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EVALUATION OF DIFFERENT CONTRA-FLOW STRATEGIES FOR HURRICANE EVACUATION IN CHARLESTON, SOUTH CAROLINA

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EVALUATION OF DIFFERENT CONTRA-FLOW STRATEGIES FOR HURRICANE EVACUATION IN CHARLESTON, SOUTH CAROLINA

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

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by
Liz Mary Stephen
May 2007

Accepted by:
Dr. Mashrur A. Chowdhury, Committee Chair
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Dr. Kevin Taaffe

ABSTRACT

The number of category four and five hurricanes has nearly doubled over the past decade. Charleston, the second most populous city in South Carolina, is located on a very low peninsula, making it susceptible to floods during hurricanes and storm surges. In the event of a hurricane, the population at-risk must be evacuated to safety as quickly as possible. The Interstate system is the primary mode to evacuate at-risk population out of Charleston. Effective traffic management strategies are needed to manage the significant increase in demand on highways during the evacuation and contra-flowing traffic has been applied as a strategy to meet this need. This study evaluated the reduction in delay by proposing a new ramp and implementing different contra-flow strategies, along the I-26 corridor out of Charleston using a microscopic simulation tool called PARAMICS. This study found that the addition of a ramp along with contra-flow strategies significantly reduces traffic delay during an evacuation.

DEDICATION

This work is dedicated to my family and friends.

.

ACKNOWLEDGMENTS

I am truly grateful to God for making this thesis possible. I would like to express my deepest appreciation for my advisor and committee chair Dr. Ronnie Chowdhury, for his excellent advice, expert guidance and constant encouragement. I must also thank my committee members Dr. Jennifer Ogle and Dr. Kevin Taaffe for their beneficial suggestions and reviews. I am truly grateful to my parents and my brother for being a wonderful source of inspiration and encouragement. I am thankful to Carol for her friendship and selfless support, and for generously sharing her wisdom and vast knowledge. Imran has been an exceptional friend and guide, always generous with his time and sharing his experience and expertise. Without these two people this thesis would be far less than it is now. Ryan and Max helped me enormously at critical points of this research for which I will always be indebted. My friends and roommates have always been there for me with encouragement and strength when I needed it; I am grateful for their tremendous support.

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CHAPTER 1

INTRODUCTION

1.1.Problem Statement

According to recent studies, the strength and destructive capability of hurricanes have doubled over the last 35 years (Georgia Institute of Technology and NCAR, 2007). This increase in strength is attributed to global warming, and the trend is expected to continue. The National Oceanic and Atmospheric Administration describes a 'hurricane' as the most severe category of the tropical cyclone, a low-pressure system that is accompanied by thunderstorms, generally forming in the tropics. The birth and life of a hurricane is a complex combination of atmospheric processes that ultimately results in the formation of a large and violent storm system that can devastate an area and cause significant harm to life and property (FEMA, 2007).

Hurricanes are classified into five categories, according to the strength of the winds, using the Saffir-Simpson Scale, with category 1 having the lowest wind speeds and Category 5 having the highest. This categorization does not reflect the amount of damage the storm may cause; rather damage infliction depends upon the area that is hit. Vast destruction can also be caused by flooding alone. Hurricanes have caused devastating ruin to coastlines, as well as hundreds of miles inland. The damage estimates for Hurricane Floyd in 1999 range from 3 to over 6 billion dollars, insured losses totaled 1.325 billion dollars (Pasch et al., 2000). Every year, ten tropical storms form over the

Atlantic Ocean, Caribbean Sea and the Gulf of Mexico on average, and approximately six develop into hurricanes, in an average 30- year period, approximately five hurricanes hit the US coastline, killing roughly 50 to 100 people (NOAA, May 1999).

Charleston is a coastal city of South Carolina whose geographical location and low elevation make it susceptible to hurricanes and storm surges. Charleston County is one of the top ten fastest growing places in the state (Georgia Institute of Technology and NCAR, 2007). Mount Pleasant and North Charleston, adjacent metropolitan areas, are also important economic centers. According to the 2002 US Census Bureau statistics, the population of Charleston County was 350,000.

All along the Atlantic coastline, tourism is a major economic engine, and the same is true with South Carolina's coastal counties. Charleston is a popular tourist destination and during the summer season, it experiences a 40 percent increase in population to over 1.2 million people and the traffic volumes increase by around 30 percent. Approximately 207,000 jobs are supported by the tourist industry contributing $9.4 billion to the Gross State Product. This industry is vulnerable to hurricanes because the coastal regions are low-lying and can be easily inundated by storm surges from even minor tropical storms. For example, the storm surge from Hurricane Hugo flooded 80 miles of coastline from Charleston to Myrtle Beach, South Carolina.

Additionally, the Port of Charleston is the fourth busiest container port in the United States, handling over $3 million every hour in cargo (SCDOT, 2002). The port is vulnerable to severe hurricanes, and sensitive cargo is also at risk and may have disastrous effects if damaged (Environmental Defense, 2006).

According to reports from the Federal Highway Administration, evacuation efforts for Hurricane Floyd faced a number of issues that created severe congestion and delay, increasing the normally two and a half hour journey from Charleston to Columbia to take fourteen to eighteen hours. A combination of the absence of a well-established contra-flow plan, the presence of un-manned traffic signals in small towns, the timing of the evacuation order and the public's response to the order brought about the traffic mismanagement and consequent delay. The primary cause for the disorganization, the South Carolina Department of Transportation and the South Carolina Department of Public Safety had not yet agreed on a contra-flow plan when the evacuation order was issued.

After the events of Hurricane Floyd, the South Carolina Department of Transportation developed an evacuation plan for its coastal cities, including detailed directions for the evacuees to travel to safer areas. While the entire state currently uses the interstates I-26, I-95, I-20, and I-77 to evacuate, lane reversal was not used in the mandatory evacuation during Hurricane Floyd in 1999. As the post-Floyd evacuation plan includes contra-flowing traffic, consequently, it would be helpful to test this plan to ensure its workability and smooth function before it is used during an emergency.

Currently, South Carolina's well-formulated evacuation plan is mapped and available online. It is a statewide plan and involves several agencies. The South Carolina Department of Transportation (SCDOT) checks all evacuation routes each year to ensure that all signs are operational. Evacuation during a critical event such as a hurricane emergency is sensitive to delays and difficulties. The SCDOT is well prepared to set up resources essential to launching a contra-flow evacuation. Contra-flow is not a new traffic management strategy and similar lane reversal techniques are commonly used in cities across the U.S. to increase roadway capacity by temporarily changing the lane direction of one or more lanes during morning and evening peak hours and special events (Wolshon, 2001). Different types of contra-flow strategies exist, such as one-lane, two-lane, and all-lane contra-flow are available. Usually, contra-flow during evacuation reverses all in-bound lanes to out-bound lanes. Contra-flow may or may not be implemented during re-entry operations.

In the event of a hurricane, the at-risk population must be evacuated to safety as quickly as possible. Highways are the primary mode to evacuate at-risk population out of Charleston. Effective traffic management strategies are needed to manage the significant increase in demand on highways during the evacuation and contra-flowing traffic has the potential to better manage this need. Intelligent Transportation Systems (ITS) tools, such as dynamic message and lane designation signs are commonly used by public transportation agencies to support contra-flow operation. A model that represents specific freeway and traffic conditions, and examines its efficiency and benefits in terms of reduction of travel time and delay, will provide a significant insight to evacuation preparation. Simulation is a cost-effective tool to evaluate different traffic management strategies and several previous studies have applied traffic simulation as a decision support tool in evacuation planning (Chien and Opie, 2006).

1.2. Objectives

The objectives of this study are

- To evaluate the effects and analyze the benefits of different contra-flow strategies for traffic management during evacuation through simulation analysis.
- To evaluate the effects and analyze the benefits of a proposed connection ramp in combination with various contra-flow strategies.

1.3. Organization of the Thesis

Chapter 2 includes a brief review of the literature related to hurricane evacuation and simulation of traffic management strategies. Chapter 3 discusses the methodology adopted to study the problem and suitable strategies and Chapter 4 deals with a detailed analysis of the research method and strategies tested. Chapter 5 closes the report with conclusions and the recommendations for further research and implementation of the findings.

