH 69E to SH 358	0.75 mi east of Beckendorff Rd to SH 71	US 90 to SH 105	1.5 mi north of SH 1078 to US 96
TxDOT district	HOU	CRP	YKM	BMT	BMT
Length (miles)	15.26	11.91	17.65	20.29	21.68
Lanes	4 (2 per direction, divided)	4 (2 per direction, divided)	4 (2 per direction, divided)	2 (1 per direction)	2 (1 per direction)
Speed limit (mph)	65	65	75	65	40
Toll	Yes	No	No	No	No
Roadway parameters					
Capacity (vph)	4,000	4,000	10,000	2,000	2,000
Time critical (ratio)	58.5 (0.53)	14.75 (0.13)	82.75 (0.75)	13.25 (0.12)	4.25 (0.04)
Evaculane	No	No	Yes	Yes	No
Contraflow	No	No	Yes	No	No
Gas stations (per mile)	31 (2.03)	4 (0.34)	10 (0.57)	12 (0.59)	1 (0.05)
EV charging stations (per mile)	11 (0.72)	4 (0.34)	3 (0.17)	1 (0.05)	0 (0)
Hospitals (per mile)	4 (0.26)	0 (0)	1 (0.06)	0 (0)	0 (0)
ITS device parameters					
Cameras, Bluetooth, RVSD (per mile)	37 (2.42)	0 (0)	5 (0.28)	2 (0.1)	4 (0.18)
DMS (per mile)	8 (0.52)	0 (0)	1 (0.06)	0 (0)	0 (0)

The profiles and data attributes shown in Table 5.8 were applied to the utility functions and scoring method defined in Table 5.7, giving a final prioritization score for each of the five road segments. These alternatives are ranked by the highest score, shown in Table 5.9, and the prioritization is assigned in a descending order, shown in Figure 5.8. The alternatives are grouped to provide a category of "Low," "Medium," or "High" priority for future ITS device implementations with the goal of aiding hurricane evacuation operations.

Table 5.9 – Summary of prioritization scoring results

Factor	**Utility**	**k value**	**Route**				
			1	**2**	**3**	**4**	**5**
Capacity criticality	U_{Cap}	25.1	0.57	0.19	0.95	0.09	0.03
Evacuation route status	U_{Eva}	22.5	0.30	0.30	0.90	0.50	0.30
Critical facility access	U_{Fac}	21.9	0.78	0.29	0.33	0.27	0.02
ITS devices	U_{Dev}	16.1	0.23	1.00	0.71	0.91	0.83
ITS compatibility	U_{Com}	14.5	0.50	0.50	0.50	0.50	0.50
TOTAL SCORE (P)			**49.07**	**41.17**	**69.97**	**41.39**	**28.65**

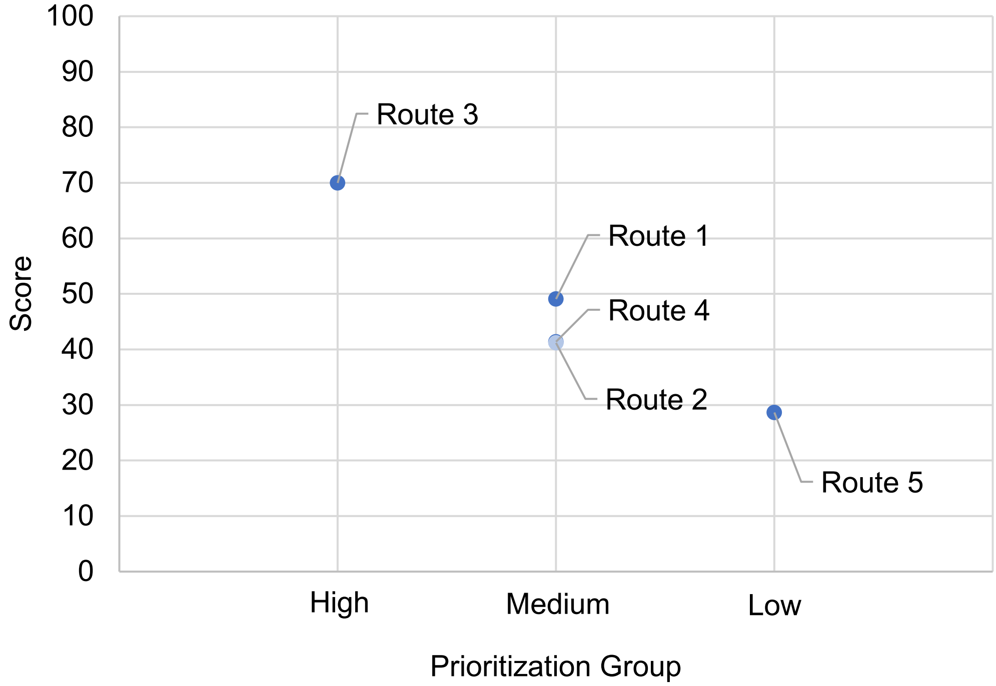


Figure 5.8: Prioritization result grouping

5.7. Prioritization Recommendations

From the results of the case study, the IH 10 corridor west of Houston was determined to be the highest priority. This road corridor scored highly as it is high capacity, was at capacity for a relatively long time during the network simulation, has both Evaculane and contraflow designations, provides access to some critical facilities, and has relatively few ITS devices installed currently. Therefore, this road received a "High" prioritization score and is a good candidate for implementing more ITS devices to aid with future hurricane evacuations. Three roadways – SH 99, SH 44, and SH 321 – received similar scores and a "Medium" priority. These roadways have a mixture of features and critical facilities, yet all achieve a similar score. One advantage of the proposed scoring system is that no one attribute explicitly qualifies or disqualifies an alternative from being selected, meaning that the final priority score accounts for all data in a manner that is consistent with the TxDOT rankings obtained from AHP. Finally, SH 62 received a priority score of "Low." This is due to a relatively low-capacity utility score and access to few critical facilities as this route is a rural highway. While this route may still be important for ITS device installation, limited funds may be better spent on the corridors that are "High" or "Medium" priority as the benefits seen during a hurricane evacuation may be greater. Further analysis is required to fully support these findings from a safety and economic perspective.

From this analysis, methods are presented that demonstrate how agency perspectives and professional engineering opinions may be integrated into a quantitative scoring system to prioritize alternatives. The scoring results provide a relative comparison between selected roadways in the network and result in categorization of the alternatives into groupings for priority of device installation. The roadways that are the highest priority should be assessed for specific locations for ITS device installation, and a cost analysis should be performed. With complete asset data regarding statewide ITS device locations, age, condition, replacement cost, and device power/IT systems, a full analysis could be performed for the statewide ITS device system and results could inform a more specific deployment schedule and cost estimation.

While these methods highlight techniques that may be used to integrate real-time traffic monitoring devices into hurricane evacuation operations, in practice officials should seek to incorporate these methods into traditional techniques, which may focus on safety, capacity, locations of recurring congestion, or device costs when determining asset management actions for ITS devices. It is important that hurricane evacuations are adequately monitored to provide accurate real time travel information to agency employees and evacuees, but also that devices are installed in locations where they are needed during regular, non-hurricane traffic conditions as well.

5.8. Summary

This chapter summarizes the methods and findings of the device prioritization process. The primary objective entails developing a prioritized schedule for optimal deployment of traffic monitoring devices. The project team assessed different multi-criteria decision analysis tools to identify the most crucial criteria for prioritizing system upgrades and expansion. The Analytical Hierarchy Process (AHP) was selected given its ease-of-use and user-friendly advantages. AHP uses pairwise comparisons between two variables on a ratio scale, and consists of three tiers: objectives, goals, and factors.

TxDOT PMC members selected "Enhance safety," "Improve mobility," and "Enhance transportation system resilience" as the Level 2 goals and "Compatibility with existing monitoring device system," "Presence of existing monitoring devices on road corridor," "Influence on traffic volume characteristics," "Whether the roadway is an evacuation route or not," and "Access to critical facilities during an evacuation" as the Level 3 factors. These Level 2 and Level 3 items were included in the AHP hierarchy.

An Excel spreadsheet-based tool was created to collect the AHP pairwise comparisons. A series of workshops were conducted with TxDOT employees to explain the concepts of AHP, provide instructions on how to fill out the tool, and to assist the participants with completion of the tool. Once all responses were collected, the final AHP weights were calculated. These were then used to provide a prioritized schedule for a series of derived project alternatives to provide TxDOT with findings for future implementation to aid with real time traffic data during hurricane evacuations and also demonstrate how the methodology used herein is applied in practice.

The final AHP weights were leveraged in a scoring system that employed utility functions and discrete values to assign roadway corridor alternatives a prioritization score. Data from the simulation in Chapter 4, public agency datasets, and open-source data was used to perform the analysis. A case study was conducted to rank five alternatives and assign a value of "Low," "Medium," or "High" priority to each corridor. These findings demonstrate methods that, with complete statewide ITS device and cost data, can be used by TxDOT to develop short and long-term strategic plans for implementing ITS devices with application to hurricane evacuation operations.

These methods and results should be used to supplement existing methods for determining the resource allocation and project selection of traffic monitoring device systems in Texas. The methods and results presented herein are applicable to hurricane evacuation scenarios and may or may not provide the optimal solution for the installation of new roadway monitoring devices for non-evacuation purposes, such as routine recurring congestion or commuter travel time monitoring.

Chapter 6. Estimate Operating and Maintenance Costs

6.1. Introduction

Chapter 6 estimates the costs of the ITS system. These efforts will support sustainable life cycle cost assessment by evaluating the cost-effectiveness of each device type under a variety of scenarios. The results of this process help shed insight into the funding level needed to ensure the long-term, sustainable operation of the Texas ITS system on evacuation routes.

To understand the costs associated with the installation and maintenance of traffic monitoring devices, efforts were undertaken to collect cost data through interviews and correspondence with Texas Department of Transportation (TxDOT) district employees. The researchers obtained parameter values for traffic monitoring devices and their associated costs. The device and cost data collected from participating staff represent operations at various districts. The findings reflect operations experienced by some TxDOT staff, but no TxDOT administration was included in the outreach and the findings do not represent TxDOT as a whole.

Pan-tilt-zoom (PTZ) cameras and dynamic message signs (DMS) are the two major devices in the TxDOT ITS. Cameras assist with incident detection, while DMS help drivers determine their evacuation routing. For each type of device, the primary cost components are the device purchase cost, installation cost, and associated maintenance costs over the lifespan of the device. Each TxDOT district has a specified budget to maintain the current system and replace broken or obsolete devices. In this task, a base case was established, and then two scenarios were calculated to estimate the cost for ITS devices on hurricane evacuation routes under different traffic camera spacings and different replacement rates for obsolete devices. These methods allow for a sensitivity analysis of the estimated total system cost to variations in these parameters.

6.2. Current Level of ITS Implementation in Texas

In Texas, ITS devices are maintained at the district-level, with each district planning and coordinating device installation, upgrades, and maintenance. TxDOT districts create ITS master plans and include them in their Transportation Systems Management and Operations (TSMO) Program Plan documents. The researchers searched for publicly available TSMO plans, which were acquired for several districts. The most recent TSMO plans available are from 2021. Complete TSMO plans for all districts could not be located online. The ITS device plans for several TxDOT districts are summarized in Table 6.1, with installation and maintenance costs details listed in their TSMO plans.

Table 6.1 – Summary of device plans for selected TxDOT districts

District	Information Included in TSMO Plan

Amarillo District (Amarillo District, 2021)	• Unit cost of various ITS equipment types
	  ○ Details on the components included for each equipment
	  ○ Cost breakdown for each component
	• Capital cost and yearly maintenance cost
	  ○ Based on Texas Department of Transportation (TxDOT) statewide average bid item prices as of September 2020

Yoakum District (Yoakum District, 2021)	• Cost of the ITS devices based on various projects ○ Roadway monitoring incident management and information dissemination • Capital cost, yearly maintenance, and operation cost
San Angelo District (San Angelo District, 2021)	• Breakdown of the total cost for each proposed TMS project ○ Equipment required and their respective costs • Not categorized into capital cost and maintenance cost
El Paso District (El Paso District, 2020)	• Detailed cost information for the installation of each TMS ○ Breakdown of the unit cost • Does not include the yearly maintenance cost
Dallas-Fort Worth District (Dallas-Fort Worth District, 2021)	• Cost information is presented in a semi-quantitative manner ○ Categorized as low, medium, or high • Does not include the yearly maintenance cost

While these TSMO plans provide some useful information on ITS device costs at district-level, the researchers were not able to obtain the plans of all districts in Texas. As the objective of this project is to investigate the usage of ITS devices for hurricane evacuations, the researchers focused on districts that contain evacuation routes. Therefore, targeted efforts were made to collect more detailed data for districts located along- and to the east of- the IH 35 corridor in the eastern portion of the state.

6.3. TxDOT Detailed ITS Data Collection

To acquire more specific details, significant outreach efforts were undertaken to contact relevant TxDOT employees. Through the RTI project manager, email communications were distributed to TxDOT districts to collect additional cost information. A total of 15 districts were selected based on the location of the evacuation network, as shown in Figure 6.1. In the email correspondence with each district, the data requested was outlined as three primary components:

1. Location (latitude/longitude) of ITS devices (PTZ cameras and DMS) in table or GIS format.
2. For each type of device (PTZ cameras and DMS), general or typical values for:
    a. Purchase cost,
    b. Installation cost,
    c. Annual operating cost, and
    d. Expected device lifespan.
3. Miscellaneous general information such as common brand names, frequency of system upgrades or device replacement, and typical recurring maintenance requirements.

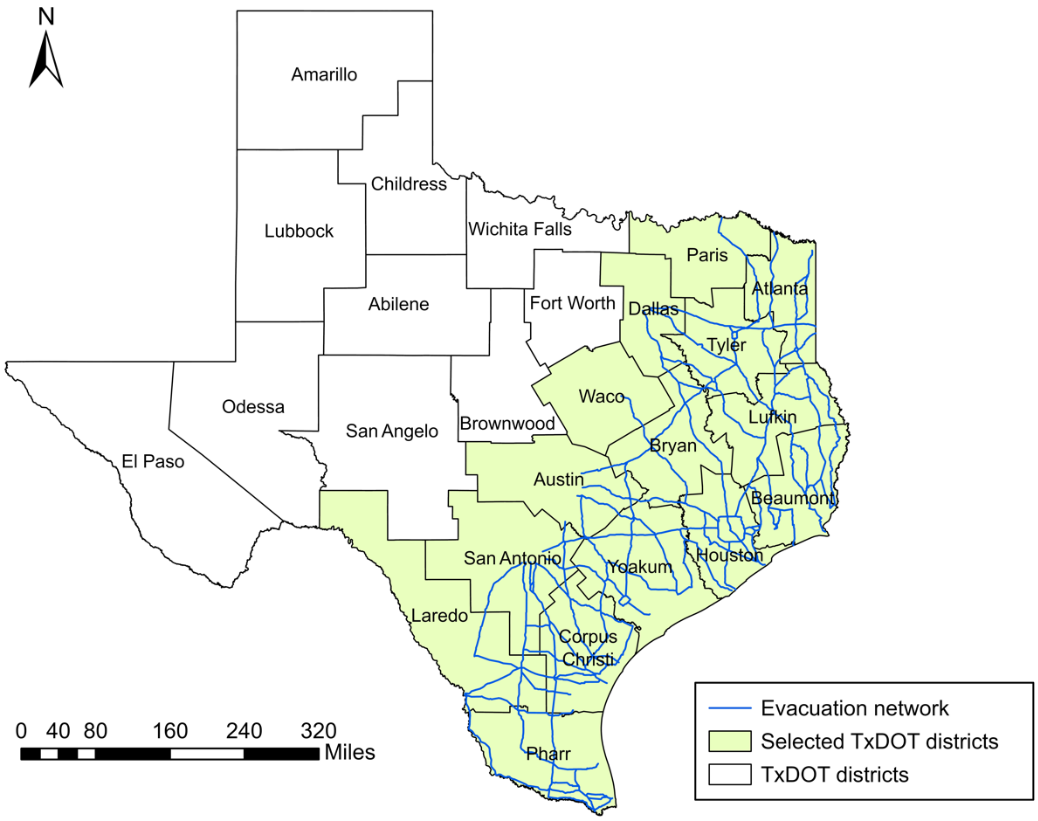


Figure 6.1: Map of selected TxDOT districts based on evacuation network.