CHAPTER 2

LITERATURE REVIEW

The following chapter summarizes the literature review for this thesis. It includes the following sections

- Available Traffic Management Strategies for Evacuation Support
- Simulation Tools to Evaluate Different Traffic Management Strategies
- Effects of Traffic Management Strategies for Evacuation

2.1. Available Traffic Management Strategies for Evacuation Support

During traffic evacuation, traffic management strategies are employed to expedite the evacuation process, minimize delays and maximize safety. Commonly used evacuation traffic management strategies are use of the shoulder as a travel lane, contraflowing traffic and phased evacuation (Goodwin and Pisano, 2002). The Texas Department of Transportation (2007) utilized an emergency shoulder-lane to accommodate the surge in traffic in its emergency evacuation plan. They developed an urban and rural plan, each operating with an additional shoulder lane. However, there are some advantages as well as disadvantages to using shoulder lanes for evacuation purposes. Wolshon (2001) reported several advantages of opening shoulder lanes for evacuation purposes, in comparison to other strategies like contraflow, because several time consuming tasks are avoided:

- Setting up the system prior to implementing
- Clearing of reversed lanes
- Barricading of ramps
- Altering signal times and reversing signs
- Assembling crew to handle preparatory tasks taking several hours
- Shoulder lanes may be used as an outbound lane for unlimited time

The Florida Department of Transportation uses the shoulder as an additional outbound lane during emergency evacuation, and prefers not to implement contraflow and has never had to in the past because of good planning, timely evacuee response and inter agency cooperation (USDOT and USDHS 2006). However, shoulder lanes are generally unused in evacuation plans, Wolshon et al (2001) reasoned that this was because of the following limitations

- Structurally inadequate pavements
- Dissimilar shoulder cross slopes
- Discontinuous shoulders
- Used for access to at risk areas by law enforcement and highway patrol
- Used for parking stalled vehicles

Phased evacuation involves staging the evacuation process in a sequential manner, different geographical locations are warned to evacuate at different time periods, for example coastal areas exposed to higher risk are warned to evacuate before inland areas (Sorenson and Vogt, 2006). A phased evacuation is based on the time of predicted landfall and geographical locations of the areas of concern (GAO 2006). The Government Accountability Office (GAO) (2006) recommended the use of a multi-phased evacuation plan to allow for the speedy evacuation of residents in areas at most risk and those who are incapable of evacuating on their own. Based on an assessment of the evacuation failures during Hurricane Katrina the GAO reported the need for interstate cooperation, coordination of evacuation plans and educating the public on the possible evacuation routes in order to implement a successful phased evacuation (2006). Accordingly, it was planned that Phase I begins 50 hours before the storm winds are forecasted to reach those areas of concern, which are vulnerable to category 1 and 2 hurricanes, Phase II commences 40 hours prior to the onset and is pertinent to those regions vulnerable to category 2 and higher storms, and Phase III is initiated 30 hours ahead of the onset of the hurricane and it is applicable to those areas that are vulnerable to storms of category 3 and higher. In this case, phases I and II have no route restrictions, during phase III route restrictions are present and the lane-reversal plan is implemented.

Wolshon described contraflow, as "the use of one or more lanes of inbound travel for traffic movement in the outbound direction (2001)." It is an increasingly popular traffic management tool for evacuation advocated by the public, lawmakers and several studies throughout the United States and abroad (Tuydes and Ziliaskopoulos, 2005, Wolshon 2001, Theodoulou, 2001). During Hurricane Katrina, the failure to launch contraflow for evacuation traffic, was one of the transportation related problems encountered (Litman 2006). The concept in itself is not new; in fact, contraflow is commonly used to increase roadway capacity during daily rush hours by alternating the use of one or more lanes for inbound and outbound traffic during morning and evening peak hour. For example, Washington, D.C. practices this strategy on a daily basis on Connecticut Avenue. Special events also warrant the use of contraflow, where the normal lanes are incapable of accommodating the traffic volume. In his paper "One-Way-Out", Brian Wolshon (2001) analyzed different types of contraflow for a two-lane road, such as

- Normal plus one lane contraflow
- Normal and shoulder plus one lane contraflowed
- Normal plus two lanes contraflowed

Table 1 Evacuation Contraflow Use Strategies (Wolshon et al., 2005)

Strategy	**State**									
	NJ	MD	VA	NC	SC	GA	FL	AL	LA	TX
All lanes outbound		X	X	X	X	X	X	X	X	X
One lane reversed + one lane inbound for emergency/service vehicle access	X									
One lane reversed + one lane inbound for normal traffic entry	X				X					
One lane reversed + outbound left shoulder									X	

Table 1 exhibits the use of different contraflow strategies in the United States. Wolshon reported that the most commonly implemented contraflow technique is reversing all the inbound lanes to serve as outbound lanes, the major advantage to this technique is the increase in capacity. In this case, ramps are barricaded to prevent entry onto the inbound freeway lanes; this prevents vehicles on the reversed lanes to exit the freeway to use roadside facilities. According to Wolshon, some safety concerns that go hand in hand with contraflowing traffic is driver confusion due to reversal of freeway lanes with features like signs, markings and safety features designed specifically for one way travel. In addition, the inability to exit for fuel, food and other facilities while traveling on reversed lane is stressful and problematic. Another important safety issue is the complete prohibition of inbound travel during contraflow, the National Guard and other service vehicles need access to the evacuating area before and after the storm. Wolshon said that a probable solution to this was allowing a single inbound lane to be used for entry purposes; however, this reduces the total capacity, yet another alternative is using parallel secondary highway routes for service access.

Wolshon went on to say that, the high monetary expense of planning, designing, and operating contraflow is a priority for the responsible agencies. Even though the cost was insignificant when compared with the potential threat, it must still be taken into account. The primary cost for lane-reversal lay in planning and implementation. Setting up and operating contraflow is labor intensive, and practice drills are conducted to ensure safety. Another major fraction of the expense lies in the required infrastructure enhancement. This again is a one-time investment, other expenses include the use of variable message signs and barricades, but these are also used during regular traffic management. Alternatively, the author stated that, when a single lane contraflow is practiced, the adjacent inbound lanes may be used by emergency vehicles. Shoulder lanes may be used instead as additional outbound evacuation lanes. Until recently, emergency evacuation was largely the responsibility of local emergency agencies. This created considerable chaos due to congestion when passing through different counties.

Recently, inter and intra state coordination has gained attention and the problem is being addressed. Oversights that occurred during Hurricane Floyd have instigated inter-state coordination. The Georgia, the North and the South Carolina Departments of Transportation are combining their efforts to remove deficiencies in the state evacuation plans. As part of the South Carolina evacuation plan by the SCDOT, I-26 has been contra-flowed for a length of 95 miles originating in Charleston and ending in Columbia.

2.2.Simulation Tools to Evaluate Different Traffic Management Strategies

Simulation modeling is an increasingly popular tool for studying a variety of dynamic problems that cannot be analyzed by other means (Lieberman and Rathi, 1992). The same study classified various simulation software into microscopic, mesoscopic and macroscopic. Microscopic tools depict all model entities and interactions at a high level of detail, mesoscopic tools describes model entities at a high level of detail but their interactions are at a lower level of detail that a microscopic model. Thirdly, a macroscopic model portrays system entities as well as their interaction at a low level of detail.

Microscopic simulation models were considered for this study because of their efficiency in terms of driver/vehicle behavioral modeling, detailed data extraction, calibration of model parameters, and cost of operation. In microscopic simulation, the vehicles interact with traffic signals, signs, other vehicles and roadway geometrics. All microscopic simulation models portray driver behavior such as following, gap acceptance, and lane changing (Gettman and Head, 2003). The simulation tools evaluated for this study were CORSIM (USA), Sim Traffic (USA), VISSIM (Germany), PARAMICS (UK).

Table 2 Simulation Software

Modeling Software	Built in Network size Limit	Application Programming Interface	Detailed Output Reports	Dynamic Trip Assignment
CORSIM	X	X	X	X
SIMTRAFFIC	X	-	-	-
VISSIM	-	X	X	X
PARAMICS	-	X	X	X

CORSIM (CORridor microscopic SIMulation) was developed by the Federal Highway Administration; it is 30 years old and is the most widely used microsimulation tools for traffic behavior simulation or urban roadway networks in the United States (Gettman and Head, 2007). It works on the car following theory and driver behavior algorithms, and uses a fixed one second time step interval for updating generated variables. CORSIM allows adjustment of driver behavior parameters, timed and actuated signals, and incorporates high occupancy vehicles and transit in the model (Ruehr et al. 2004). The software is inexpensive and the FHWA provides online help on the website. However, it has some disadvantages such as a limitation in the number of nodes, links and vehicles during simulation.

Simtraffic is an offshoot of SYNCHRO, (Ruehr et al. 2004) it has a more user friendly interface than most tools; however, the same author says it lacks API functions, detailed outputs of traffic variable information and the resolution of other tools like AIMSUN, VISSIM, or PARAMICS. The study also reported that it allows modification of driver behavior and vehicle characteristics such as acceptable gaps, acceleration factors, average speeds. Although it is relatively easier to use, it is rudimentary and does not function accurately under oversaturated conditions.

VISSIM, it is capable of detailed output reports of vehicle variables and represents on-street parking behavior and double parking (Ruehr et al., 2004). This paper reported that VISSIM was designed to model freeway applications such as merging and weaving, however, it can be used to simulate different kinds of interchanges including signalized, stop controlled and roundabouts and 3D modeling. AIMSUN is micro-simulation software developed in Spain, with capabilities more powerful than CORSIM or SimTraffic; it features dynamic trip assignment, simulates the impacts of Intelligent Transportation Systems, and can create a 3-D animation visual (Gettman and Head, 2003).

PARAMICS is a powerful microsimulation tool; it is a traffic modeling platform developed by Quadstone along with SIAS Ltd. based in Edinburgh. The name is an acronym derivation of PARAllel computer MICroscopic Simulation. PARAMICS is a stochastic, time step, microscopic and behavior based modeling tool (Bertini 2002). It can be used to model a single intersection, a congested freeway or a city traffic system (Ozbay et al., 2005). PARAMICS provides an Application Programming Interface (API), which can add a new functionality or modify an existing one. Various traffic policies and control strategies can be modeled using this tool and their effects such as vehicle delays and emissions can be evaluated.

2.3.Effects of Traffic Management Strategies for Evacuation

Recently several studies have been conducted to research various evacuation strategies, to evaluate existing evacuation plans and to examine the errors in past evacuation attempts and propose suitable improvements. Chien and Opie (2006) conducted a simulation study on Cape May, New Jersey to evaluate the effectiveness of the existing New Jersey State Police Lane Reversal Plan for Routes 47/347 in Cape May and Cumberland Counties in New Jersey. The study concludes that under the assumed parameters the existing contraflow plan needs to be changed, as congestion would result in a bottleneck south of Route 83. Chien and Opie (2006) stated that evacuation demand generation is a necessary part of the study, necessitating the determination of a vehicle equivalent to the evacuating regional population. The authors collected statistics from the US Census 2000 based on a United States Army Corps of Engineering estimation of housing and mobile units by evacuation district and storm surge inundation level. The volume was determined using a vehicle per household factor obtained from Census 2000 data. The tourist/seasonal surge in population and vehicles were also considered in this study.

According to Chien and Opie (2006), the location of the housing unit, category of the storm and the type of housing unit varied the evacuee participation rate. Due to lack of specific information, participation rates were adopted from another study (the Delmarva Evacuation Study) for this research. Traffic distribution was modeled assuming that all evacuees depart from their residence or seasonal accommodation, based on this, the evacuation districts were subdivided and the smaller zones used as origin zones. Vehicle routing was based on the highway network available for evacuation.

According to Behavioral response curves or Sigmoid curves, three response speeds were simulated, slow, medium and rapid. The Cape May study devised and simulated eight cases, where the scenarios were varied under four categories, namely traffic operations, area population, hurricane intensity and behavior response. The two traffic operation strategies tested were normal operations, and contraflow operated evacuation. The two population alternatives modeled were considering peak season (Labor Day weekend) and off-peak season (late September). Two categories of hurricane intensity were considered, category 1 and the other category 2 and higher. Three vehicle generation rates were simulated, fast response, medium response and slow response rates. Totally 24 scenarios were simulated. The researchers used PARAMICS to simulate the model in the study. Due to its stochastic nature, an average result between runs of the same scenario was taken as the result for the scenario. The results of different scenarios were compared and the differences analyzed. The study concludes that total evacuation would take 16-25 hours to be completed after the order and that assumed behavior responses is the primary influence on duration. Evacuation demand varies according to hurricane intensity and seasonal population.

The California Department of Transportation (Caltrans) conducted a study using PARAMICS to simulate small area evacuation (Church and Sexton, 2002). The purpose of the research was to test evacuation scenarios in the Mission Canyon neighborhood in

Santa Barbara, CA. that lies within an acknowledged high fire risk area. PARAMICS was selected as the most suitable software to use for the purpose because PARAMICS provides a number of special features and Caltrans has deployed PARAMICS in each of its district offices. PARAMICS provides dynamic information feedback on drivers, they can be given periodic information updates allowing them to change queues after waiting in one for a period. The study used these features to represent special radio channels broadcasting information. Caltrans modeled 18 scenarios, each representing a variable set of model assumptions, which were as follows:

- Number of vehicles evacuating per household
- Opened a dirt road leading out of the neighbored that is currently closed
- Blocked normal traffic from using Foothill Rd which is the most important road used in the area
- Implemented traffic control, such as optimized intersections, contraflowed some links, and control by officers

Based on the study findings, Church and Sexton (2002) concluded the following

- Residents must be encouraged to use only vehicles that they need and must not attempt to save all the vehicles they own to ensure a safe and quick evacuation.
- By improving the Foothill Road stretch between Mission Canyon Road and Alamar Road increasing its capacity, more traffic can be carried to safety in time.
- The simulation model can be used to increase awareness and educate residents as well as county officials.

Another study conducted by the University Transportation Center for Alabama (Sisiopiku et al., 2004) developed and tested response plans to a number of hypothetical traffic emergencies in the Birmingham, Alabama region to demonstrate the potential benefits of using micro-simulation models when developing emergency response strategies (Sisiopiku et al., 2004). The study findings were used to evaluate the implications of the proposed strategies on the traffic network and assist the transportation officials in Birmingham, Alabama to employ necessary traffic management strategies in the event of an emergency. CORSIM was selected as the modeling tool because it combines both arterial and freeway modeling; it does not limit the number of links, segments or vehicles fed in, and because of its extensive use and prior validation. The researchers modeled traffic incidents, traffic evacuation and evaluated the existing Birmingham emergency preparedness plans. They developed a network for the Birmingham region consisting of primary freeways and arterial corridors. Incident management strategies such as changeable message signs (CMS), highway advisory radio (HAR), and advanced traveler information were simulated. When forecasting the travel demand for evacuation simulation, parameters considered were traffic generation, traffic distribution, mode choice and evacuation route choice. The traffic management strategies modeled in the project were, altering traffic signal timings and traffic control, evacuation-related information dissemination, roadway clearance and access restriction, timed release of traffic and contraflowing lanes. The study findings indicated that the use of traffic diversion showed significant improvement in network performance and implementation of Intelligent Transportation Systems technologies (CMS, CCTV, HAR, etc) would prove advantageous in emergency events.

CHAPTER 3

METHODOLOGY

The methodology used in this study employed data from past hurricanes and hurricane behavior in combination with current population estimates to develop an evacuation model. This model was then used in a simulation application to evaluate various traffic management strategies such as contra-flow and phased evacuation. Figure 1 shows the process for modeling evacuation operations for different contra-flow operation under various evacuation time frames.

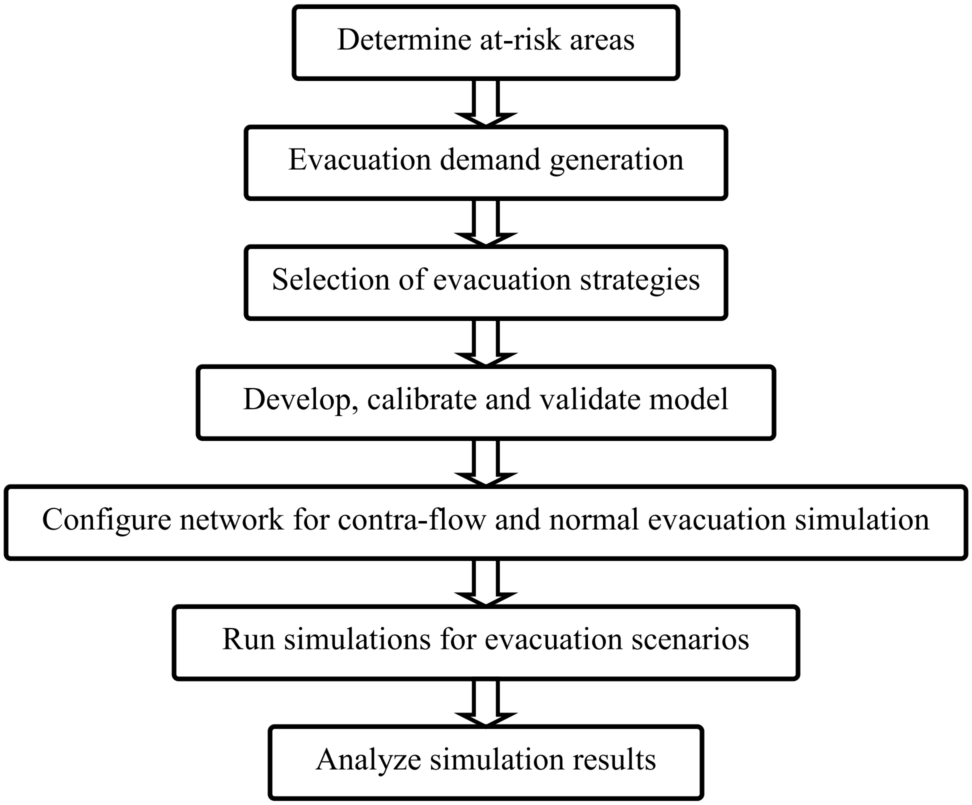


Figure 1 Process of Modeling Traffic Evacuation

3.1.Determination of At-Risk Areas

Charleston, SC, a coastal city of South Carolina, is a popular tourist destination. However, the low elevation of the area is at constant risk during the hurricane season. Even a Category 1 hurricane may create a storm surge in some areas. Due to the risk factors faced by this city, an effective evacuation plan is extremely important. According to the evacuation plan developed by the SCDOT, the freeways used for evacuation purposes are I-26, US 278, US 21, US 17 and US 501. The scope of this study includes evacuation using I-26; thereby, the areas considered in this study as highlighted with red stars in Figure 2, were as follows:

- James Island
- Folly Beach
- Charleston city
- Mount Pleasant
- Sullivan’s Island
- Isle of Palms

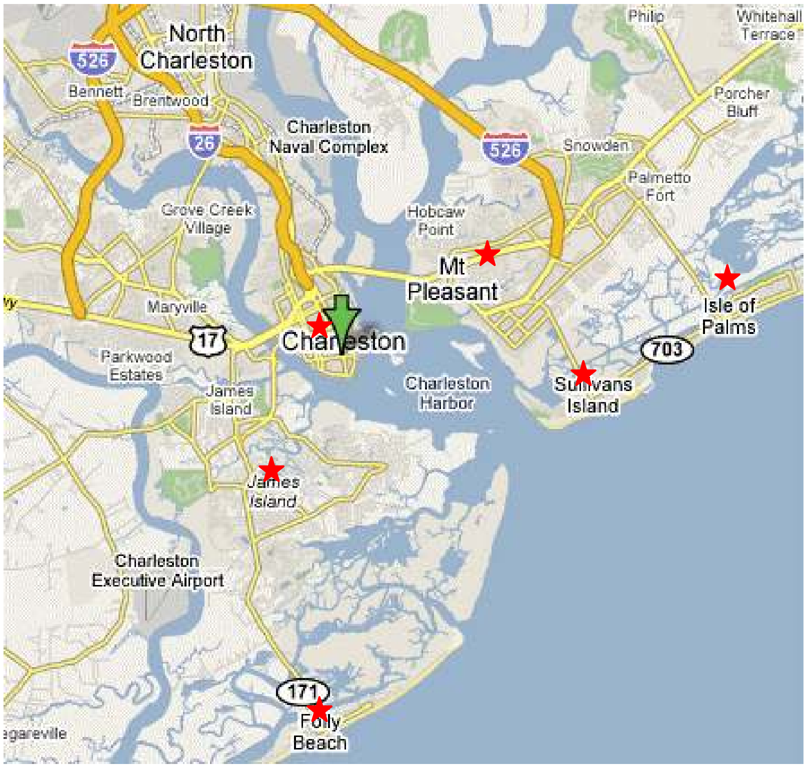


Figure 2 Evacuation Study Sites

According to the vulnerability analysis conducted as part of the United States Army Corps of Engineering hurricane study, Report on South Carolina (2007), the Charleston peninsula including the areas considered in this study are at risk in the event of a Category 2 hurricane. The areas are vulnerable to the hurricane itself, as well as to a consequent storm surge. The extent of flooding will depend on the hurricane path and tide levels at the time of the hurricane. Therefore, these areas need to be prepared for evacuation in case of a category 2 and higher tropical storm. Figure 3 displays a storm surge map of coastal South Carolina.