TxDOT maintains an online interactive GIS dashboard that allows users to view real-time camera images and DMS posted text at https://its.txdot.gov/its. Efforts were made to acquire this data at a statewide level from one entity to ensure data continuity and cohesiveness. Extensive communication was made with TxDOT to acquire the ITS device locations. The data was obtained for the north, south, and western portions of the state.

Individual districts, when responding to the data request, typically did not provide location data in latitude/longitude format, but rather in text format describing the intersection or crossroads of the device locations. While descriptive, this data is not easily imported into GIS or other software applications for analysis. We suggest that TxDOT work with the districts to maintain better consistency in data formatting and storage to ensure such data is maintained in an appropriate format for future use. Of the 14 districts contacted, responses were received from 12 districts: Austin, Houston, Pharr, Dallas, San Antonio, Yoakum, Atlanta, Bryan, Tyler, Laredo, Corpus Christi, and Beaumont. From this group, the data provided ranged from a short explanation of the device types and their age present in a given district, to detailed data in table form for individual devices.

The Atlanta district provided comprehensive information regarding the cost and location associated with PTZ cameras and DMS. While values varied, it was noted that the typical combined purchase and installation cost for a PTZ camera is around $49,000. A similar value for a DMS is $140,000. Individual DMS proves to be more costly on a per unit basis than cameras as DMS screen panels may be relatively expensive and DMS devices have additional costs such as the sign superstructure and foundation. The district also noted that a typical lifespan until replacement for a PTZ camera is 7-10 years and for a DMS is 10-15 years. Finally, the district noted that the total annual maintenance costs for all devices were about $90,000.

An in-depth interview was conducted with an employee from the Houston District to gain a better understanding of various costs types associated with ITS devices and the maintenance requirements for the system. The employee shared a wealth of information, helping to verify estimated ranges for the costs of certain devices. Additionally, it was determined that the Houston district annually spends around $4-5 million for maintenance and $2-3 million for replacement on all ITS devices combined. The system is continually being upgraded with old or obsolete devices being replaced. The employee mentioned that about 10% of all cameras in the district are replaced every year.

The interviewee provided the brand names for the most commonly purchased devices and also confirmed that districts across Texas likely employ similar brands and models of traffic monitoring devices as there are purchase requirements to ensure that any device is able to be integrated with existing state data platforms. This detail was very beneficial, and the ensuing cost estimate analysis assumed that the same devices could be used across all districts on the basis of this information. Regarding the operation of ITS devices in hurricane scenarios, it was explained that TxDOT staff conducts routine checks on the monitoring devices located on evacuation routes before May and repairs any devices that are malfunctioning to ensure that traffic monitoring devices function acceptably during hurricane events. There are also backup generators around Houston that can be deployed to maintain power supply in cases of widespread, long-term electricity outages.

Based on the data obtained through email communications and interviews with TxDOT employees, typical values for the cost of PTZ cameras and DMS boards were determined and listed in Table 6.2. The values are assumed to be consistent across coastal TxDOT districts. Compared with PTZ cameras, DMS generally costs more with a wide cost range. In addition, the guidance for the placement of PTZ cameras is every 0.5 miles along a roadway, while DMS are to be located primarily at decision points, such as intersections or interchanges. As such, there are considerably fewer DMS on the system than cameras. Due to the uncertain cost and the relatively infrequent need for DMS, it is very challenging to conduct a quantitative cost analysis. Therefore, this task does not include DMS boards and focuses on PTZ camera coverage for Texas hurricane evacuation routes.

Table 6.2 – Typical values for Texas ITS device costs

Parameters	PTZ cameras	Dynamic Message Signs (DMS)
Cost per unit	\$5,000 - \$6,000	\$80,000 - \$100,000
Installation cost per unit (camera and new pole)	\$43,000	Varies, \$60,000-\$120,000 range is commonly observed
Installation cost per unit (on an existing camera pole)	\$3000	\$18,000
Maintenance cost	\$1,500	\$4,500
Placement strategy	Every 0.5 mile	Decision points (major intersections or interchanges)
Replacement rate	10% of system, annually	Not sure

6.4. Cost Estimation Methodology

To estimate the costs of ITS devices identified in this project, a life cycle cost analysis (LCCA) was conducted, focusing on all hurricane evacuation routes in Texas. The analysis assumed that the ITS devices to be implemented would be PTZ cameras, and these cameras would be installed along the evacuation routes with a certain spacing. The base case scenario provides a reasonable cost estimate on the funding required for installing new traffic monitoring devices and maintaining the remaining devices along every designated evacuation route in Texas. It is acknowledged that some routes are either not currently equipped with devices or may be less suitable for installation, particularly if they are low-volume or rural routes. However, the primary goal of this estimation is to quantify the funds needed to install and maintain cameras at a desired interval across the entire evacuation network. It is also noted that this estimate only targets cameras located on officially designated evacuation routes. Therefore, this estimate is intended to guide districts aiming to enhance their traffic monitoring capabilities on hurricane evacuation routes and may complement efforts to enhance day-to-day traffic operations at a district-wide level.

The number of cameras needed (6-1) and overall annual cost (6-2) equations were used for cameras in the analysis.

$$N = \frac{D}{s} + 1 \tag{6-1}$$

$$A = (P + I) * N * replace\_r + M * N * (1 - replace\_r) \tag{6-2}$$

D: centerline distance of evacuation routes in the system or a certain district

s: spacing between two cameras

A: the overall annual cost of the traffic monitoring devices

P: the purchase cost of cameras

I: the installation cost of cameras

N: the number of cameras in the system or a certain district

M: annual maintenance cost of cameras

$replace\_r$: annual replacement rate of cameras in the system or a certain district

Equation (6-1) serves as the component factor used in Equation (6-2). More precisely, Equation (6-1) determines the number of cameras used in the hurricane evacuation system or a specific district by dividing the centerline distance by the spacing between cameras. Following this, Equation (6-2) calculates the total annual cost of cameras in the ITS system. This total annual cost is divided into two parts: the first part computes the annual cost of camera replacement, while the second part calculates the maintenance cost for the remaining cameras.

To examine the influence of various parameters in the cost estimation, two scenarios are constructed under two installation options, as shown in Figure 6.2. The baseline scenario has fixed parameters for costs ($5,300 purchase and $1,500 annually for maintenance), replacement rate (10% annually), and device spacing (0.5 miles), with values obtained from Table 6.1. For each scenario, there are two installation options: replacing only cameras on the existing construction poles and replacing both the pole and camera. Each scenario calculates the annual, system-wide cost for cameras to be installed and maintained on Texas hurricane evacuation routes under the two installation options.

In contrast, the two scenarios demonstrate sensitivity by adjusting certain parameters. Scenario 1 involves the adjustment of the spacing between cameras, ranging from 0.5 mile to 1 mile at a 0.1-mile interval. Similarly, Scenario 2 explores variations in the replacement rate between 5% and 15% with a step size of 1%, while keeping all other parameters fixed. These scenarios aim to provide the agency with an understanding of how varying parameters can influence the total cost of ITS systems.

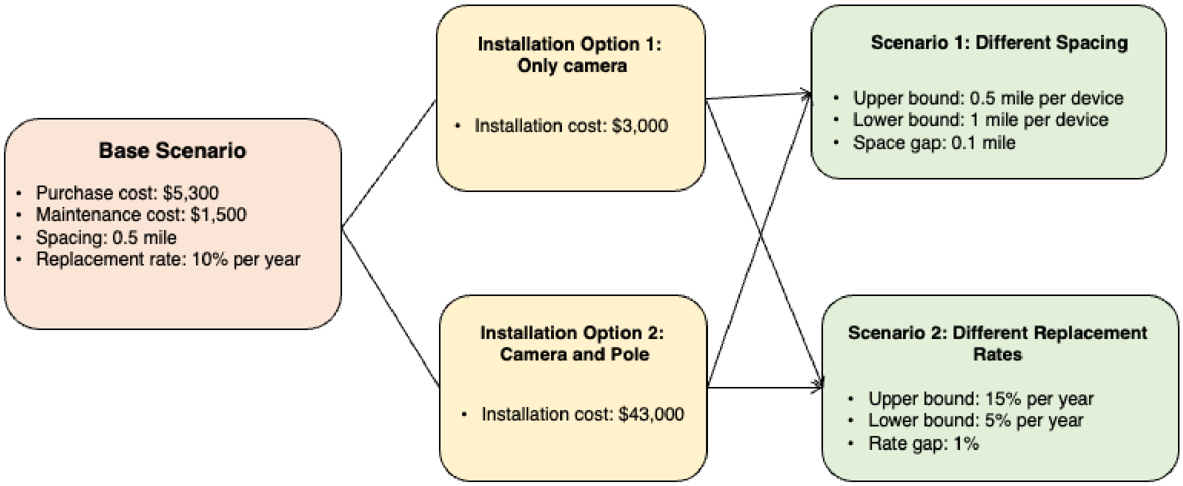


Figure 6.2: Cost estimation scenarios

6.5. O&M Cost Estimation Results

Annual costs for cameras along hurricane evacuation routes in Texas were calculated under different scenarios, as illustrated in Figures 6.3 to 6.4, with the baseline scenario highlighted in burnt orange in each figure. Given the total evacuation centerline mile in Texas is approximately 7,909 miles, using the input parameter values in Figure 6.2, the annual cost for the base scenario in Texas is $97.8 million without existing camera poles and $34.5 million for those involving existing cameras.

However, this is not the case for different spacing and replacement rates. Figure 6.3 shows the total annual cost for ITS cameras along Texas hurricane evacuation routes with varying spacing from 0.5 mile to 1 mile. In comparison to the baseline scenario of 0.5 mile spacing with an annual cost of $97.8 million, requiring construction on camera poles, the annual cost decreases to $48.9 million when the spacing increases to 1 mile, approximately half of the base scenario. Similarly, compared to the baseline scenario of $34.5 million annually by only replacing or upgrading cameras themselves, the budget decreases to half at around $17.2 million annually.

This is because that larger space indicates fewer camera devices, which results in lower annual cost. Differences in costs with 0.1-mile spacing result in cost variance between $5.4 million (0.9 mile spacing vs. 1.0 mile spacing) to $16.3 million (0.5 mile spacing vs. 0.6 mile spacing) for installation option of replacing camera poles. This provides insights on the impacts of device spacing on annual cost. For example, the annual cost is larger in high AADT routes with smaller device spacing and lower in areas with larger spacing.

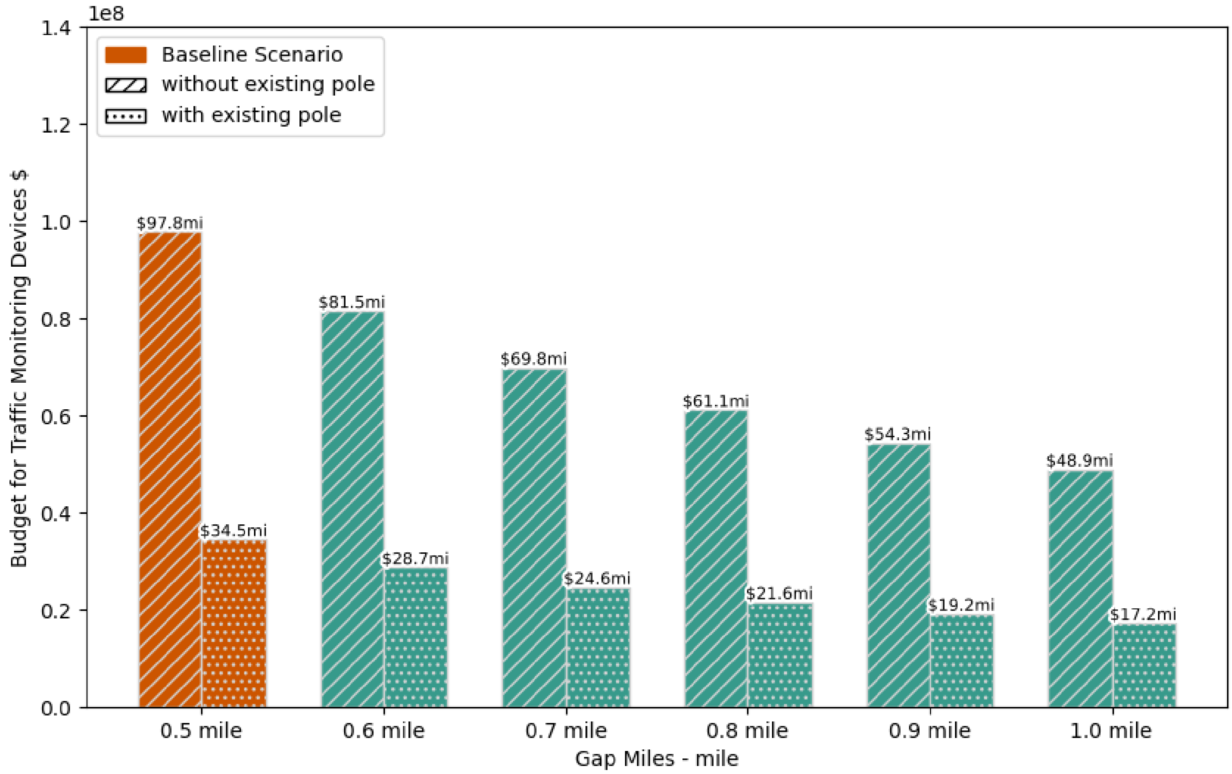


Figure 6.3: Annual cost for ITS cameras on Texas hurricane evacuation routes with varying device spacing

Different device replacement rates also play a role in annual costs, as shown in Figure 6.4. As devices become obsolete or broken, they must be replaced or upgraded with newer technology. The base scenario assumes that 10% of all cameras on the network are replaced every year. Compared to a 10% replacement rate that results in a cost of $97.8 million or $34.5 million for two installation options, a 5% annual replacement rate reduces the total annual system cost to $60.7 million or $29.1 million, approximately $37 million or $5 million in savings. Conversely, a 15% replacement rate per year increases the cost to around $134.8 million or $39.9 million, approximately $27 million or $5 million more. The annual cost shows a $8 million or $1 million difference for two installation options for every 1% change in the replacement rate across Texas evacuation systems.