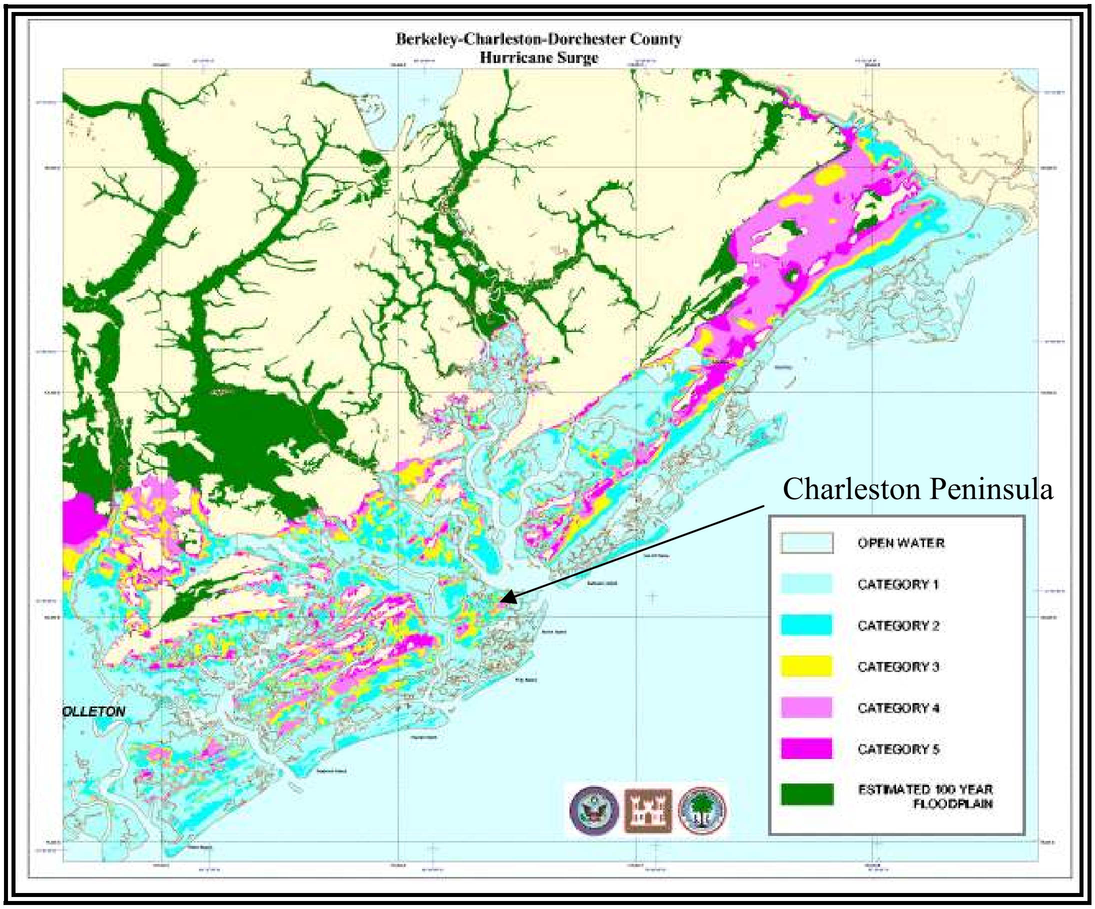

Charleston Peninsula

Figure 3 Storm Surge Map of the Atlantic Coast (FEMA, 2007)

3.2. <u>Evacuation Demand Generation</u>

The estimation of the evacuation demand includes determining the at-risk population, the participation rate, and the evacuation route and traffic distribution. The evacuation demand was entered into the simulation model in terms of evacuating vehicles, and this volume was determined based on previous hurricane studies.

This study applied the participation rate model evaluated by Wilmot and Mei (2004) to generate evacuation demand. The participation rate model requires input in anticipated participation rates by the at-risk population. This study adopted the participation rates reported by the FEMA based on Hurricanes Bertha, Fran and Floyd for South Carolina. Table 3 exhibits participation rates for South Carolina based on a behavioral study on past hurricanes. It refers to three kinds of at-risk population. The storm surge area/vulnerable population are at the highest risk to the effects of hurricanes and storm surge, they reside in very low elevation areas. Mobile home owners are also considered to be at a high risk due to the lack of stability of the mobile home. The non-vulnerable population are at the lowest risk as compared to the other two, however in the event of a severe hurricane all populations require to be evacuated. The formula used for calculations is given in Equation 3.1

Travel demand = Area population X Participation Rate -Equation 3.1

Table 3 Participation Rates (FEMA, 2007)

Population	Participation Rate
Storm surge area/vulnerable population	100%

Mobile homes	100%
Non-vulnerable population	1-15%

The South Carolina Hurricane Restudy Technical Report examined post-hurricane evacuation behavioral surveys of Bertha/Fran (1996) and Floyd (1999). Based on hundreds of telephone interviews conducted by the USACE as part of the Behavioral Studies for the Hurricane Restudy Technical Report (2007), the number of evacuees, their destination and their planned shelters were determined. The study also estimated the time required to evacuate the population to safer areas before the landfall of the hurricane. The USACE assumption that 100% of the residents of storm surge areas and all mobile homes evacuate is applied to this thesis, by adopting full participation of the six areas evacuating through I-26. This study assumed the evacuees used 65-75% of the vehicles available in each household (USACE, 2007).

The United States Census (2000) was used to determine area population estimates and average number of vehicles owned per household. The estimates considered the population surge during the tourist season. A growth factor was applied to each of these values to account for the population growth and urban development between 2000 and 2007, along the South Carolinian coast. Equation 3.2 was used to compute vehicular volume.

$$\text{Vehicular volume} = \text{Average number of vehicles/household} \times \text{Number of households} \times \text{Growth factor} \qquad \text{-Equation 3.2}$$

The behavioral curves generated by the USACE as given in Figure 4 were used for this study. The Figure 4 is shows the sigmoid curves or s-curves used to determine behavioral response. The three curves represent rapid response, medium response and long response to the evacuation order. The graph shows traffic generation as a percentage beginning at two hours before the evacuation order is passed. The traffic loading is distributed between five hours to eleven hours, as rapid, medium and long responses.

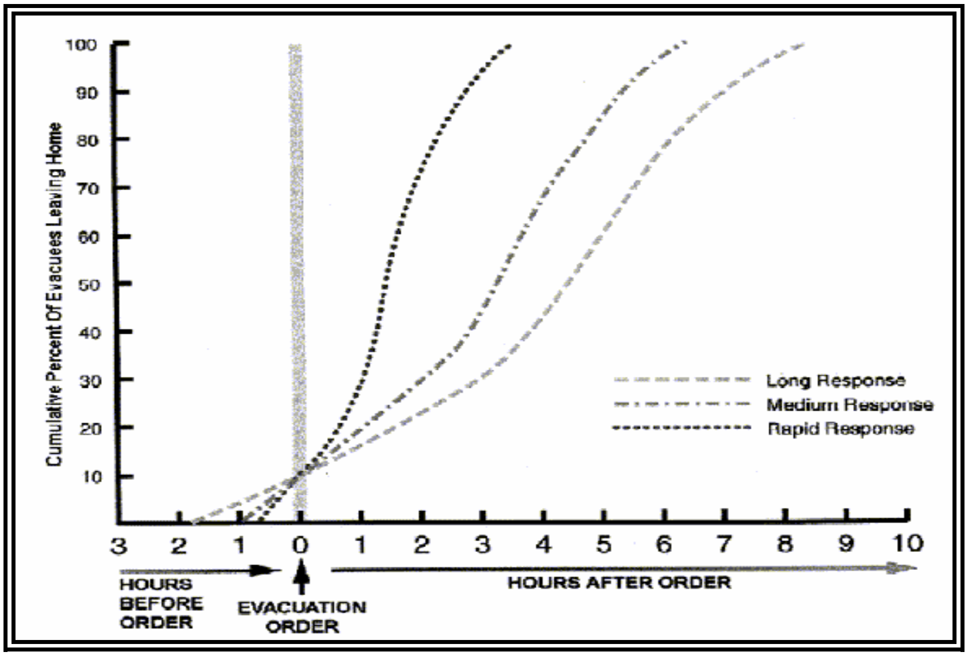


Figure 4 Behavioral response curves, S-curve

The value for the vehicular volume for each area was input to the participation rate method formula to generate the evacuation demand as shown in Equation 3.3. Based on the evacuation plan developed by the SCDOT, the calculated demand was distributed between the respective zones to create an origin-destination matrix for the network. The matrix was then input to the PARAMICS database to accurately model the evacuation scenarios.

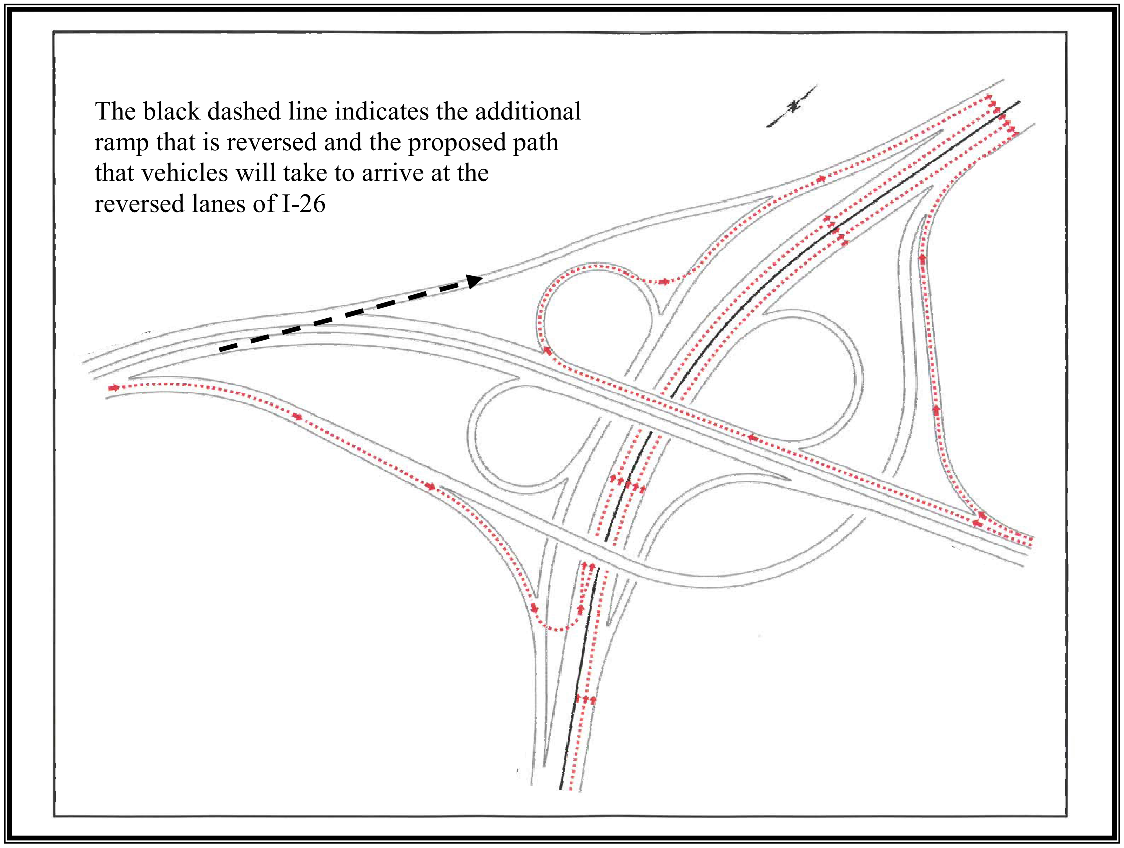
Travel demand = Vehicular Volume X Participation Rate -Equation 3.3

3.3. Selection of evacuation strategies

As mentioned earlier two primary conditions were modeled in this study, they are:

- Existing geometric layout
- Proposed geometric layout

The proposed layout was designed based on several considerations. The initial simulations indicated a congestion due to the single lane ramps designed by the SCDOT specifically for evacuation purposes. Hence, as this congestion was affecting the traffic entering from I-526 East, the proposed design distributes this traffic between two existing ramps. Of these two ramps, one is used by the current plan, the other is not and it is proposed to be contra-flowed to accommodate the additional traffic volume. Figure 5 displays the proposed design. An economic method to implement this connector on the field is to use a short stretch of road surfaced using gravel, linking the Eastbound and Westbound lanes of I-526 at this location.



The black dashed line indicates the additional ramp that is reversed and the proposed path that vehicles will take to arrive at the reversed lanes of I-26

Figure 5 Proposed Design

The following strategies, including one normal flow, three contra-flow configurations for the existing as well as the proposed geometric lay outs were evaluated:

- Normal lane operation (3 lanes outbound) - This strategy refers to the use of only normal outbound lanes for evacuation and the inbound lanes remain open for inbound use.
- Normal plus one contra-flow lane - In this case, the normal outbound lanes remain the same, and in addition, one inbound lane is contra-flowed.
- Normal plus two contra-flow lanes - In addition to the normal outbound lanes, two inbound lanes are reversed to accommodate evacuating traffic.

- Normal plus three contra-flow lanes - All inbound and outbound lanes are used for evacuating traffic in the outbound direction.

Figure 6 shows the configuration of these four strategies.

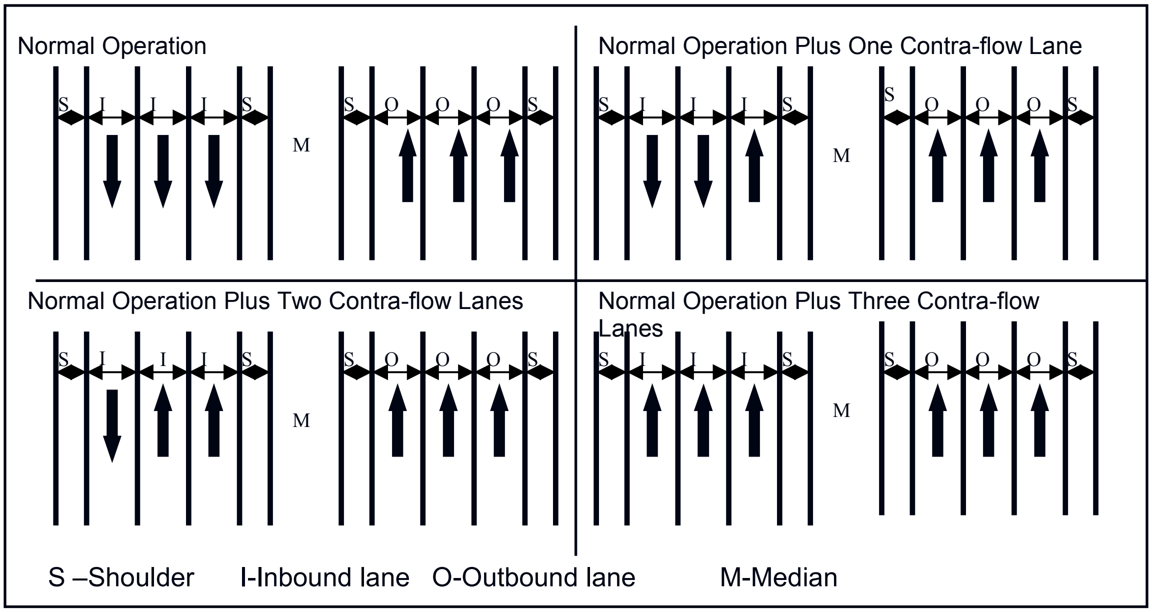


Figure 6 Freeway contra-flow lane use configuration

In addition, three evacuation response rates were also studied; these rates were based on response curves generated by the USACE (2007).

- Long response – the evacuation demand generation is distributed over a period of 11 hours.
- Medium response –the evacuation demand generation is distributed over a period of 8 hours.
- Rapid response - the evacuation demand generation is distributed over a period of 5 hours.

Twenty-one scenarios were developed from the three contra-flow strategies, normal flow and the three response rates explained previously. These twenty-one scenarios are presented in Table 4. The simulation tool adopted for the study was PARAMICS.

Table 4 Selected Scenarios

Scenario	Lane Operation	Road Geometry	Response Type
1	1 lane contra-flow + normal outbound 3 lanes	Existing	Long
2	2 lane contra-flow + normal outbound 3 lanes	Existing	Long
3	3 lane contra-flow + normal outbound 3 lanes	Existing	Long
4	1 lane contra-flow + normal outbound 3 lanes	Existing	Medium
5	2 lane contra-flow + normal outbound 3 lanes	Existing	Medium
6	3 lane contra-flow + normal outbound 3 lanes	Existing	Medium
7	1 lane contra-flow + normal outbound 3 lanes	Existing	Rapid
8	2 lane contra-flow + normal outbound 3 lanes	Existing	Rapid
9	3 lane contra-flow + normal outbound 3 lanes	Existing	Rapid
10	1 lane contra-flow + normal outbound 3 lanes	Proposed	Long
11	2 lane contra-flow + normal outbound 3 lanes	Proposed	Long
12	3 lane contra-flow + normal outbound 3 lanes	Proposed	Long
13	1 lane contra-flow + normal outbound 3 lanes	Proposed	Medium
14	2 lane contra-flow + normal outbound 3 lanes	Proposed	Medium
15	3 lane contra-flow + normal outbound 3 lanes	Proposed	Medium
16	1 lane contra-flow + normal outbound 3 lanes	Proposed	Rapid
17	2 lane contra-flow + normal outbound	Proposed	Rapid

	3 lanes		
18	3 lane contra-flow + normal outbound 3 lanes	Proposed	Rapid
19	normal outbound only	Existing	Long
20	normal outbound only	Existing	Medium
21	normal outbound only	Existing	Rapid

3.4. Configure network for contra-flow and normal evacuation simulation

The Charleston network model used for this thesis was developed in PARAMICS. Model building in PARAMICS constitutes several steps. The roadway geometric data, lane details, and intersection data were input as nodes and links. The links were coded with roadway characteristic data such as speed, number of lanes, etc. Accurate geometric data was imported using ArcGIS and integrated into the PARAMICS network using the Shape to PARAMICS tool. Figure 7 shows the 11-mile Charleston network constructed in PARAMICS, constituted of 7 interchanges and 20 origins and destinations.