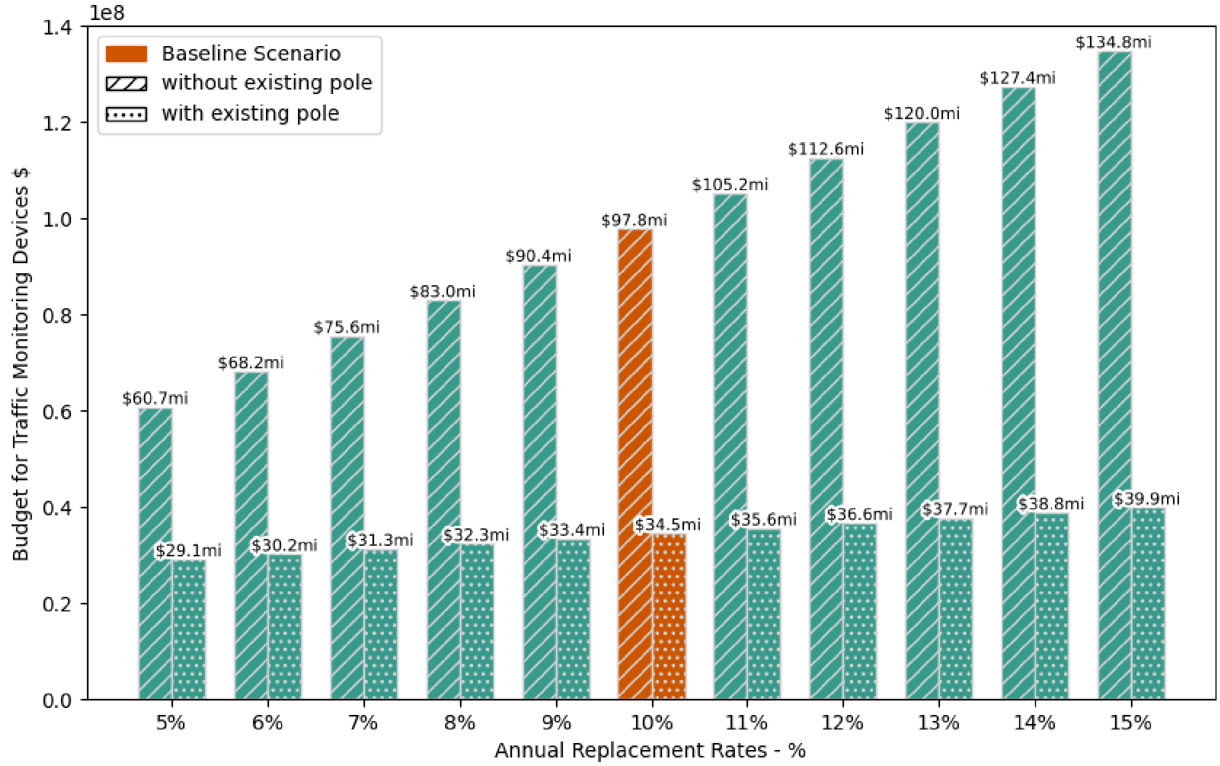


Figure 6.4: Annual cost for ITS cameras on Texas hurricane evacuation routes with varying replacement rates

To illustrate heterogeneity across TxDOT districts, we calculated the annual cost of camera devices along evacuation routes for the 15 districts in Figure 6.1. The 15 districts were chosen as they contain the hurricane evacuation routes in the state, while the remaining 10 districts do not have any evacuation routes and therefore were not selected. All the parameters used in this calculation were derived from the base scenario shown in Figure 6.2. The evacuation route distance for each district, as displayed in Table 6.3, was used to calculate the number of cameras needed with a spacing of 0.5 mile.

Table 6.3 – Hurricane evacuation route centerline miles for targeted districts

#	District	Evacuation Route Centerline Miles
1	Corpus Christi	718.00
2	Pharr	630.24
3	Yoakum	617.48
4	Houston	569.23
5	Beaumont	559.06
6	Lufkin	427.59
7	Tyler	425.71
8	San Antonio	425.68
9	Atlanta	381.55
10	Bryan	377.44
11	Laredo	321.08
12	Austin	217.27
13	Dallas	161.58
14	Paris	46.63
15	Waco	37.29

The results reveal heterogeneity across different TxDOT districts, as depicted in Figures 6.5 and 6.6. Figure 6.5 displays the annual costs for each district under installation option 1, involving the construction of new poles for every camera replacement, while Figure 6.6 indicates the annual cost for ITS cameras under installation option 2 by only replacing cameras under the existing poles. The red bars in the figures represent five coastal districts, namely Corpus Christ, Pharr, Yoakum, Houston, and Beaumont. Given that these coastal districts have longer evacuation routes in centerline miles, their annual costs are correspondingly higher, ranging from \$6.9 million to \$8.9 million per year for the first installation strategy and \$2.4 million to \$3.1 million for the second installation strategy. The districts that contain hurricane evacuation routes but are located further inland have lower annual cost estimates. This provides valuable insights for each district, providing both upper bound and lower bounds for annual costs when planning the budget for camera installations in future years.

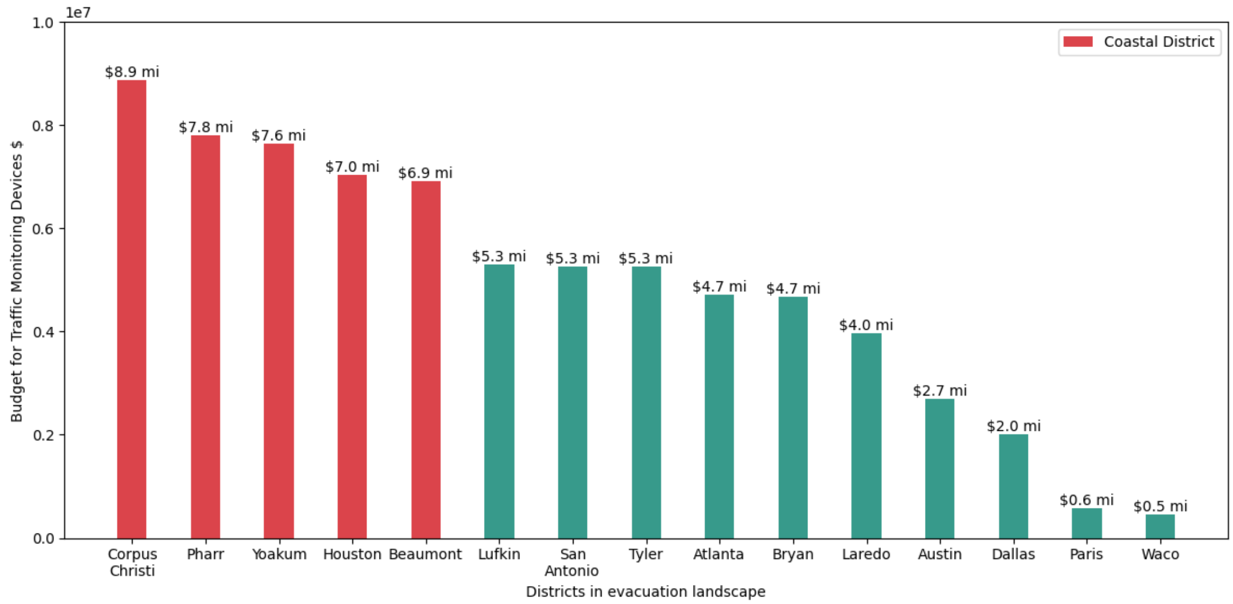


Figure 6.5: Annual costs for ITS cameras on Texas hurricane evacuation routes by TxDOT district (Installation option 1: replacing both cameras and camera poles)

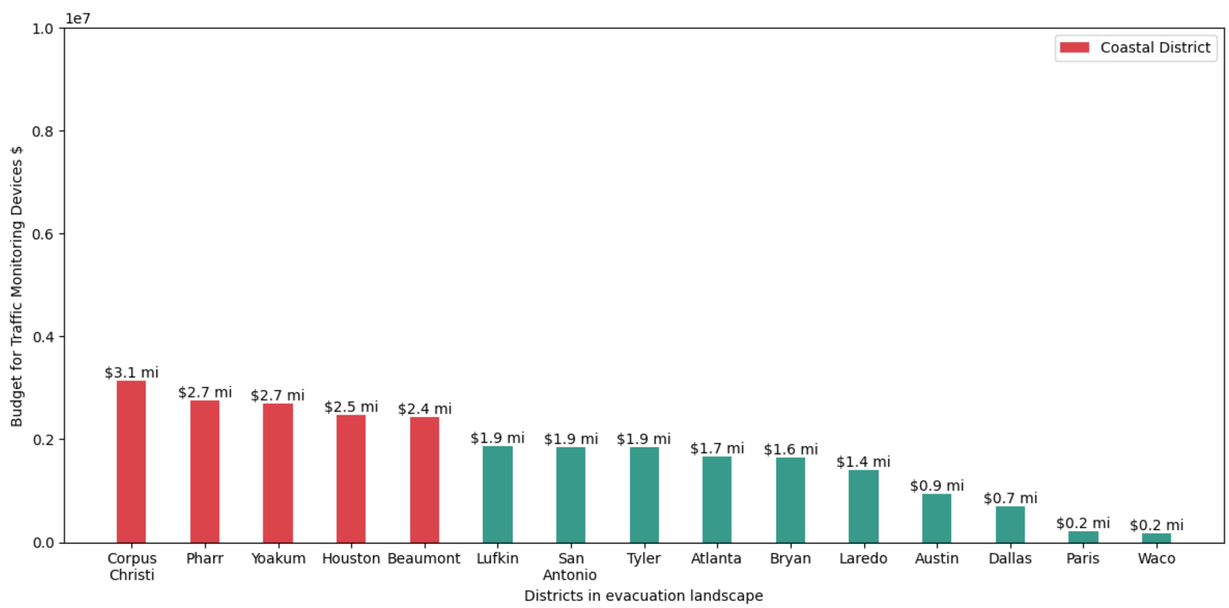


Figure 6.6: Annual costs for ITS cameras on Texas hurricane evacuation routes by TxDOT district (Installation option 2: replacing or upgrading only cameras)

6.6. Summary

A comprehensive method is presented to calculate the expected annual budget needed to install and maintain traffic cameras along all hurricane evacuation routes in Texas. To ensure accuracy in the cost estimation, significant efforts were undertaken to reach out to TxDOT employees to collect ITS device data. The device location, expected costs, and information on common brands, device lifespans, and more were obtained through email correspondence and interviews. Based on these data collection activities, typical values were determined that fell within the range of the collected data.

To perform the cost analysis, sensitivity analysis scenarios were computed to determine the impacts of certain parameters on the cost estimate, including spacing of traffic cameras and annual device replacement rate under two installation strategies, one involving the construction of camera poles and the other not.

The estimated annual cost to install and maintain cameras on all Texas hurricane evacuation routes is around $97.8 million with new cameras and poles, and around $34.5 million by only replacing or upgrading cameras, considering a camera spacing of 0.5 miles and an annual device replacement rate of 10%. Furthermore, we extended our analysis to the district level, revealing that the annual cost of the five coastal districts is higher due to longer centerline miles of evacuation routes. The results of the sensitivity analysis show how small changes in the desired device spacing or replacement rate can affect the final total budget required. Our findings provide insights to each district on the estimated annual cost of cameras along hurricane evacuation routes within their boundary.

Chapter 7. Develop Resilient System for Information Transfer

7.1. Introduction

This chapter discusses necessary measures to keep the communication system functional when one or more components fail. The results of this process help shed insight on the resilience of the ITS telecommunication system during hurricane evacuations.

TxDOT employs essential components in its emergency preparedness and response operations, utilizing resources such as the DriveTexas webpage, the TxDOT Travel Information phone line, media communications, and dynamic message signs located along evacuation routes. Congestion in cellular networks and power outages can cause communication delays and disruption which can have disastrous implications across many services (Genasys, 2023). Recognizing communication systems and potential events during evacuations is crucial for both agencies and providing effective support to the public in emergency events.

This chapter begins by providing an overview of the key elements of the existing communication systems in Texas. Then we discuss potential hazardous events resulting from hurricanes and tropical storms, and we conclude by proposing mitigation measures to ensure telecommunication resilience.

7.2. Current ITS Communication Systems in Texas

Several ITS Architecture Reports have been published for regions across Texas (Kimley-Horn and Associates, Inc. and ConSysTec Corp, 2003a; PBS&J and Battelle, 2003). These reports contain detailed versions of the National ITS Architecture "sausage" diagram. Though they were both published in 2003, and most of the individual devices have since been replaced, the overall flows of data remain the same today. We will focus specifically on the Corpus Christi and Houston regions since those regions were in the hurricane-prone zones and examined in earlier chapters of this report. The ITS Architecture diagrams from both of their reports are shown in Figure 7.1 and Figure 7.2 respectively.

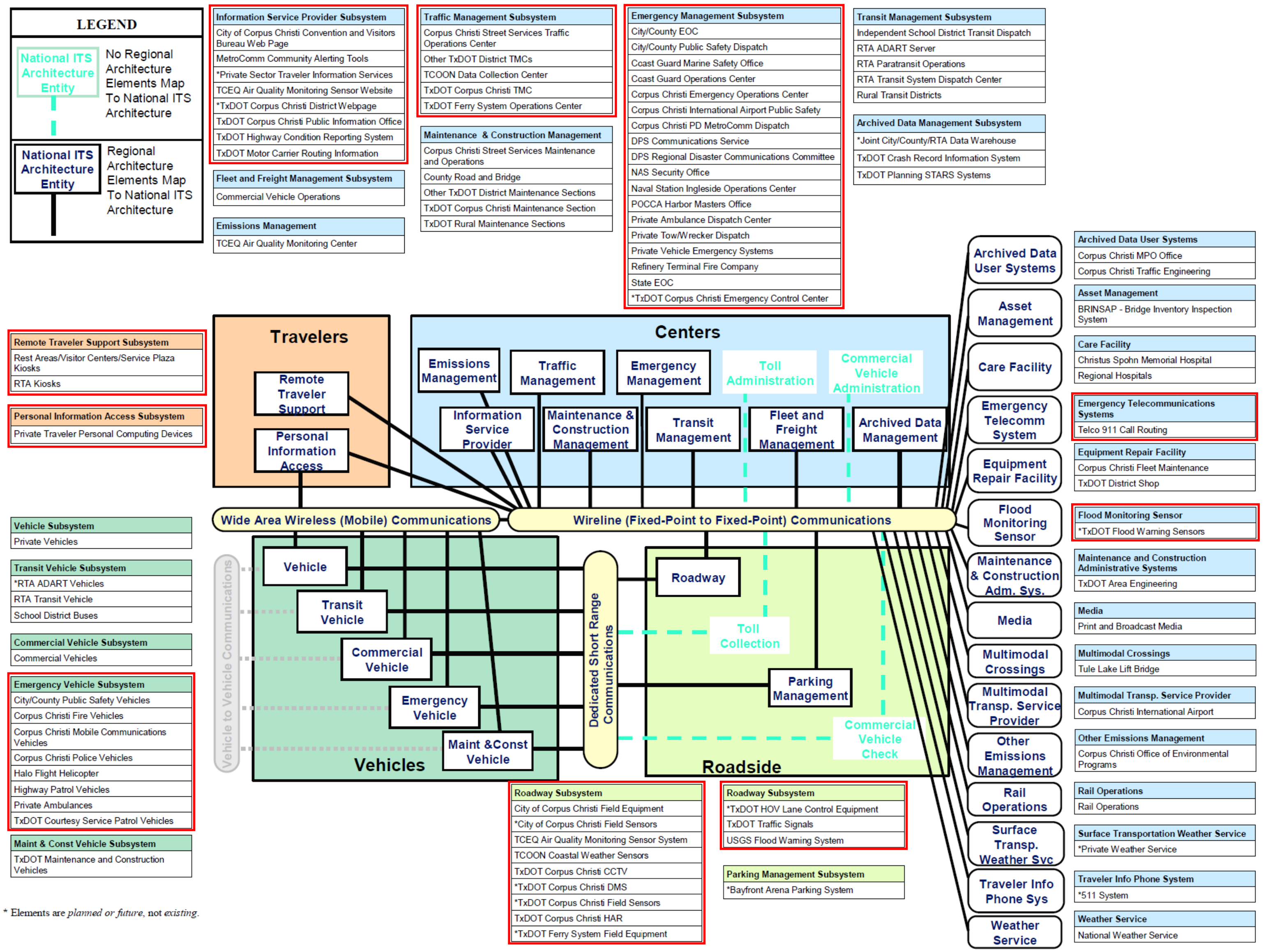


Figure 7.1: Corpus Christi regional ITS interconnection diagram (Kimley-Horn and Associates, Inc. and ConSysTec Corp, 2003a)

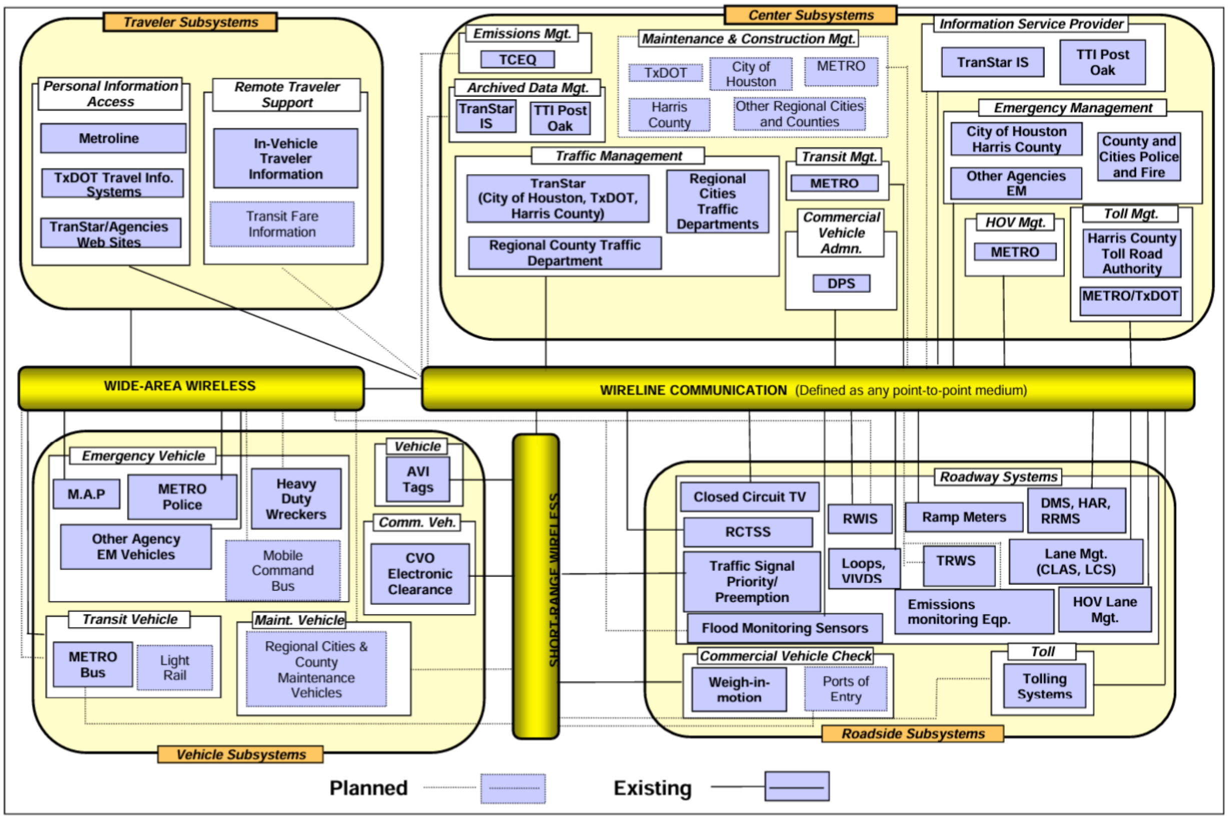


Figure 7.2: Houston regional ITS interconnection diagram (PBS&J and Battelle, 2003)

The major communication systems in both diagrams are wide-area wireless communications, wireline communications, and short-range wireless communications. These three types of communications systems are critical to maintaining a functional information collection and dissemination network during hurricane evacuations. The red boxes in Figure 7.1 denote the subsystems which are most important to maintain during evacuations. Flood and traffic monitoring data must be transmitted from the roadway to regional traffic and emergency management centers. Some information must also be provided to the information service provider, all through fixed wireline communication systems. That data must be provided to travelers, sometimes through wireline connections, but often through wireless communication systems, via the remote traveler support and personal information access subsystems. Additional information must also be collected from or disseminated to emergency vehicles, as well as other personal and commercial vehicles, through both wide-area wireless and short-range wireless communication systems (Kimley-Horn and Associates, Inc. and ConSysTec Corp, 2003a).

Cellular network overload and power outages can cause major disruptions in information flow. The impacts of these disruptions can be seen from the flow of information in Figure 7.2. Cellular network overload can cause individuals to experience problems accessing the internet and can also cause problems with wireless data transfer. Though many ITS systems are linked to traffic centers through wired connections, emergency vehicles, including police, ambulances, and even emergency helicopters, rely on wireless communications for dispatch and routing. Individual travelers can also be impacted, causing problems with travelers receiving real time routing information, as well as information about shelter and essential services access and gas availability. Power outages often have less impact on data flows, but instead disrupt the actual data collection of individual ITS devices. These devices include CCTV and other traffic sensors, as well as air quality monitoring and flood monitoring devices. When power fails, these devices will not provide real-time information to policymakers and stakeholders. Further, other field devices, such as signals and DMS, also rely on power and are negatively impacted by outages.

We also provide several flow charts for data flows developed in the Houston Region ITS Architecture Report which provide more detailed information on evacuations and emergency management specifically. Figure 7.3 depicts the process of information dissemination during evacuations. This process includes collection of roadway data which must be transmitted to the relevant TMCs. Information about the evacuation plan and status (evacuation routes, congestion, shelter availability, and information about other essential services) must also be transmitted to the media and the public through various channels including dynamic message signs and the TranStar website. Figure 7.4 depicts the actual evacuation monitoring process. In addition to monitoring the traffic on individual roadways, weather data, including flood data, must be monitored. Information collected from the media can also be included to determine the overall progress of the evacuation and the effectiveness of evacuation orders. Once data is collected, it must be processed and sent back in the form of updates to the relevant traffic control on individual roadways.

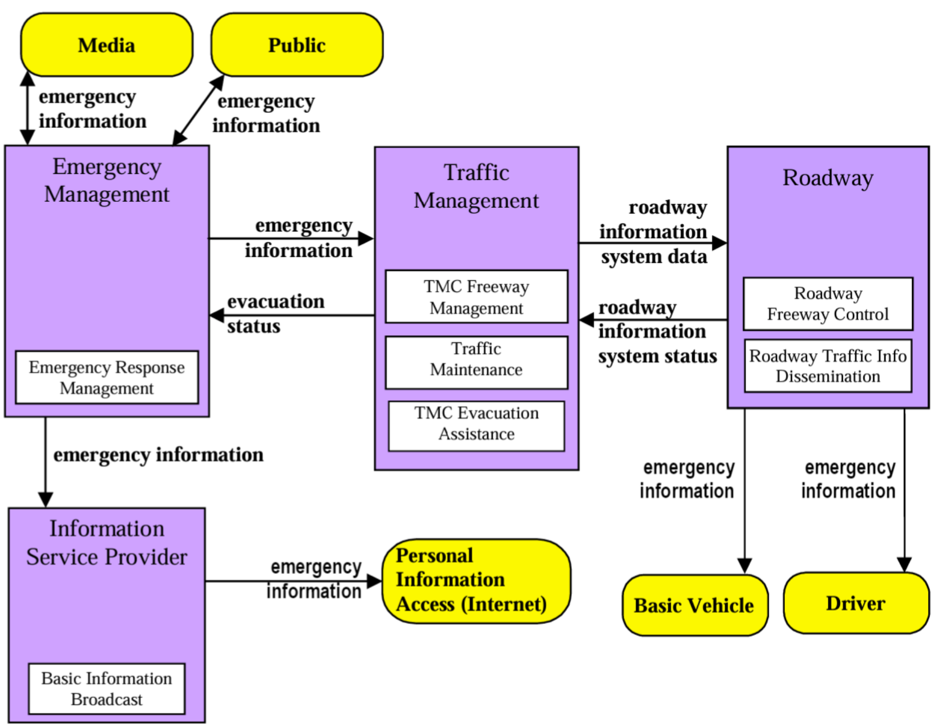


Figure 7.3: Aux-mp3 evacuation information dissemination (PBS&J and Battelle, 2003)

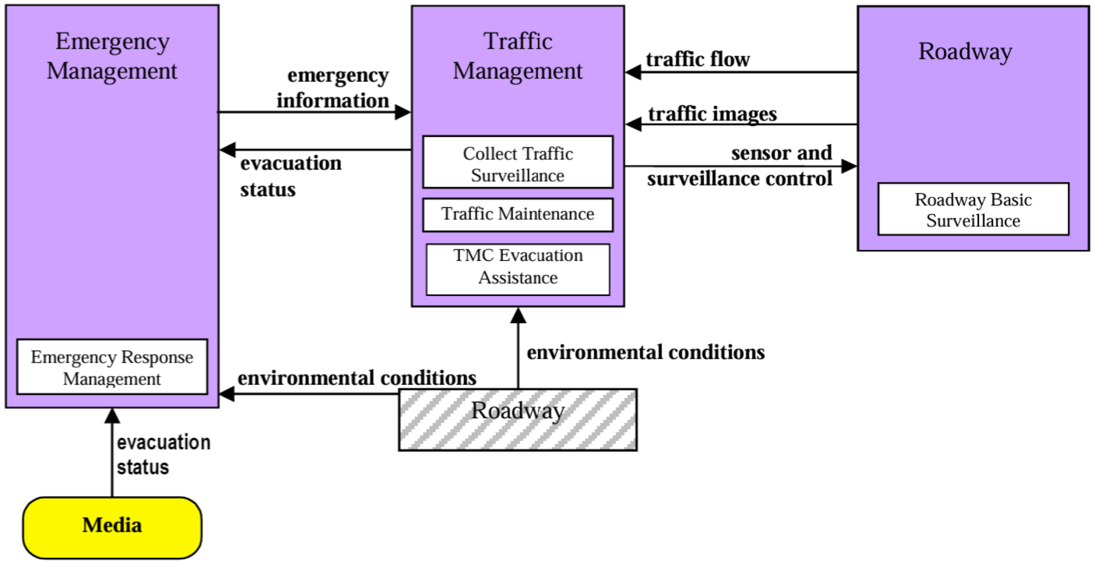


Figure 7.4: Aux-mp2 evacuation monitoring (PBS&J and Battelle, 2003)

The Houston Regional ITS Architecture Report also provides detailed flow charts for transportation during evacuations, the flood data collection system, and more general emergency management system which are critical components of evacuation plans (PBS&J and Battelle, 2003). We also refer the interested reader to the El Paso Region ITS Report from 2003 (Kimley-Horn and Associates, Inc. and ConSysTec Corp, 2003b) and their updated version from 2022 (El Paso Metropolitan Planning Organization, 2022). The updated version provides much more detailed flows of individual pieces of data and splits up stakeholders and data interfaces into many more individual pieces. Since the El Paso region does not focus on hurricane evacuation specifically, these flow charts are not analyzed in detail in this report.

7.3. Potential Events during Evacuations

Breakdowns in the communication system can have wide ranging impacts on many areas of health and safety during hurricane evacuations (Genasys, 2023). Due to the severe logistical and operational challenges associated with mass evacuations, individual travelers are reliant on information about resource availability, as well as relying on cell service for communication with family and other loved ones. Public agencies are also reliant on these communication services to coordinate emergency services, ensure transportation facilities are moving smoothly, and route resources to the correct locations. Three main challenges can affect smooth information transfer:

Communication and Information Transfer Challenges

1. **Telecommunication network congestion**: Difficulty in making calls or accessing the internet due to network congestion.
2. **Misinformation spread**: Spread of false information leading to confusion about evacuation procedures and safe areas.

3. **Lack of coordination between agencies**: Individual cities, counties, and regions using different systems to communicate can make it difficult for the public to find vital information.

During hurricane evacuations, several events can occur that may complicate the process and pose additional challenges for both evacuees and emergency services. A resilient communication system is critical to ensuring that these challenges are met with the appropriate resources promptly. Some of these potential events include (Bian et al., 2023; CDC, 2023; Genasys, 2023):

Travel and Transportation Challenges

1. **Traffic congestion**: Slowed or halted movement on evacuation routes due to heavy traffic.
2. **Flooding of evacuation routes**: Impassable roads due to flooding.
3. **Disruption of public transport**: Changes or suspension of public transportation services.
4. **Vehicle breakdowns and accidents**: Increased likelihood of vehicle-related issues under evacuation stress and road condition.

Resource Availability and Management

1. **Fuel shortages**: Gas stations running out of gas, impeding the ability to evacuate.
2. **Power outages**: Loss of electricity, impacting communication, lighting, and heating/cooling.
3. **Shortage of essential supplies**: Lack of water, food, batteries, and other necessities due to panic buying.
4. **Lack of accommodation in safe zones**: Insufficient space in shelters and hotels for evacuees.

Health and Safety Concerns

1. **Inefficient emergency services response**: Strained emergency services, leading to delayed response times.
2. **Lack of health emergencies**: Increased risk of medical issues due to stress, exhaustion, and pre-existing conditions.
3. **Separation of families**: Risk of family members getting separated in the chaos of evacuation.
4. **Pets and livestock issues**: Challenges in evacuating animals safely and finding pet-friendly shelters.

The potential events are summarized through four aspects: communication and information transfer challenges, travel and transportation challenges, resource availability and management, and health and safety concerns. Of the events listed above, telecommunication network congestion, misinformation spread, and power outages are relevant to ITS systems and resilient data transfer.

Cell phone network congestion occurs when too many users attempt to send data, such as phone calls, text messages, or multi-media messages, over a cellular network at the same time, which is a common situation in disaster evacuation. This increased demand leads to difficulties with accessing the internet or sending messages to others. During an evacuation, this is detrimental as evacuees may not be able to access internet-based sources of real-time data. Navigation apps and official resources such as the DriveTexas website may be offline and inaccessible. This can lead to circumstances where drivers are unable to view up-to-date information on roadway congestion levels, disabled vehicles or other incidents, alternate routes, and road closures. Evacuees may also struggle to communicate with friends, family members, and emergency services if a traffic incident or health emergency occurs. The lack of functioning telecommunication systems can have a significant influence on the safety and efficiency of an evacuation. Therefore, it is necessary to make efforts to mitigate the impacts of potential cellular network congestion.

The spread of misinformation may be a consequence of various factors. If real-time data is unable to be distributed or collected, evacuees may be exposed to inaccurate or unverified information through various channels. Lack of official communications to spread accurate and complete information through multiple channels will contribute to the dissemination of misinformation. Moreover, uncertainty and panic during evacuations may lead to a higher chance of spreading incomplete details or rumors. This poses a threat to safety and evacuation efficiency and further motivates the need for backup plans to ensure the continued operation of the ITS devices.

Finally, power outages also disrupt the functioning of the ITS network. If cameras and message signs are powered with a connection to the local electric grid, then outages caused by hurricane weather conditions can result in ITS devices being non-operational. This is different from the issues caused by telecommunication network congestion, where real-time data is collected but is unable to be distributed. When there are power outages, the devices responsible for collecting data are out of service themselves. Mitigation measures that can account for power outages are necessary.

7.4. Recommendations for Potential Mitigation Measures

After discussing the direct and indirect challenges during evacuations, we explore mitigation measures to create a resilient information transfer system. The mitigation measures are explored from the perspective of the four dimensions of resilience (Bruneau et al., 2003): robustness, redundancy, rapidity, and resourcefulness, as shown in Figure 7.5. Note that solid lines represent a direct impact on information transfer, while dashed lines indicate an indirect relationship to the information transfer system.