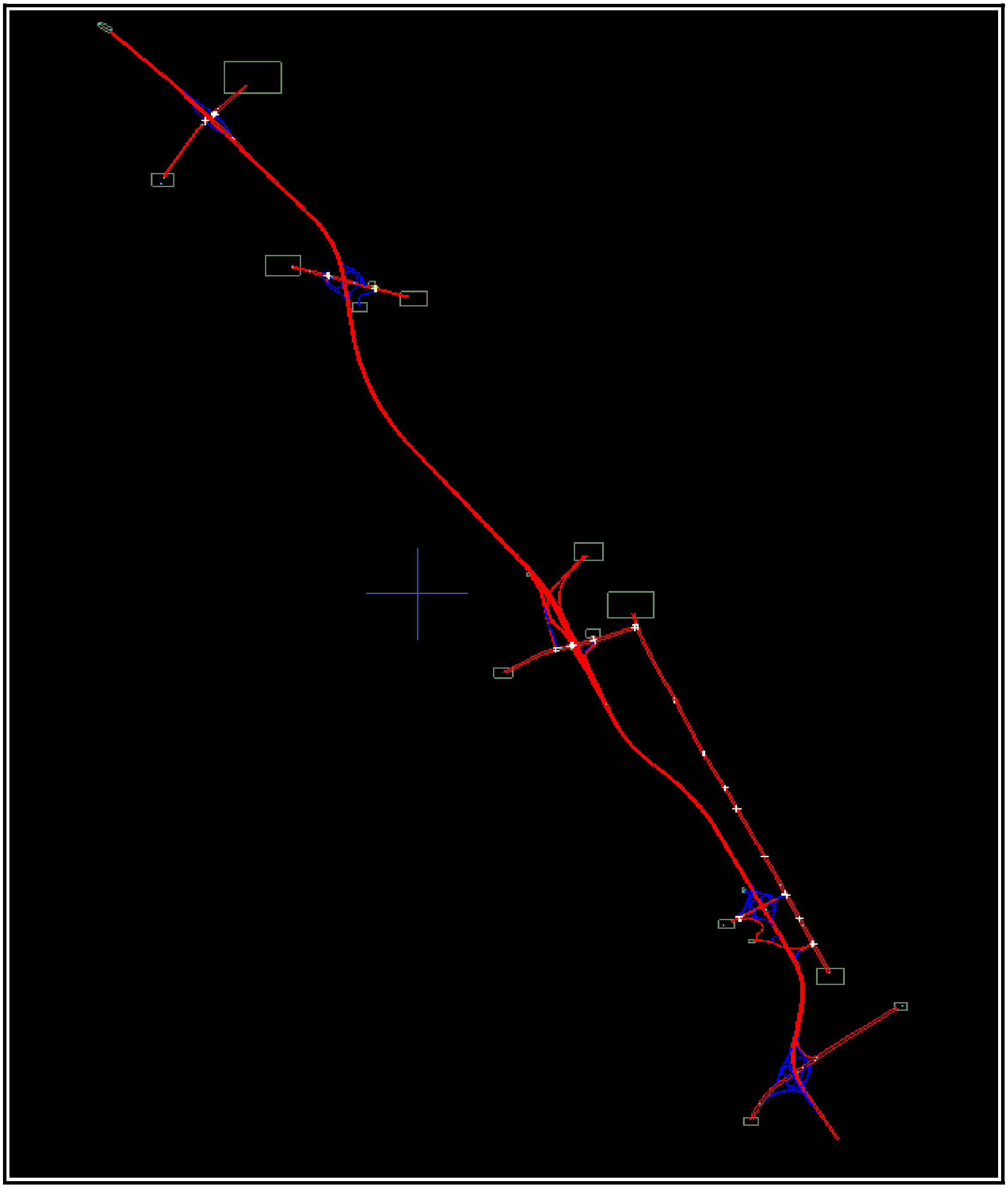


Figure 7 PARAMICS Network

Model calibration is an important part of building the model. It is necessary to verify and establish the accuracy and reliability of the model. Calibration was performed using field data collected from various intersections along the selected I-26 network in Charleston. Travel time and queue length data were collected for validating the model.

The calibrated network was then modified to simulate evacuation. Several changes were made to model contra-flow in PARAMICS. The lane configuration for each of the twenty-one scenarios was built into the network. Accordingly, network and database files were adapted in PARAMICS to simulate each scenario. Figure 8 shows the SCDOT lane reversal plan for the I-526/I-26 interchange. The black dots in the figure trace the normal and contra-flow routes over the interchange. Two ramps have been connected to the eastbound lanes of I-26 to allow the vehicles onto the reversed lanes.

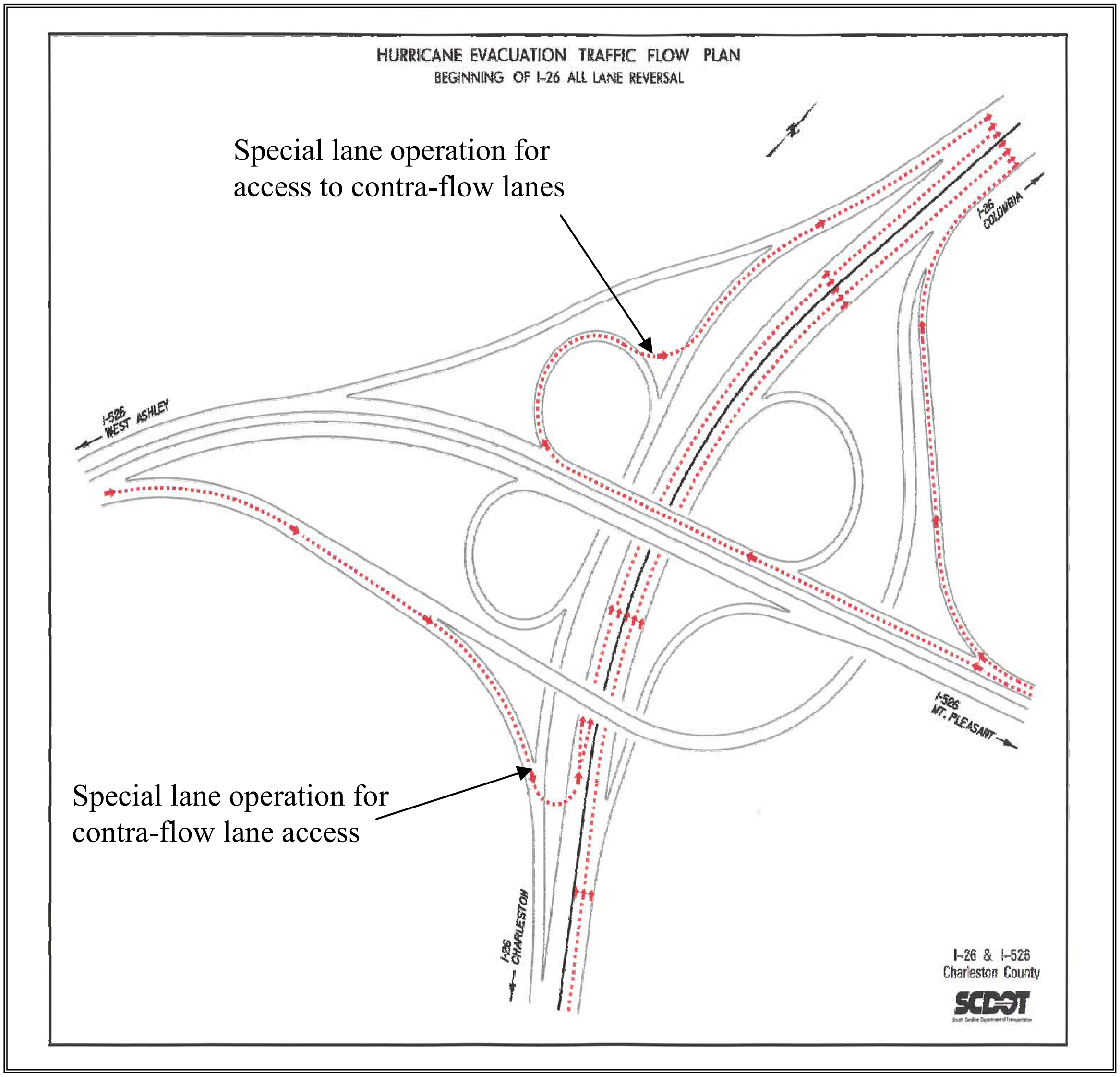


Figure 8 SCDOT Lane Reversal Plan for I-526 I-26 Interchange (SCDOT 2007)

Figure 9 shows the same I-526/I-26 interchange modeled in PARAMICS. Additionally, Figure 9 shows a full contra-flow operation, where the small white boxes represent vehicles moving along the evacuation route proposed by the SCDOT.