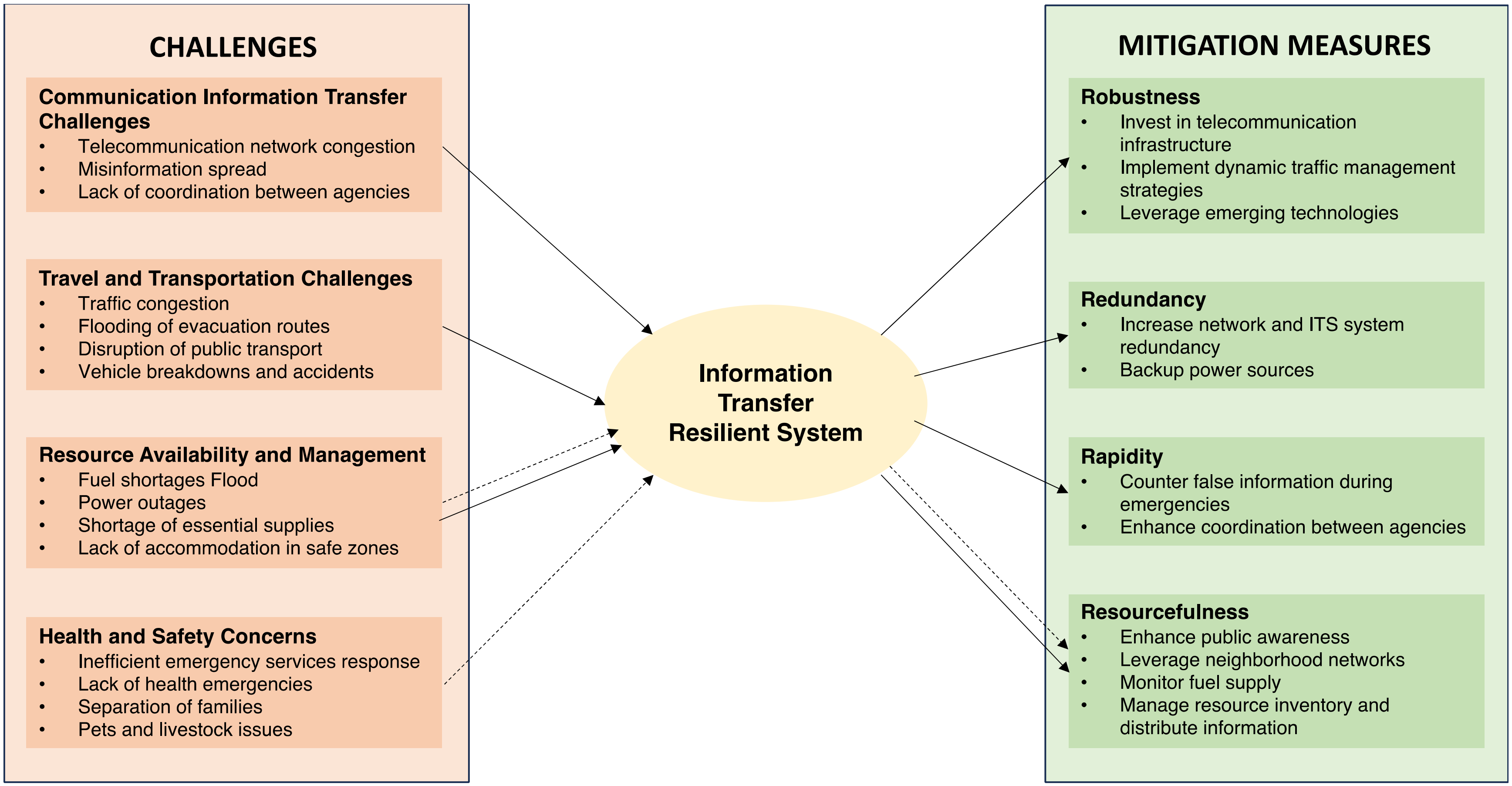


Figure 7.5: Challenges and mitigation measures to ensure a resilient system for information transfer

Robustness

- **Invest in telecommunication infrastructure:** Ensuring that the telecommunication infrastructure is robust and capable of withstanding the impact of high volume of traffic during hurricanes (UtilitiesOne, 2024a). Increase investment in the communication infrastructure restoration plan. Once communication system infrastructure damage occurs, an emergency working group should be promptly deployed for the communication restoration phase.
- **Implement dynamic traffic management strategies:** Continue implementing dynamic traffic management strategies, such as reversing travel lanes, using shoulders as emergency travel lanes, opening toll lanes, and adjusting traffic signals to improve traffic flow during emergencies. These systems should require minimal external intervention to ensure continuous operation even in the event of communication failures elsewhere in the system (Davis et al., 2021). Additionally, consider employing variable speed limit signs to temporarily reduce speed in response to high wind during hurricanes on evacuation routes. This measure could enhance overall safety (Ali et al., 2023; US Department of Transportation, 2024).
- **Leverage emerging technologies:** Take advantage of emerging technologies such as Connected and Autonomous Vehicles (CAVs), Unmanned Aerial Vehicles (UAVs), Artificial Intelligence (AI), and Mobility as a Service (MaaS). These technologies offer an opportunity for infrastructure to facilitate seamless communication between drivers and roadway facilities. During an evacuation, traffic management centers could leverage CAV infrastructure to provide real-time estimates and accurate information about evacuation route status. Additionally, UAV technology can be employed to collect damage assessment data, while remote sensing imagery from satellites can assist in determining the appropriate timing for evacuees to return home safely.

Redundancy

- **Increase network and ITS system redundancy:** Building redundancy into the telecommunication systems can provide additional capacity that may be activated during an emergency, leading to more disaster-resilient systems (UtilitiesOne, 2024b). Ensure the presence of multiple communication channels so that damaged infrastructure does not affect all channels simultaneously.
- **Backup power sources**: Establish backup power systems, including backup power sources and communication lines for ITS devices and traffic management center to ensure critical ITS functions can be maintained or quickly restored after a disruption.

Rapidity

- **Counter false information during emergencies:** To address misinformation or delays in information dissemination during evacuations, it is crucial to establish a centralized source of information to distribute across all channels and increase the update frequency. In addition, setting up reliable communication lines connecting the public, government agencies, and emergency responders, fostering collaboration with credentialed digital volunteers, and employing pre-scripting messages will be beneficial (Department of Homeland Security, 2018).
- **Enhance coordination between agencies:** Cities, counties, and regions should coordinate to ensure seamless communication with compatible resources and plans. Developing platforms and data streams that are accurate, up-to-date, and cohesive can assist the public in finding the information that is important to them (Genasys, 2023).

Resourcefulness

- **Enhance public awareness:** Policymakers should strive to increase public awareness of the available services and resources that contribute to the information transfer system. Initiatives could include public awareness campaigns such as organizing free seminars in libraries and schools. These efforts could assist individuals in identifying and using appropriate tools and resources for evacuation during severe circumstances, ultimately fostering trust in communication tools used by public agencies.
- **Leverage neighborhood networks:** Utilize neighborhood networks to disseminate information within communities and promote participation in the sharing economy. This can be achieved by leveraging ride-hailing services or by sharing available car seats with those without vehicles during evacuations (Stephen Wong, 2020).
- **Monitor fuel supply:** It is essential to manage fuel supplies leading up to the storm's landfall (Bian et al., 2023). Require gas station operators to maintain daily communications and monitor fuel supplies to be prepared for landfall and evacuation needs. Furthermore, publicize the locations of gas stations widely in case of communication network failure during the evacuation (Islam et al., 2020).
- **Manage resource inventory and distribute information:** Emergency management teams and agencies should distribute information on essential resource inventory across channels such as social media. Essential resources may include freshwater, food, fuel, electricity, and medical goods. Agencies can stockpile before the hurricane season and publicize safe areas to access critical supplies in advance of the storm (Committee on Building Adaptable and Resilient Supply Chains After Hurricanes Harvey, Irma, and Maria et al., 2020).

It is important to link several major hurricane information transfer challenges with the mitigation measures discussed above. First, infrastructure damage will be detrimental to information transfer when hurricanes happen, and having a robust infrastructure system is needed. Telecommunication systems that can withstand a certain amount of stress when high wind speeds or floodwaters are present are a necessary design consideration. In addition, leveraging emerging technologies such as CAVs and UASs to achieve seamless communication between vehicles and infrastructure is essential to reduce congestion during future mass evacuations.

Second, increasing network and ITS redundancy and having backup power systems for ITS devices at decision points in the evacuation network is beneficial to counteract power outages, since having a certain level of substitutability is key when communication system damage happens. We suggest assigning a certain budget for deploying additional cameras and DMS at certain corridors for redundancy purposes and staging backup power supply equipment such as generators in central locations before the arrival of a forecast hurricane.

Third, since communication network congestion is a common evacuation issue, ensuring rapid and reliable real-time traffic information dissemination to the public is important. Besides having functional DMS and variable speed limit signs along the evacuation corridor, countering false information during evacuation is also important. Agencies should coordinate and have one centralized information source to distribute information across multiple channels. In addition, leveraging neighborhood networks could increase the speed of message sharing and offer assistance inside the communities for those who physically need help or lack essential resources. Preparation before the evacuation can also build trust in communication systems, particularly when messaging is consistent across platforms and sources (Dow and Cutter, 2000, 1998).

7.5. Summary

In this chapter, we discuss the current ITS communication systems in Texas, primarily using information from the communication systems in Houston and Corpus Christi. We also examined potential disruptions from four aspects: communication and information transfer challenges, travel and transportation challenges, resource availability and management, and health and safety concerns. For these four aspects, mitigation measures are provided along the lines of the four dimensions of resilience: robustness, redundancy, rapidity, and resourcefulness. In addition, we specifically discussed three information transfer challenges regarding infrastructure damage, power outages, and accurate information transfer among the public. Communication systems are critical during disasters and building more resilient networks will require investments in infrastructure to increase robustness and build in redundancy. Emerging technologies, such as dynamic traffic management and connected infrastructure technologies, also have the potential to improve communication system resilience. Additional strategies such as preparation before the evacuation begins and consistency in messaging can help reduce the spread of misinformation and help reduce the negative impacts of communication system delays or failures.

References

Álvarez, M., Moreno, A., & Mataix, C. (2013). The analytic hierarchy process to support decision-making processes in infrastructure projects with social impact. *Total Quality Management & Business Excellence*, *24*(5–6), 596–606. https://doi.org/10.1080/14783363.2012.669561

Ahuja, R. K., Magnanti, T. L., & Orlin, J. B. (1988). Network flows.

Akbarzadeh, M., & Wilmot, C. G. (2014). Time-dependent route choice in hurricane evacuation. *Natural Hazards Review*, 16(2). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000159

Al-Abdallah, A., Al-Emadi, A., Al-Ansari, M., Mohandes, N., & Malluhi, Q. (2010). Real-time traffic surveillance using ZigBee. *2010 International Conference on Computer Design and Applications, ICCDA 2010, 1.* https://doi.org/10.1109/ICCDA.2010.5540694

Ali, Y., Raadsen, M.P.H., Bliemer, M.C.J. (2023). Modelling speed reduction behaviour on variable speed limit-controlled highways considering surrounding traffic pressure: A random parameters duration modelling approach. Anal. Methods Accid. Res. 40, 100290. https://doi.org/10.1016/j.amar.2023.100290

Aljehani, M., & Inoue, M. (2016). Multi-UAV tracking and scanning systems in M2M communication for disaster response. *2016 IEEE 5th Global Conference on Consumer Electronics, GCCE 2016.* https://doi.org/10.1109/GCCE.2016.7800524

Amarillo District. (2021). *Transportation Systems Management and Operations* [AMARILLO DISTRICT ITS MASTER IMPLEMENTATION PLAN].

Arslan, T. (2009). A hybrid model of fuzzy and AHP for handling public assessments on transportation projects. *Transportation*, *36*(1), 97–112. https://doi.org/10.1007/s11116-008-9181-9

Asif, M. T., Dauwels, J., Goh, C. Y., Oran, A., Fathi, E., Xu, M., Dhanya, M. M., Mitrovic, N., & Jaillet, P. (2014). Spatiotemporal patterns in large-scale traffic speed prediction. *IEEE Transactions on Intelligent Transportation Systems, 15*(2), 794–804. https://doi.org/10/f5w36f

Bai, Q., Labi, S., & Li, Z. (2008). *Trade-off Analysis Methodology for Asset Management* (FHWA/IN/JTRP-2008/31). Joint Transportation Research Program, Indiana Department of Transportation and Purdue University. https://doi.org/10.5703/1288284314305

Balid, W., Tafish, H., & Refai, H. H. (2018). Intelligent vehicle counting and classification sensor for real-time traffic surveillance. *IEEE Transactions on Intelligent Transportation Systems, 19*(6), 1784-1794. https://doi.org/10.1109/TITS.2017.2741507

Ballard, A. J., & Borchardt, D. W. (2006). Recommended practices for hurricane evacuation traffic operations (No. FHWA/TX-06/0-4962-P2). Texas Transportation Institute, Texas A & M University System.

Ballard, A. J., Ullman, B. R., Trout, N. D., Venglar, S. P., Borchardt, D. W., Voigt, A. P., ... & Rajbhandari, R. (2008). Hurricane evacuation traffic operations (No. FHWA/TX-08/0-4962-1). Texas Transportation Institute, Texas A & M University System.

Basyoni, Y., Abbas, H. M., Talaat, H., & El Dimeery, I. (2017). Speed prediction from mobile sensors using cellular phone-based traffic data. *IET Intelligent Transport Systems*, *11*(7), 387–396. https://doi.org/10/gb4s8b

Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., & Ignatius, J. (2012). A state-of the-art survey of TOPSIS applications. *Expert Systems with Applications*, *39*(17), 13051–13069. https://doi.org/10.1016/j.eswa.2012.05.056

Besson, E. (2012). Road from Rita: Timing of return can be as tricky as evacuation. The Texas Tribune and Beaumont Enterprise. https://apps.texastribune.org/road-from-rita/the-difficult-return/

Bian, R., Murray-Tuite, P., Edara, P., & Triantis, K. (2022). Modeling the impact of traffic management strategies on households' stated evacuation decisions. *Progress in Disaster Science*, *15*, 100246. https://doi.org/10.1016/j.pdisas.2022.100246

Bian, R., Smiley, K.T., Parr, S., Shen, J., Murray-Tuite, P. (2023). Analyzing Gas Station Visits during Hurricane Ida: Implications for Future Fuel Supply. Transp. Res. Rec. J. Transp. Res. Board 03611981231186600. https://doi.org/10.1177/03611981231186600

Bierling, D. H., Lindell, M. K., Peacock, W. G., Abuabara, A., Moore, R. A., Wunneburger, D. F., Mullins III, J. A., & Borchardt, D. W. (2020). *Coastal Bend hurricane evacuation study: Hurricane Harvey evacuation behavior survey outcomes and findings*. Texas A&M Hazard Reduction & Recovery Center, University of Washington Institute for Hazard Mitigation Planning and Research, and Texas A&M Transportation Institute. https://hdl.handle.net/1969.1/188203

Bin Yang, Kaul, M., & Jensen, C. S. (2014). Using incomplete information for complete weight annotation of road networks. *IEEE Transactions on Knowledge and Data Engineering, 26*(5), 1267–1279. https://doi.org/10/f57pp5

Blake, E. S., Rappaport, E. N., Jarrell, J. D., & Landsea, C. (2005). The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2004 (and other frequently requested hurricane facts).

Borchardt, D. W., & Puckett, D. D. (2008). Real-time data for hurricane evacuation in Texas (No. SWUTC/08/167764-1). Southwest Region University Transportation Center (US).

Bowser, G. C., & Cutter, S. L. (2015). Stay or Go? Examining Decision Making and Behavior in Hurricane Evacuations. *Environment: Science and Policy for Sustainable Development*, *57*(6), 28–41. https://doi.org/10.1080/00139157.2015.1089145

Boyd, E., Storesund, R., & Lopez, J. (2014). A systems engineering based assessment of the Greater New Orleans Hurricane Surge Defense System using the multiple lines- of-defense framework. https://www.researchgate.net/publication/294876166_A_Systems_Engineering_Based_Assessment_of_The_Greater_New_Orleans_Hurricane_Surge_Defense_System_Using_the_Multiple_Lines-_of-_Defense_Framework

Boyles, S. D. (2013). *Statewide mesoscopic simulation for Wyoming* (No. FHWA-WY-13/05F). Wyoming Dept. of Transportation. https://rosap.ntl.bts.gov/view/dot/27319/dot_27319_DS1.pdf

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthq. Spectra 19, 733–752. https://doi.org/10.1193/1.1623497

Bureika, G., Liudvinavičius, L., Vaičiūnas, G., & Bekintis, G. (2013). Applying analytic hierarchy process to assess traffic safety risk of railway infrastructure. *Eksploatacja i Niezawodność*, *Vol. 15*(4). http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-2f8938cc-9ad3-45f9-95b4-1ff03403c797

Burnside, R., Miller, D. M. S., & Rivera, J. D. (2007). The impact of information and risk perception of the hurricane evacuation decision-making of Greater New Orleans

residents. *Sociological Spectrum*, 27(6), 727–740. https://doi.org/10.1080/02732170701534226
CDC (2023). Evacuating During Hurricanes [WWW Document]. URL https://www.cdc.gov/nceh/hsb/disaster/evacuating-during_hurricanes.html (accessed 1.3.24).
Chaudhary, S., Indu, S., & Chaudhury, S. (2018). Video-based road traffic monitoring and prediction using dynamic Bayesian networks. *IET Intelligent Transport Systems, 12*(3), 169–176. https://doi.org/10/gc6vbp
Chin, S.-M., Franzese, O., Greene, D. L., Hwang, H. L., Gibson, R., Oak Ridge National Laboratory, University of Tennessee, K., & UT-Battelle. (2004). *Temporary Losses of Highway Capacity and Impacts on Performance: Phase 2* (ORNL/TM-2004/209). https://rosap.ntl.bts.gov/view/dot/37083
Collins, A. J., Robinson, R. M., Jordan, C. A., Foytik, P., & Ezell, B. C. (2013). Generic incident model for use in large-scale evacuation simulations. *2013 IEEE International Conference on Technologies for Homeland Security (HST)*, 26–31. https://doi.org/10.1109/THS.2013.6698971
Committee on Building Adaptable and Resilient Supply Chains After Hurricanes Harvey, Irma, and Maria, Office of Special Projects, Policy and Global Affairs, National Academies of Sciences, Engineering, and Medicine (2020). Chapter 4: 4 Strategies to Foster More Effective Conveyance and Distribution of Critical Relief and Recovery Supplies, in: Strengthening Post-Hurricane Supply Chain Resilience: Observations from Hurricanes Harvey, Irma, and Maria. National Academies Press, Washington, D.C., p. 25490. https://doi.org/10.17226/25490
Cooksey, S. R., Jeong, "David" Hyung Seok, & Chae, M. J. (2011). Asset Management Assessment Model for State Departments of Transportation. *Journal of Management in Engineering*, *27*(3), 159–169. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000055
Daganzo, C. F. (1994). The cell transmission model: a dynamic representation of highway traffic consistent with the hydrodynamic theory. *Transportation Research Part B 28*(4), 269–287.
Dallas-Fort Worth District. (2021). *Transportation Systems Management and Operations* [TxDOT Dallas and Fort Worth TSMO Program Plan].
Darko, A., Chan, A. P. C., Ameyaw, E. E., Owusu, E. K., Pärn, E., & Edwards, D. J. (2019). Review of application of analytic hierarchy process (AHP) in construction. *International Journal of Construction Management*, *19*(5), 436–452. https://doi.org/10.1080/15623599.2018.1452098
Dash, N., & Gladwin, H. (2007). Evacuation decision-making and behavioral responses: Individual and household. *Natural Hazards Review*, 8(3), 69–77. https://doi.org/10.1061/(ASCE)1527-6988(2007)8:3(69)
Davis, L., Qu, X., Seong, Y. (2021). REAL TIME RECOMMENDATIONS FOR TRAFFIC CONTROL IN AN ITS SYSTEM DURING AN EMERGENCY EVACUATION. North Carolina A&T State University (NCAT).
Department of Homeland Security (2018). Countering False Information on Social Media in Disasters and Emergencies.
DeYoung, S. E., Wachtendorf, T., Farmer, A. K., & Penta, S. C. (2016). NOAA Radios and Neighbourhood Networks: Demographic Factors for Channel Preference for Hurricane

Evacuation Information. *Journal of Contingencies and Crisis Management*, *24*(4), 275–285. https://doi.org/10.1111/1468-5973.12123

Dong, H., Halem, M., & Zhou, S. (2013). Social Media Data Analytics Applied to Hurricane Sandy. *2013 International Conference on Social Computing*, 963–966. https://doi.org/10.1109/SocialCom.2013.152

Dow, K., Cutter, S.L. (1998). Crying wolf: Repeat responses to hurricane evacuation orders. Coast. Manag. 26, 237–252. https://doi.org/10.1080/08920759809362356

Dow, K., Cutter, S.L. (2000). Public orders and personal opinions: household strategies for hurricane risk assessment. Glob. Environ. Change Part B Environ. Hazards, Hurricane Floyd 2, 143–155. https://doi.org/10.1016/S1464-2867(01)00014-6

Dow, K., & Cutter, S. L. (2002). Emerging Hurricane Evacuation Issues: Hurricane Floyd and South Carolina. *Natural Hazards Review*, *3*(1), 12–18. https://doi.org/10.1061/(ASCE)1527-6988(2002)3:1(12)

El Paso District. (2020). *Transportation Systems Management and Operations* [TxDOT El Paso ITS Master Implementation Plan].

El Paso Metropolitan Planning Organization (2022). Transportation Systems Management and Operations (TSMO) - Corpus Christi District Program Plan. Texas Department of Transportation.

Elloumi, M., Dhaou, R., Escrig, B., Idoudi, H., & Saidane, L. A. (2018). Monitoring road traffic with a UAV-based system. *IEEE Wireless Communications and Networking Conference, WCNC, 2018-April*. https://doi.org/10.1109/WCNC.2018.8377077

Farhan, J., & Fwa, T. F. (2009). Pavement Maintenance Prioritization Using Analytic Hierarchy Process. *Transportation Research Record: Journal of the Transportation Research Board*, *2093*(1), 12–24. https://doi.org/10.3141/2093-02

Federal Highway Administration. (2016). 2016 traffic monitoring guide. U.S. Department of Transportation/Federal Highway Administration. Retrieved December 17, 2021, from https://www.fhwa.dot.gov/policyinformation/tmguide/

Fonseca, D. J., Lou, Y., Moynihan, G. P., & Gurupackiam, S. (2013). Incident Occurrence Modeling during Hurricane Evacuation Events: The Case of Alabama's I-65 Corridor. *Modelling and Simulation in Engineering*, *2013*, e168126. https://doi.org/10.1155/2013/168126

Gao, M., Hugenholtz, C. H., Fox, T. A., Kucharczyk, M., Barchyn, T. E., & Nesbit, P. R. (2021). Weather constraints on global drone flyability. *Scientific Reports*, 11(1). https://doi.org/10.1038/s41598-021-91325-w

Garrote Sanchez, D., Gomez Parra, N., Ozden, C., Rijkers, B., Viollaz, M., & Winkler, H. (2021). Who on Earth Can Work from Home? *The World Bank Research Observer*, *36*(1), 67–100. https://doi.org/10.1093/wbro/lkab002

Genasys (2023). Communication Breakdowns Common During a Hurricane [WWW Document]. https://genasys.com/. URL https://genasys.com/blog/solving-common-communication-breakdowns-during-a-hurricane/ (accessed 1.3.24).

Gladwin, C. H., Gladwin, H., & Peacock, W. G. (2001). Modeling Hurricane Evacutaion Decisions with Ethnographic Methods. *International Journal of Mass Emergencies & Disasters*, *19*(2), 117–143. https://doi.org/10.1177/028072700101900201

Gottumukkala, R., Kolluru, R., & Smith, M. (2011). *Technical report: Evacuation behavior survey report*. National Incident Management Systems and Advanced Technologies at the University of Louisiana at Lafayette.

https://nimsat.louisiana.edu/sites/nimsat/files/DNR%20Evacuation%20Behavior%20Report.pdf
Gunarathna, P., & Hassan, R. (2020). Sustainability assessment tool for road transport asset management practice. *Road & Transport Research*, *25*(4), 15–26. https://doi.org/10.3316/informit.727056982254899
Haas, R., Carter, M., Perry, E., Trombly, J., Bedsole, E., & Margiotta, R. (2009). iFlorida model deployment final evaluation report (No. FHWA-HOP-08-050). United States. Federal Highway Administration.
Haddal, C. C., & Gertler, J. G. (2010). CRS report for Congress Homeland Security: Unmanned aerial vehicles and border surveillance. www.crs.gov
Hara, Y., & Kuwahara, M. (2015). Traffic monitoring immediately after a major natural disaster as revealed by probe data–A case in Ishinomaki after the Great East Japan Earthquake. *Transportation research part A: policy and practice, 75,* 1-15. https://doi.org/10.1016/j.tra.2015.03.002
Hart, P. E., Nilsson, N. J., & Raphael, B. (1968). A formal basis for the heuristic determination of minimum cost paths. *IEEE Transactions on Systems Science and Cybernetics SSC4 4*(2), 100–107.
Harrell, F. E. (2015). *Regression Modeling Strategies: With Applications to Linear Models, Logistic and Ordinal Regression, and Survival Analysis*. Springer International Publishing. https://doi.org/10.1007/978-3-319-19425-7
Harris County Toll Road Authority. (2020, August 25). *Tolls waived*. Retrieved December 16, 2022, from https://www.hctra.org/TollsWaived#:~:text=By%20order%20of%20Commissioners%20Court,declaration%20of%20a%20local%20disaster
Hasan, S., Ukkusuri, S., Gladwin, H., & Murray-Tuite, P. (2010). Behavioral model to understand household-level hurricane evacuation decision making. *Journal of Transportation Engineering*, 137(5), 341–348. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000223
HCM 2010: Highway capacity manual (2010). Washington D.C.: Transportation Research Board.
Helmer, O. (1967). *Analysis of the Future: The Delphi Method* (AD0649640). RAND Corporation. https://apps.dtic.mil/sti/citations/AD0649640
Hill, C. (2016). Oregon DOT partners with Waze on Tripcheck.com. Equipment world. Retrieved December 17, 2021, from https://www.equipmentworld.com/better-roads/article/14965498/oregon-dot-partners-with-waze-on-tripcheckcom
Houston-Galveston Area Council. (2021). Hurricane evacuation planning. https://www.h-gac.com/hurricane-evacuation-planning
Huang, S. K., Lindell, M. K., & Prater, C. S. (2015). Who Leaves and Who Stays? A Review and Statistical Meta-Analysis of Hurricane Evacuation Studies. Environment and Behavior, 48(8), 991–1029. https://doi.org/10.1177/0013916515578485
Huang, S.-K., Lindell, M. K., Prater, C. S., Hao, Wu, C., & Siebeneck, L. K. (2012). Household Evacuation Decision Making in Response to Hurricane Ike. Natural Hazards Review, 13(4), 283–296. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000074
Huang, S.-K., Lindell, M. K., & Prater, C. S. (2016). Who Leaves and Who Stays? A Review and Statistical Meta-Analysis of Hurricane Evacuation Studies. *Environment and Behavior*, *48*(8), 991–1029. https://doi.org/10.1177/0013916515578485

Ikpong, A., Chandra, A., & Bagchi, A. (2021). Alternative to AHP approach to criteria weight estimation in highway bridge management. *Canadian Journal of Civil Engineering*, *48*(9), 1181–1191. https://doi.org/10.1139/cjce-2020-0215

Islam, S., Namilae, S., Prazenica, R., Liu, D. (2020). Fuel shortages during hurricanes: Epidemiological modeling and optimal control. PLOS ONE 15, e0229957. https://doi.org/10.1371/journal.pone.0229957

Janecek, A., Valerio, D., Hummel, K. A., Ricciato, F., & Hlavacs, H. (2015). The Cellular Network as a Sensor: From Mobile Phone Data to Real-Time Road Traffic Monitoring. *IEEE Transactions on Intelligent Transportation Systems*, *16*(5), 2551–2572. https://doi.org/10/f7s7bb

Jiang, K. (2023). *Survey Analysis for Evacuee Preferences on Real-Time Traffic Monitoring Systems in Texas*. The University of Texas at Austin.

Ji, Y. beibei, Jiang, R., Qu, M., & Chung, E. (2014). Traffic Incident Clearance Time and Arrival Time Prediction Based on Hazard Models. *Mathematical Problems in Engineering*, *2014*, e508039. https://doi.org/10.1155/2014/508039

Kanhere, N. K., Birchfield, S. T., Sarasua, W. A., & Khoeini, S. (2010). Traffic monitoring of motorcycles during special events using video detection. *Transportation research record, 2160*(1), 69-76. https://doi.org/10.3141/2160-08

Kanistras, K., Martins, G., Rutherford, M. J., & Valavanis, K. P. (2013). A survey of unmanned aerial vehicles (UAVs) for traffic monitoring. *2013 International Conference on Unmanned Aircraft Systems, ICUAS 2013 - Conference Proceedings.* https://doi.org/10.1109/ICUAS.2013.6564694

Keim, D. K., Muller, R. A., & Stone, G. W. (2007). Spatiotemporal patterns and return periods of tropical storm and hurricane strikes from Texas to Maine. *Journal of Climate, 20*(14), 3498–3509. https://doi.org/10.1175/JCLI4187.1

Khalid, O., Khan, M. U. S., Huang, Y., Khan, S. U., & Zomaya, A. (2016). EvacSys: A cloud-based service for emergency evacuation. *IEEE Cloud Computing, 3*(1), 60-68. https://doi.org/10.1109/MCC.2016.10

Kheybari, S., Rezaie, F. M., & Farazmand, H. (2020). Analytic network process: An overview of applications. *Applied Mathematics and Computation*, *367*, 124780. https://doi.org/10.1016/j.amc.2019.124780

Kimley-Horn and Associates, Inc., ConSysTec Corp (2003a). State of Texas Regional ITS Architectures and Development Plans Corpus Christi Region. Texas Department of Transportation.

Kimley-Horn and Associates, Inc., ConSysTec Corp (2003b). State of Texas Regional ITS Architectures and Development Plans El Paso Region. Texas Department of Transportation.

Knabb, R. D., Brown, D. P., & Rhome, J. R. (2006). *Tropical Cyclone Report, Hurricane Rita, 18-26 September 2005*. Miami, FL.

Li, J., & Zou, P. (2008). Risk Identification and Assessment in PPP Infrastructure Projects using Fuzzy Analytical Hierarchy Process and Life-Cycle Methodology. *Construction Economics and Building*, *8*(1), Article 1. https://doi.org/10.5130/AJCEB.v8i1.2996

Li, R., Pereira, F. C., & Ben-Akiva, M. E. (2018). Overview of traffic incident duration analysis and prediction. *European Transport Research Review*, *10*(2), 22. https://doi.org/10.1186/s12544-018-0300-1

Lighthill, M., & Whitham, G. (1955). On kinematic waves II: A theory of traffic flow on long crowded roads. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 317–345.