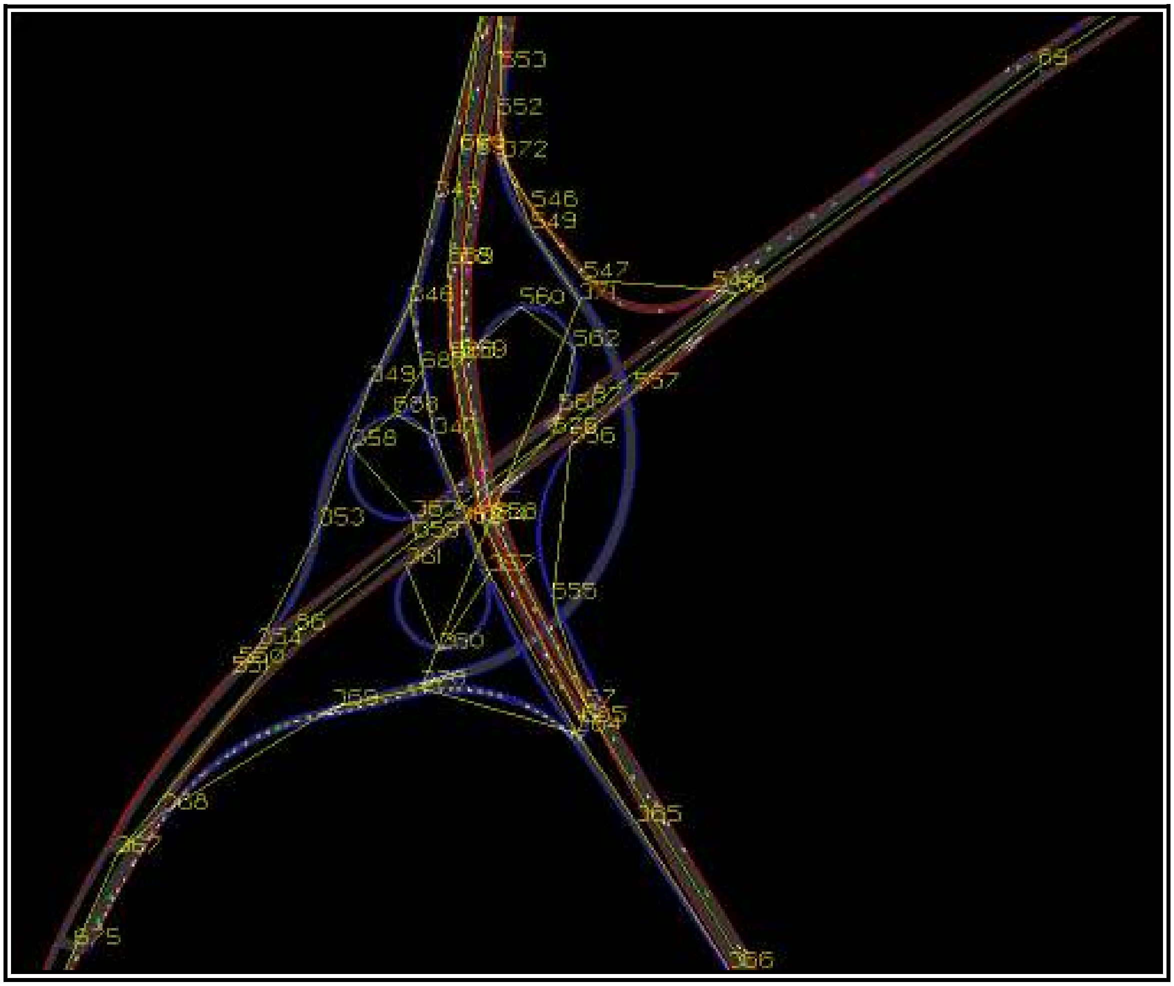


Figure 9 Modeled Lane Reversal Plan for I-526 I-26 Interchange

In addition to these changes, the proposed connecting road was built in the model linking I-526E to the ramp connecting I-26E to I-526W. The traffic on this ramp is contra-flowed. Vehicles routed to enter the reversed lanes of I-26, traveling along the right lanes of I-526 E are programmed to use the existing ramp leading onto the reversed lanes of I-26, and those vehicles on the left lanes are programmed to use the proposed connecting road to enter the ramp leading to the reversed lanes of I-26

3.5. Simulations for Evacuation Scenarios

As described above, twenty-one scenarios were simulated. For each scenario, assuming a normal distribution, the number of runs required to obtain a 95% confidence interval was determined based on the following statistical formula.

$$N = (1.96\,\sigma)^2/E^2 \qquad \text{Equation 3.4}$$

Where,

N= number of simulation runs

σ= standard deviation

E= margin of error

3.6. Analyze Simulation Results

Based on the simulation results, the travel time and evacuation duration for each scenario were analyzed. In support of the analysis Statistical Analysis Software (SAS), was used to test whether:

- There is an interaction between response time and lane operation
- There is a difference in the travel time due to use of different number of reversed lanes for long, medium and rapid response time
- There is a difference in travel time due to different response times for using 0, 1, 2, and 3 lane reversals, and if so which presents the lowest travel time.

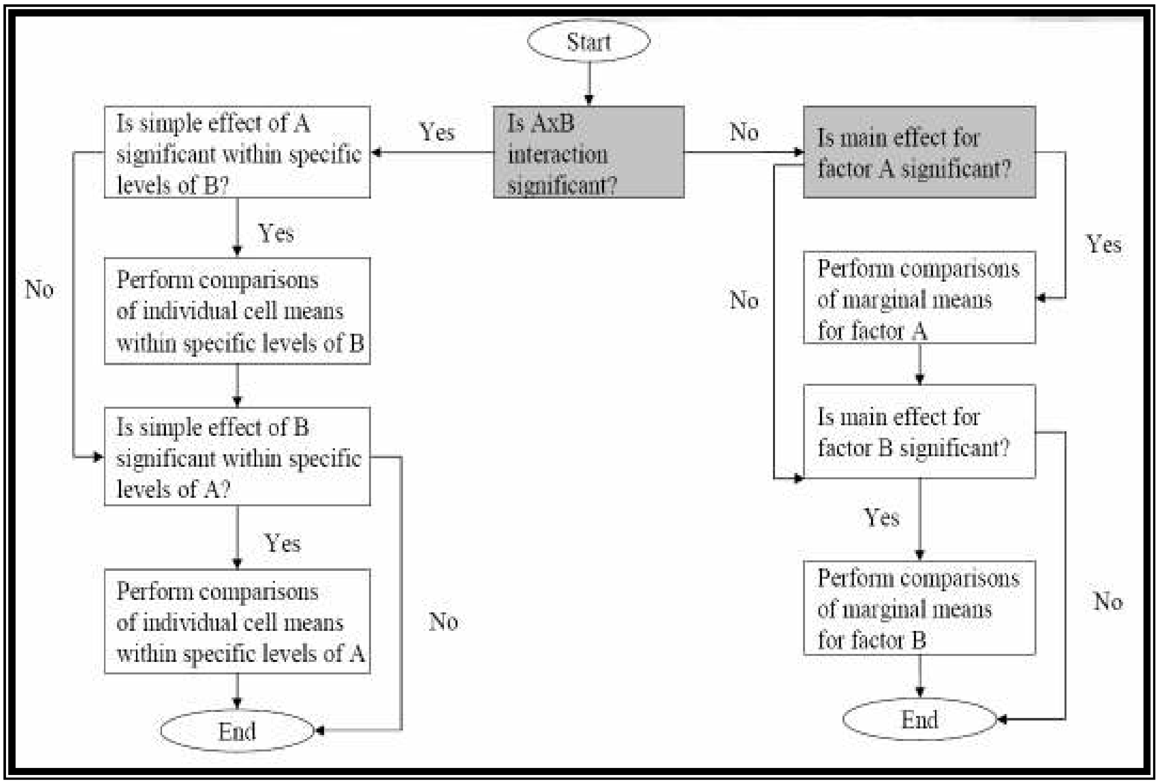


Figure 10 Process of a Two Factorial Experiment

The two factorial ANOVA analysis is used to conduct a statistical analysis if there are two variables, which in this study are the response type and lane operation. Figure 10 describes the analysis procedure. If the two factors do not interact significantly a one-way analysis for the marginal means of factor A, lane operation is conducted, and similarly the same for factor B, response type. If there is significant interaction between the factors, then a one-way analysis for the travel time means for lane operation within each level of the response type is conducted, and similarly a one-way analysis for the travel time means for response type within each level of lane operation is conducted.

Bottlenecks invariably occur during on roads carrying high traffic volumes, in order to identify potential bottleneck areas during an evacuation, the delay on selected network links at intervals were studied. The Analyzer module of PARAMICS was used to obtain the link delay values from the simulation outputs.

CHAPTER 4

ANALYSIS AND RESULTS

This chapter presents the analysis of the results obtained from simulation analysis. Travel time, delay and evacuation duration were used as measures of effectiveness (MOE) for evaluating the effectiveness of various contra-flow and evacuation response strategies.