Lindell, M. K., Ge, Y., Huang, S., Prater, C. S., Wu, H., & Wei, H. L. (2013). *Behavioral study, valley hurricane evacuation study, Willacy, Cameron, and Hidalgo Counties, Texas*. Texas A&M Hazard Reduction & Recovery Center. https://tamucoa.b-cdn.net/app/uploads/2021/10/ValleyBehavioralStudy.pdf

Lindell, M. K., Kang, J. E., & Prater, C. S. (2011). The logistics of household hurricane evacuation. *Natural Hazards*, *58*(3), 1093–1109. https://doi.org/10.1007/s11069-011-9715-x

Lindell, M. K., Prater, C. S., & Peacock, W. G. (2007). Organizational Communication and Decision Making for Hurricane Emergencies. *Natural Hazards Review*, *8*(3), 50–60. https://doi.org/10.1061/(ASCE)1527-6988(2007)8:3(50)

Liu, X., Peng, Z.-R., & Zhang, L.-Y. (2019). Real-time UAV rerouting for traffic monitoring with decomposition based multi-objective optimization. *Journal of Intelligent & Robotic Systems, 94*(2), 491-501. http://doi.org/10.1007/s10846-018-0806-8

Lv, Y., Duan, Y., Kang, W., Li, Z., & Wang, F.-Y. (2014). Traffic flow prediction with big data: A deep learning approach. *IEEE Transactions on Intelligent Transportation Systems,* 1–9. https://doi.org/10/cjcd

Maghelal, P., Xiangyu, L., & Peacock, W. G. (2017). Highway congestion during evacuation: Examining the household's choice of number of vehicles to evacuate. *Natural Hazards, 87*, 1399–1411. https://doi.org/10.1007/s11069-017-2823-5

Mail Tribune. (2015). New traffic cameras go live Oregon Department of Transportation. Moving ahead with ODOT. Retrieved December 17, 2021, from https://odotmovingahead.com/2015/04/new-traffic-cameras-go-live/

Mandatory evacuation, 4 T.G.C. § 418.185 (2021) https://statutes.capitol.texas.gov/Docs/GV/htm/GV.418.htm#418.185

Melendez, B., Machiani, S. G., & Nara, A. (2021). Modelling traffic during Lilac Wildfire evacuation using cellular data. *Transportation Research Interdisciplinary Perspectives, 9*, 100335. https://doi.org/10.1016/j.trip.2021.100335

Menon, N., Staes, B., & Bertini, R. L. (2020). Measuring transportation network performance during emergency evacuations: A case study of Hurricane Irma and Woolsey Fire. Center for Transportation, Equity, Decisions and Dollars (CTEDD). https://doi.org/10.21949/1503647

Middleton, D., Rajbhandari, R., Brydia, R., Songchitruksa, P., Kraus, E., Hernandez, S., ... & Turner, S. (2012). TxDOT uses of real-time commercial traffic data: Opportunity matrix (No. 0-6659-P1). Texas Transportation Institute.

Monitoring weather, 4 T.G.C. § 418.048 (2021) https://statutes.capitol.texas.gov/Docs/GV/htm/GV.418.htm#418.048

Monteiro, R., Ferreira, J. C., & Antunes, P. (2022). Green Infrastructure Planning Principles: Identification of Priorities Using Analytic Hierarchy Process. *Sustainability*, *14*(9), Article 9. https://doi.org/10.3390/su14095170

Mullins III, J. A., Borchardt, D. W., Bierling, D., Peacock, W. G., Wunneburger, D. F., &e Abuabara, A. (2020). *Coastal Bend Study Area hurricane evacuation study: Transportation analysis report*. Texas A&M Transportation Institute and Texas A&M Hazard Reduction & Recovery Center. https://hdl.handle.net/1969.1/188204

NOAA. (2010). NHC issuance criteria changes for tropical cyclone watches/warnings. https://www.nhc.noaa.gov/watchwarn_changes.shtml

NOAA. (1999). Hurricane basics.

North Carolina Department of Transportation Division of Aviation. (2018). Real-time data and imagery for hurricane response.

Nyström, B., & Söderholm, P. (2010). Selection of maintenance actions using the analytic hierarchy process (AHP): Decision-making in railway infrastructure. *Structure and Infrastructure Engineering*, *6*(4), 467–479. https://doi.org/10.1080/15732470801990209

Office of the Texas Governor. (2020, August 25). Governor Abbott waives Houston-area tolls ahead of Hurricane Laura. https://gov.texas.gov/news/post/governor-abbott-waives-houston-area-tolls-ahead-of-hurricane-laura#:~:text=With%20this%20action%2C%20all%20tolls,storm%2C%22%20said%20Governor%20Abbott.

OpenStreetMap contributors. (2017). *Planet dump retrieved from https://planet.osm.org* [dataset]. OpenStreetMap contributors

Oswald Beiler, M. R., & Treat, C. (2015). Integrating GIS and AHP to Prioritize Transportation Infrastructure Using Sustainability Metrics. *Journal of Infrastructure Systems*, *21*(3), 04014053. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000245

PBS&J, Battelle (2003). Houston Region ITS Architecture. Houston-Galveston Area Council.

Peacock, W. G., Abuabara, A., Wunneburger, D. F., Bierling, D. H., Mullins, J. A., III, Moore, R. A., & Borchardt, D. W. (2020). *Coastal Bend hurricane evacuation study: Evacuation zone development report*. Texas A&M Transportation Institute and the Texas A&M Hazard Reduction & Recovery Center. https://hdl.handle.net/1969.1/188202

Pham, E. O., Emrich, C. T., Li, Z., Mitchem, J., & Cutter, S. L. (2020). Evacuation departure timing during Hurricane Matthew. *Weather, Climate, and Society, 12*(2), 235–248. https://doi.org/10.1175/WCAS-D-19-0030.1

Phased reentry plan, 4 T.G.C. § 418.050 (2021) https://statutes.capitol.texas.gov/Docs/GV/htm/GV.418.htm#418.050

Porras-Alvarado, J. D., Murphy, M. R., Wu, H., Han, Z., Zhang, Z., & Arellano, M. (2017). Analytical Hierarchy Process to Improve Project Prioritization in the Austin District, Texas. *Transportation Research Record*, *2613*(1), 29–36. https://doi.org/10.3141/2613-04

Porras-Alvarado, J. D., Peters, D., Han, Z., & Zhang, Z. (2015). Novel Utility-Based Methodological Framework for Valuation of Road Infrastructure. *Transportation Research Record*, *2529*(1), 37–45. https://doi.org/10.3141/2529-04

Qin, L., & Smith, B. L. (2001). *Characterization of accident capacity reduction*. https://rosap.ntl.bts.gov/view/dot/15831

Rappaport, E. N., & Blanchard, B. W. (2016). Fatalities in the United States indirectly associated with Atlantic tropical cyclones. *Bulletin of the American Meteorological Society*, 97(7), 1139–1148. https://doi.org/10.1175/BAMS-D-15-00042.1

Rashidi, M., Ghodrat, M., Samali, B., Kendall, B., & Zhang, C. (2017). Remedial Modelling of Steel Bridges through Application of Analytical Hierarchy Process (AHP). *Applied Sciences*, *7*(2), Article 2. https://doi.org/10.3390/app7020168

Richards, P. (1956). Shock waves on the highway. *Operations Research 4*(1), 42–51.

Robinson, R. M., & Khattak, A. (2012). Evacuee route choice decisions in a dynamic hurricane evacuation context. *Transportation Research Record*, 2312(1), 141–149. https://doi.org/10.3141/2312-15

Robinson, R. M., & Khattak, A. (2011). Selection of Source and Use of Traffic Information in Emergency Situations. *Transportation Research Record*, *2234*(1), 71–78. https://doi.org/10.3141/2234-08

Roy, K. C., Hasan, S., Abdul-Aziz, O. I., & Mozumder, P. (2022). Understanding the influence of multiple information sources on risk perception dynamics and evacuation decisions: An agent-based modeling approach. *International Journal of Disaster Risk Reduction*, *82*, 103328. https://doi.org/10.1016/j.ijdrr.2022.103328

Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation*. McGraw-Hill International Book Co. http://www.gbv.de/dms/hbz/toc/ht000345674.pdf

Saaty, T. L. (1988). What is the Analytic Hierarchy Process? In G. Mitra, H. J. Greenberg, F. A. Lootsma, M. J. Rijkaert, & H. J. Zimmermann (Eds.), *Mathematical Models for Decision Support* (pp. 109–121). Springer. https://doi.org/10.1007/978-3-642-83555-1_5

San Angelo District. (2021). *Transportation Systems Management and Operations* [San Angelo District ITS Master Plan].

Sipahi, S., & Timor, M. (2010). The analytic hierarchy process and analytic network process: An overview of applications. *Management Decision*, *48*(5), 775–808. https://doi.org/10.1108/00251741011043920

Smith, J. T., & Tighe, S. L. (2006). Analytic Hierarchy Process as a Tool for Infrastructure Management. *Transportation Research Record*, *1974*(1), 2–9. https://doi.org/10.1177/0361198106197400101

Smith, S. K., & Mccarty, C. (2009). Fleeing the storm(s): an examination of evacuation behavior during Florida's 2004 hurricane season. *Demography* 2009 46:1, 46(1), 127–145. https://doi.org/10.1353/DEM.0.0048

Southworth, F. (1991). Regional evacuation modeling: A state of the art reviewing.

Statewide Long-Range Transportation Plan 2035 Executive Summary. (2011). Texas Department of Transportation. http://txdot.gov/en/home/projects/planning/ttp/slrtp-2035.html

Stone, C. D. (2014). *A methodological framework for economic evaluation of existing roadway assets* [Thesis, University of Texas at Austin]. https://repositories.lib.utexas.edu/handle/2152/25856

Subramanian, N., & Ramanathan, R. (2012). A review of applications of Analytic Hierarchy Process in operations management. *International Journal of Production Economics*, *138*(2), 215–241. https://doi.org/10.1016/j.ijpe.2012.03.036

Texas Department of Transportation. (2016). TxDOT evacuation routes. TxDOT open data portal. Retrieved December 15, 2021, from https://gis-txdot.opendata.arcgis.com/datasets/txdot-evacuation-routes/explore

Texas Department of Transportation. (2016). TxDOT permanent count stations. TxDOT open data portal. Retrieved December 15, 2021, from https://gis-txdot.opendata.arcgis.com/datasets/txdot-permanent-count-stations/explore

Texas Department of Public Safety. (2021). *DPS Responsibilities*. https://www.dps.texas.gov/section/about-dps/dps-responsibilities

Texas Department of Transportation. (2021). Hurricanes. Retrieved December 15, 2021, from https://www.txdot.gov/inside-txdot/division/traffic/safety/weather/hurricane.html

Texas Department of Transportation. (2021). ITS. Retrieved December 15, 2021, from https://its.txdot.gov/its/District/ATL/map

Texas Department of Transportation. (n.d.-a). *Hurricane preparation—Evacuation and contraflow routes*. Retrieved September 21, 2023, from https://www.txdot.gov/safety/severe-weather/hurricane-preparation.html

Texas Department of Transportation. (n.d.-b). *Texas ITS Devices*. Retrieved September 21, 2023, from https://its.txdot.gov/its

Texas Division of Emergency Management. (2021). State of Texas emergency management plan: Hurricane annex. https://tdem.texas.gov/state-of-texas-emergency-management-plan/.

Texas Rural Transportation Plan 2035 (Component of the Statewide Long-Range Transportation Plan). (2012). Texas Department of Transportation. http://txdot.gov/en/home/projects/planning/ttp/trtp-2035.html

Texas Transportation Plan 2040. (2015). Texas Department of Transportation. http://txdot.gov/en/home/projects/planning/ttp/ttp-2040.html

Thompson, R. R., Garfin, D. R., & Silver, R. C. (2017). Evacuation from Natural Disasters: A Systematic Review of the Literature. *Risk Analysis*, *37*(4), 812–839. https://doi.org/10.1111/risa.12654

United States Census Bureau. (2022a, July 11). *Cartographic boundary files*. https://www.census.gov/geographies/mapping-files/time-series/geo/cartographic-boundary.html

United States Census Bureau. (2022b). *Data tables*. https://data.census.gov/cedsci/table

US Department of Transportation and US Department of Homeland Security. (2006). Report to Congress on catastrophic hurricane evacuation plan evaluation.

US Department of Transportation, F.H.A. (2024). Variable Speed Limits.

UtilitiesOne (2024a). Telecommunications Challenges in Disaster Recovery [WWW Document]. https://utilitiesone.com/. URL https://utilitiesone.com/telecommunications-challenges-in-disaster-recovery (accessed 1.12.24).

UtilitiesOne(2024b). The Impact of Natural Disasters on Telecommunications Network Redundancy [WWW Document]. https://utilitiesone.com/. URL https://utilitiesone.com/the-impact-of-natural-disasters-on-telecommunications-network-redundancy (accessed 1.12.24).

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research*, *169*(1), 1–29. https://doi.org/10.1016/j.ejor.2004.04.028

Vladeanu, G. J., & Matthews, J. C. (2019). Consequence-of-Failure Model for Risk-Based Asset Management of Wastewater Pipes Using AHP. *Journal of Pipeline Systems Engineering and Practice*, *10*(2), 04019005. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000370

Wang, Y., Zheng, Y., & Xue, Y. (2014). Travel time estimation of a path using sparse trajectories. *Proceedings of the 20th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining,* 25–34. https://doi.org/10/gnk7zg

Wejo. (2020). Connected vehicle data provides real-time hurricane evacuation. Retrieved December 16, 2021, from https://www.wejo.com/press/connected-vehicle-data-provides-real-time-hurricane-evacuation

Wilson-Goure, S., Houston, N., & Vann Easton, A. (2006). Task two: literature search for Federal Highway Administration (ITS-JPO): Assessment of state of the practice and state of the art in evacuation transportation management.

Wolshon, B., & Levitan, M. (2002). Evacuation route traffic, flood, and wind hazard monitoring system. *Solutions to Coastal Disasters 2002*. https://doi.org/10.1061/40605(258)32

Wong, S. D., Pel, A. J., Shaheen, S. A., & Chorus, C. G. (2020). Fleeing from Hurricane Irma: Empirical Analysis of Evacuation Behavior Using Discrete Choice Theory. *Transportation Research Part D: Transport and Environment*, *79*, 102227. https://doi.org/10.1016/j.trd.2020.102227

Wong, S., Shaheen, S., & Walker, J. (2018). *Understanding Evacuee Behavior: A Case Study of Hurricane Irma*. https://escholarship.org/uc/item/9370z127

Ye, Z., Chaudhari, J., Booth, J., & Posadas, B. (2010). Evaluation of the Use of Rural Transportation Infrastructure in Evacuation Operations. *Journal of Transportation Safety & Security*, *2*(2), 88–101. https://doi.org/10.1080/19439962.2010.487633

Stephen Wong (2020). Compliance, Congestion, and Social Equity: Tackling Critical Evacuation Challenges through the Sharing Economy, Joint Choice Modeling, and Regret Minimization.

Wu, H., Lindell, M. K., Prater, C. S., & Huang, S. (2013). Chapter 6: Logistics of hurricane evacuation in Hurricane Ike. In J. Cheung & H. Song (Eds.), *Logistics: Perspectives, approaches and challenges* (pp. 127–144). Nova Science Publishers. https://www.researchgate.net/publication/273440617_Logistics_of_Hurricane_evacuation_in_Hurricane_IKE

Xin, X., Lu, C., Wang, Y., & Huang, H. (2015). Forecasting collector road speeds under high percentage of missing data. *Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence,* 7.

Xu, Z. (2017). Macroscopic traffic states estimation based on vehicle-to-infrastructure (V2I) connected vehicle data (No. 2017-01-2013). *SAE Technical Paper*. https://doi.org/10.4271/2017-01-2013

Yang, B., Guo, C., & Jensen, C. S. (2013). Travel cost inference from sparse, spatio temporally correlated time series using Markov models. *Proceedings of the VLDB Endowment, 6*(9), 769–780. https://doi.org/10/gm5vfm

Yazici, A., Kamga, C., & Ozbay, K. (2015). Evaluation of Incident Management Impacts Using Stochastic Dynamic Traffic Assignment. *Transportation Research Procedia*, *10*, 186–196. https://doi.org/10.1016/j.trpro.2015.09.068

Yoakum District. (2021). *Transportation Systems Management and Operations* [Yoakum District ITS Master Plan].