4.1.Evacuation Demand Calculation

The evacuation demand was calculated using the participation rate method as explained in Chapter 3. Data from the US Census Bureau (2000) and the United States Army Corps of Engineers (USACE) Hurricane Restudy report were used to obtain values for variables in the participation rate equation. The traffic generated from each at-risk area was calculated using equation 4.1. An example computation of traffic generated from the Island of Palms area is demonstrated in the following Equation 4.1.

$$\text{Traffic Volume} = [(H \text{ X } v \text{ X } P_v) + (M \text{ X } P_m)] \text{ X } i \qquad \text{-Equation 4.1}$$

H -Number of households

v -Vehicles per household

P_m -Vehicular Participation Rate

P_v - Mobile home Participation Rate

M - Number of mobile homes

i -Growth Factor

$$= [(3875 \text{ X } 1.656 \text{ X } 0.675) + (6\text{X}1)] \text{ X } 1.1$$

$$= 2388 \text{ vehicles}$$

This volume is distributed equally between the normal and reversed lanes of I-26 as shown in Table 5. Table 5 displays the traffic volumes generated according to the area of origin. Each volume is calculated similar to the above example and the traffic volume is distributed according to the SCDOT evacuation route plan. In Scenarios One, Four and Seven, where one lane contra-flow strategy is used, the traffic volume generated from I - 526 West zone is evenly distributed between the normal and contra-flowed lanes of I-26 (Please refer to Chapter 3 for description of Scenario One through Twelve). This is done to prevent queue build up with overloading of the contra-flowed lane of I-26 west. Table 4.1 also shows the traffic volume assigned to the normal and reversed lanes of I-26.

Table 5 Evacuation volume on I-26

Originating area	Entering I-26 from	Traffic volume	Entering Normal/Reversed lanes of I-26
Mount Pleasant	US 17	6466	Reversed
Mount Pleasant	I 526 E	6466	Normal
Mount Pleasant	I-26	12931	Normal
Sullivan’s Island	US 17	491	Reversed
Sullivan’s Island	I 526 E	491	Normal
Isle of Palms	US 17	1194	Reversed
Isle of Palms	I 526 E	1194	Normal
James Island	I 526 W	8151	Reversed
James Island	I 526 W	9088	Normal
Folly Beach	I526 W	2200	Normal
Downtown Charleston	I-26	17239	Normal

Determination of Sample Size

The next step was to determine the number of required simulation runs. Assuming a normal distribution for travel time, the number of runs required was calculated using Equation 4.2.

$$N= (1.96\ \sigma)^2/E^2 \qquad \text{- Equation 4.2}$$

According to Equation 4.2, the number of simulation runs required was calculated for each scenario. Table 6 shows the mean, variance, standard deviation and margin of error for three runs of scenario one, i.e., using one lane contra-flowed outbound and all normal outbound lanes with long response policy. These values were used to determine the number of runs required to maintain a 95% confidence interval.

Table 6 Sample Size Calculation for Scenario One

Mean VHT for Scenario 1	Variance	SD (σ)	Margin of error (E)	% of mean	Sample Size
158398.44	-	-	-	-	1
158262.89	36747.60	191.70	265.68	0.17%	2
158578.38	316969.31	563.00	637.09	0.40%	3

After conducting similar calculations for all contra-flow and do-nothing scenarios, it was determined that 36 simulation runs were to be executed for this project.

4.2.Simulation Results

Figure 11 displays the eighteen scenarios tested in this study. The results of these scenarios are discussed in the following section.

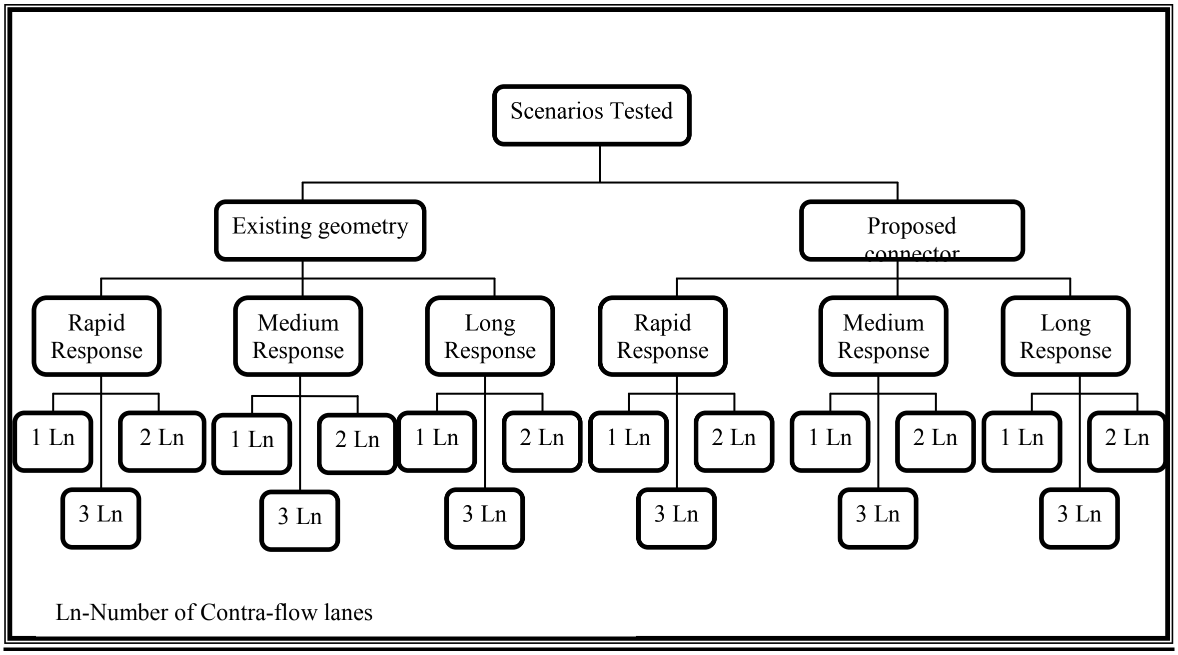


Figure 11 Scenarios Tested

The simulations were run for varying lengths based on the evacuation duration or the time required for all vehicles to exit the network. Table 7 shows the results obtained for evacuation Scenario 1, which constitutes using one reversed lane and normal outbound 3-lane operation assuming long behavioral response.

Table 7 Simulation Results for Scenario 1

Scenario 1 Long Response	Evacuation duration (hours)	Average travel time (sec)	Number of evacuating vehicles	Mean vehicle speed (mph)	Vehicle Miles Traveled (miles)	Vehicle Hours Traveled (hours)
Run 1	19:34	8,636.5	66,026	4.6	732,903	158,398
Run 2	19:29	8,607.3	66,137	4.6	734,212	158,127
Run 3	19:38	8,699	65,886	4.6	731,366	159,209
Mean values	19:38	8,647.6	66,016.33	4.6	732,827.16	158,578.38

The travel time is averaged over the entire network and entire evacuation duration. Delays due to queue build up during the evacuation are included thusly providing a good estimate of the overall situation.

4.3. Existing Road Geometry

The following section analyzes the simulation results of modeling the contra-flow strategies in combination with the response types on the existing evacuation routes as designed by the SCDOT.

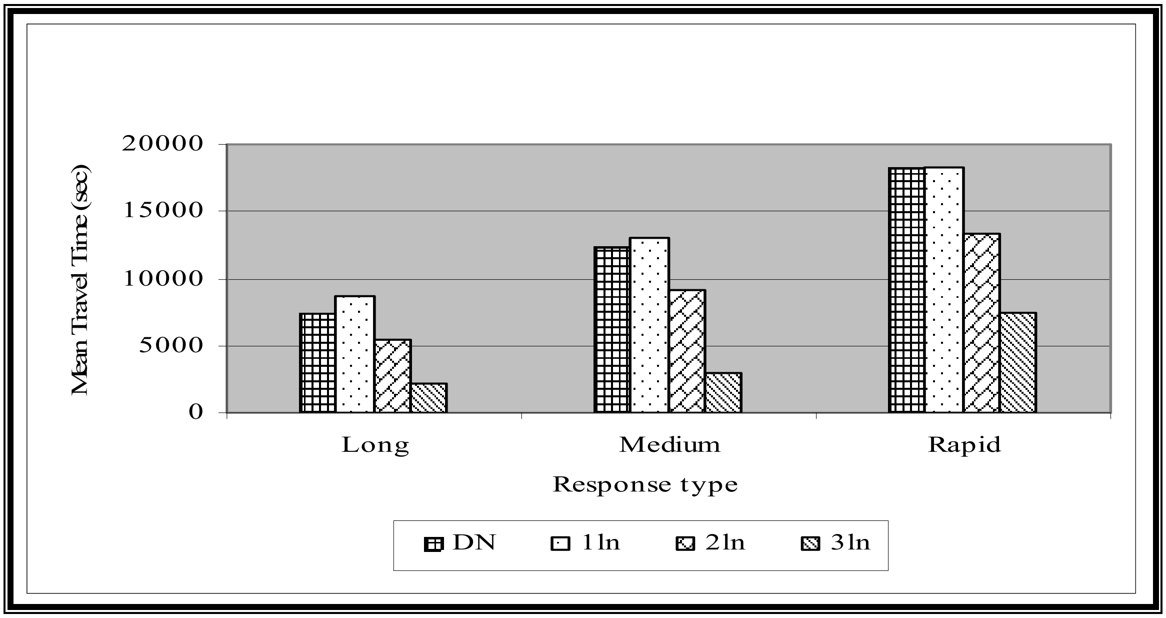


Figure 12 Mean Travel Time by Response Type (Existing)

The Figure 12 compares the mean travel time for Do Nothing, 1 lane, 2 lanes and 3 lanes contra-flow for different response types. Tables A-1 to A-12 display the simulation results as data tables. As shown in Figure 11, Do Nothing and one-lane contra-flow scenarios present very similar travel time value, with the one lane contra-flow travel time slightly lower during the long and medium response scenarios. Similar travel time between these two options is due to the large delay caused by congestion on the contra-flowing lane. Wolshon stated similar findings in a study (2001). Therefore, in order to ensure expedited evacuation, the 2 or 3 lanes contra-flow are preferable, however, full contra-flow operation may prevent emergency vehicles to enter devastated areas.