Zhang, Y., Xie, Y., & Li, L. (2012). Crash frequency analysis of different types of urban roadway segments using generalized additive model. *Journal of Safety Research*, *43*(2), 107–114. https://doi.org/10.1016/j.jsr.2012.01.003

Zhang, Z., Machemehl, R. B., & Ahson, I. (2004). *Application of the Analytic Hierarchy Process for Prioritization of Pavement Data Collection for the TxDOT PMIS* (0-4186–8; Cradle-to-Grave Monitoring of Pavements and PMIS Functionality Enhancement Planning). Center for Transportation Research, The University of Texas at Austin. https://files.library.northwestern.edu/transportation/online/unrestricted/2004/0-4186-8_DP.pdf

Zlaugotne, B., Zihare, L., Balode, L., Kalnbalkite, A., Khabdullin, A., & Blumberga, D. (2019). Multi-Criteria Decision Analysis Methods Comparison. *Environmental and Climate Technologies*, *24*(1), 454–471. https://doi.org/10.2478/rtuect-2020-0028

Appendix A. Project Summary Sheet

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Texas Department of Transportation

TxDOT Project 0-7123 Summary

Define a Statewide Plan for a Sustainable Real-Time Travel Time Network for Texas Hurricane Evacuations and Safe Citizen Return

Hurricanes in Texas pose considerable challenges to the evacuation of large populations. Real-time traffic monitoring information is a valuable resource for evacuees seeking to determine efficient routes and safe destinations. Therefore, efforts to improve the real-time evacuation traffic monitoring infrastructure in Texas are necessary to make future evacuation efforts orderly. It is essential to ensure sufficient coverage and resilience against disruptions to the real-time traffic monitoring system during hurricane evacuations. However, limited available resources and expansive network size presents several technical and economic difficulties. To implement an effective strategy to address these issues, it is crucial for the state of Texas to develop a statewide plan for the sustainability and sufficiency of the evacuation real-time traffic monitoring network.

Real-time traffic monitoring systems manage traffic conditions in real-time using a network of technologies to collect, process, and disseminate traffic information. Traffic sensors and smart cameras installed or mounted along a road are some common devices used to monitor real-time traffic conditions. Public agencies may use the collected and processed traffic data to alert the public to traffic incidents and conditions through official websites (e.g., DriveTexas), navigation apps (e.g., Google Maps), roadside intelligent infrastructure (e.g., digital message boards), and more.

TxDOT is sponsoring this project to assess the effectiveness of current evacuation traffic monitoring devices in Texas and make recommendations to guide decision-makers for the expansion and upgrade of the evacuation route network. To do so, the study will:

- Collect, tabulate, and synthesize stakeholder information
- Determine the existing system capabilities and best practices for efficient hurricane evacuation
- Make recommendations for monitoring system improvement in state-wide evacuation corridors
- Estimate costs and recommend priority scheduling for system improvement actions
- Develop recommendations for resilient communication during evacuation events

We hope you will participate in our survey and share your story with us about your involvement with Texas hurricane evacuations. We would like to gain insights into your experience using real-time traffic monitoring systems during the evacuation. We value your input and would appreciate your assistance in this project.

Dr. Zhanmin Zhang, Clyde E. Lee Endowed Professor in Transportation Engineering
Dept. of Civil, Architectural, and Environmental Engineering
The University of Texas at Austin. Email: z.zhang@mail.utexas.edu

Wade Odell, Research Project Manager
Research & Technology Implementation Division (RTI)
Texas Department of Transportation. Email: Wade.Odell@txdot.gov

COLLABORATE. INNOVATE. EDUCATE.

Appendix B. General Public Survey

Part 1: Intro and consent

Thank you for participating in this survey. This survey is prepared both in English and Spanish. Please select your language preference in the above dialog box.

This study is funded by the Texas Department of Transportation and conducted by researchers at the University of Texas at Austin - Center for Transportation Research. This research seeks to better understand Texas residents' hurricane evacuation experiences in order to better assess the current real-time traffic monitoring systems for use in evacuations in Texas. This survey aims to determine the experiences of those who resided in Texas during a past hurricane evacuation and identify potential shortcomings and suggestions regarding the existing real-time traffic monitoring systems. Results of the study may be used to guide policy decisions and planning for future evacuation procedures and infrastructure.

Real-time traffic monitoring systems manage traffic conditions in real-time using a network of technologies to collect, process, and disseminate traffic information. Traffic sensors and smart cameras installed or mounted along a road are some common devices used to monitor real-time traffic conditions. Public agencies may use the collected and processed traffic data to notify the general public for alerts and car navigation through official websites, navigation apps, and roadside intelligent infrastructure (e.g., digital message boards).

For additional information on the study, please visit:
https://utexas.box.com/s/no5fle8vi7rqorclzebak6x4qogoxftn

Click the arrow button below to begin the survey.

If you have any further questions, you may contact the researchers directly at:

Mike Murphy, Ph.D., P.E.
Deputy Director
Center for Transportation Research at UT Austin
3925 West Braker Lane, Suite 4.344
Austin, Texas 78759
Phone: (512) 232-3134
Email: michael.murphy@engr.utexas.edu

Zhe Han, Ph.D., P.E., B.Law
Research Associate
Center for Transportation Research at UT Austin
3925 West Braker Lane, Suite 4.344
Austin, Texas 78759
Phone: (512) 800-5518
Email: hanzhe@austin.utexas.edu

Connie Jiang
Graduate Research Assistant
Center for Transportation Research at UT Austin
Email: jiangka@utexas.edu

Next page

This survey contains a maximum of 32 questions and will take approximately 20 minutes to complete.

Your participation in this survey is voluntary, and you may quit the survey at any moment. Your responses will be kept strictly confidential. Personal information will be removed from the final data set as part of the research and results will be published and reported in summary form, with no individually identifying results published. All survey responses we collect from you will be stored securely in university-approved cloud-based storage platforms. Only authorized members of the research team will have access to such data. Your survey responses will be retained indefinitely.

*****

By clicking the agree button below, I acknowledge that I have read and understood the above information. I consent to participate in this survey.

- Agree
- Disagree

If "Disagree" is selected:

We are sorry that you have decided to withdraw from this survey. If you would like to reconsider, please click the "Back" button in the lower left to go back to the survey consent page. Otherwise, thank you very much for your time.

Next Page

1. Have you participated in a past hurricane evacuation in Texas?
    a. Yes/no (if "no," survey will skip to Part 4)

Part 2: Respondent information

2. If you responded yes to the previous question, which events did you evacuate in? (Select all that apply)
    a. Hurricane Laura, 2020
    b. Hurricane Imelda, 2019
    c. Hurricane Harvey, 2017
    d. Hurricane Hermine, 2010
    e. Hurricane Ike, 2008

f. Hurricane Erin, 2007
g. Hurricane Rita, 2005
h. Hurricane Allison, 2001
i. Hurricane Bret, 1999
j. Hurricane Charley, 1998
k. Other (please specify)

Please note: For the following questions, please respond to the prompt with your experiences for the most recent hurricane evacuation in which you participated.

3. Did you drive during the evacuation?
    a. Yes
    b. No
4. Zip code of residence at time of evacuation:
    a. Text response
5. Total number of people in your household, including yourself, at the time of the evacuation:
    a. 1
    b. 2
    c. 3
    d. 4
    e. 5
    f. 6+
6. What was your age at the time of the evacuation? Please select the range that most accurately describes you.
    a. Under 18
    b. 18-24
    c. 25-34
    d. 35-44
    e. 45-54
    f. 55-64
    g. 65-74
    h. Above 75
    i. Prefer not to respond
7. Which of the following best describes you?
    a. Asian
    b. Black or African American
    c. Hispanic or Latino
    d. Native American or Alaskan Native
    e. Native Hawaiian or Pacific Islander
    f. Middle Eastern or North African
    g. White
    h. Multiracial or Biracial
    i. A race/ethnicity not listed here
    j. Prefer not to respond
8. Please select your approximate annual household income:

a. Less than $10,000
b. $10,000 - $24,999
c. $25,000 - $49,999
d. $50,000 - $99,999
e. $100,000 - $199,999
f. More than $200,000
g. Prefer not to respond

9. What is your gender:
    a. Male
    b. Female
    c. Non-binary / third gender
    d. Prefer not to respond
10. What is the highest degree or level of school you have completed:
    a. No schooling completed
    b. Some high school, no diploma
    c. High school graduate, diploma or the equivalent
    d. Some college credit, no degree
    e. Associate degree
    f. Bachelor's degree
    g. Master's degree
    h. Doctorate degree
    i. Prefer not to respond
11. What was your housing arrangement at the time of evacuation?
    a. Owner of resident (outright or with a mortgage)
    b. Renter
    c. Provided by job or military
    d. Lived with parents, friends, or other
    e. Prefer not to respond
    f. Other (Please specify)

Part 3: Hurricane Evacuation Questions

Please note: For the following questions, please respond to the prompt with your experiences for the most recent hurricane evacuation in which you participated.

1. How soon prior to the forecast arrival of the hurricane did you evacuate?
    a. 0-12 hours
    b. 12-24 hours
    c. 24-36 hours
    d. 36-48 hours
    e. More than 48 hours in advance
2. What location did you evacuate to?
    a. Hotel
    b. Household of a friend or family member
    c. Public shelter
    d. RV park

   e. Found a public parking spot and stayed in vehicle
   f. Texas Travel Information Center
   g. Public building such as post office, town hall or civic center
   h. Other (please specify)
3. Where was the location you evacuated to? (Please specify "City, State")
   a. Text response
4. How far did you travel to evacuate to your destination?
   a. Within 50 miles
   b. 51 - 100 miles
   c. 101 – 200 miles
   d. 201 – 300 miles
   e. 301 – 400 miles
   f. More than 400 miles
5. Did your household evacuate using multiple vehicles?
   a. Yes
   b. No
6. What type of vehicle did you use for the evacuation? Select the answer that best describes your experience.
   a. Sedan
   b. Pickup truck
   c. SUV
   d. RV
   e. Motorcycle
   f. Public bus
   g. Commercial truck
   h. Other (please specify)
7. Did you encounter traffic issues during your evacuation? If yes, which issues are they? (Select all that apply)
   a. I did not experience any traffic issues during the evacuation
   b. Congestion or traffic jams
   c. Road closures
   d. Traffic signal malfunction
   e. Gas station shortages/lack of available fuel
   f. Car broke down
   g. Involved in a collision
   h. Did not know the routes to take for evacuation
   i. Road rage or actions of other drivers preventing orderly evacuation
   j. Obstructions on the road (e.g., flooding, fallen trees, fallen signs, downed power lines, etc.)
   k. Other (please specify)
8. Did you utilize real-time traffic data to aid in your route/destination selection during the evacuation?
   a. Yes/no
9. If you responded yes to the previous question, what platform(s) did you use? (Select all that apply)
   a. TxDOT website (DriveTexas)

    b. TxDOT roadside digital message boards
    c. In-person visit to a TxDOT Travel Information Center (TIC)
    d. Phone calls to official resources such as TxDOT TIC, 511 system, or other
    e. Social media (Twitter, Facebook, etc.)
    f. Navigation app (Google Maps, Waze, Apple Maps, etc.)
    g. TV traffic/weather channels
    h. Radio
    i. Law enforcement or TxDOT employees located along the evacuation route who directed traffic at intersections
    j. Other (please specify)
10. Please elaborate why you used the services indicated in your response to Question 9: (Select all that apply)
    a. Accessibility of service
    b. Ease of use
    c. Availability of service
    d. Accuracy of data
    e. Cost of service
    f. Familiarity with platform
    g. Source of information
    h. Other (text response)
11. How did you use the real-time traffic information during the evacuation? Select all that apply.
    a. Selected a time to depart
    b. Selected a route to take
    c. Selected a destination
    d. Adjusted route or destination during the evacuation process
    e. Monitored evacuation progress to determine traffic congestion and incidents along route
    f. Checked the location and availability of rest stops, gas stations, restaurants, etc.
    g. Other (text response)
12. What issues with the reliability or accuracy of the real-time traffic monitoring systems did you encounter during the evacuation? (Select all that apply)
    a. I did not encounter any issues.
    b. Loss of cell phone and internet service
    c. Loss of power service
    d. Unable to access traffic condition data
    e. Had no information available regarding traffic conditions
    f. Real-time travel information was not accurate
    g. Message board systems not operational or not properly functioning
    h. Other (please specify)
13. How did you ask for help or travel information if you had issues of losing cell phone, power, or internet service, etc.
    a. Text response
14. Did you use real-time traffic monitoring data when returning to your residence after the storm threat passed?
    a. Y/N

15. Compared to your initial evacuation, how would you rate the traffic data quality during your return, post-storm?
    a. Worse
    b. The same
    c. Better
16. What new issues, if any, did you encounter during your return from the evacuation?
    a. I did not encounter any issues
    b. Inaccurate information on road closures
    c. Insufficient details about route availability
    d. Loss of cell phone and internet service
    e. Loss of power service
    f. Unable to access traffic condition data
    g. Had no information available regarding traffic conditions
    h. Real-time travel information was not accurate
    i. Message board systems not operational or not properly functioning
    j. Other (please specify)
17. Do you think the current real-time traffic monitoring system is sufficient to provide the data you need to support your decision-making during evacuations?
    a. Yes/no
18. What is the most important factor you would like to see addressed to improve the current real-time traffic monitoring system to make your evacuation easier?
    a. Text response
19. In your opinion, what factors should be addressed to improve the existing evacuation real-time monitoring system in Texas? Select all that apply.
    a. Accessibility of existing services
    b. Ease of use of existing services
    c. Expand existing services to more locations
    d. Accuracy of data provided by services
    e. Cost of services
    f. Provide educational resources to increase awareness of existing resources and how to use them
    g. Other recommendations (text response)
20. In your opinion, would having multiple language options provided for real-time traffic information make your evacuation experience more seamless? What language would you like to have if you select "yes"?
    a. No
    b. Yes. Text response
21. Would you like to participate in a potential voluntary phone interview to provide more information regarding your evacuation experiences? (Your contact information will be stored securely in university-approved cloud-based storage platforms and will not be shared with anyone outside of the approved research team. Any email addresses you provide will be securely stored and permanently deleted after three years from the project completion. Deidentified notes taken from the potential interview will be retained indefinitely.)

a. If you are interested in participating, please provide your email address and you may be contacted by a member of the research team to schedule a phone call. If you would not like to participate, please leave this field blank.
b. Text response

Part 4: Hurricane Evacuation Questions (FOR PEOPLE WHO CHOSE NOT TO EVACUATE)

Please note: please respond to the following questions if you chose not to evacuate when hurricane evacuations were ordered by the government.

1. Why did you decide not to evacuate? Please select the top three responses that impacted your decision.
    a. Did not receive the evacuation order
    b. Not enough time to prepare for the evacuation
    c. Did not have a reliable transportation service to evacuate
    d. Distrust of hurricane tracking accuracy and correct prediction where the hurricane will come ashore
    e. Distrust of traffic monitoring system accuracy or reliability (not enough reliable information on travel routes, traffic conditions, or destinations)
    f. Believed it was safe to not evacuate and I could handle the situation myself
    g. Unable to take all members of household (i.e., individuals with medical conditions, pets, or other)
    h. Other (please specify)
2. If you had access to improved traffic monitoring data, do you think your decision not to evacuate would be altered?
    a. Yes
    b. No
3. If yes to above question. In the last question, you indicated that improved traffic monitoring data would change your decision to not evacuate. In your opinion, what factors should be addressed to improve the existing evacuation real-time traffic monitoring system in Texas that would increase your likelihood to evacuate? Select all that apply.
    a. Accessibility of existing services
    b. Ease of use of existing services
    c. Expand existing services to more locations
    d. Accuracy of data provided by services
    e. Cost of services
    f. Provide educational resources to increase awareness of existing resources and how to use them
    g. Other recommendations (text response)
4. Would you like to participate in a potential voluntary phone interview to provide more information regarding your hurricane evacuation decisions? (Your contact information will be stored securely in university-approved cloud-based storage platforms and will not be shared with anyone outside of the approved research team. Any email addresses you provide will be securely stored and permanently deleted after three years from the project

completion. Deidentified notes taken from the potential interview will be retained indefinitely.)

a. If you are interested in participating, please provide your email address and you may be contacted by a member of the research team to schedule a phone call. If you would not like to participate, please leave this field blank.
b. Text response

Appendix C. Social Media Post

Dates: Posted on 8/30/2022

Account: TxDOT Nextdoor account

Caption:

Have you participated in a hurricane evacuation in Texas? As part of a TxDOT-funded research project, the University of Texas at Austin – Center for Transportation Research is conducting a study to investigate traffic monitoring during hurricane evacuations. If you have experience with evacuation traffic and would like to participate, please take the survey at: https://utexas.qualtrics.com/jfe/form/SV_bwMtpq2NycWIGUK

Photo: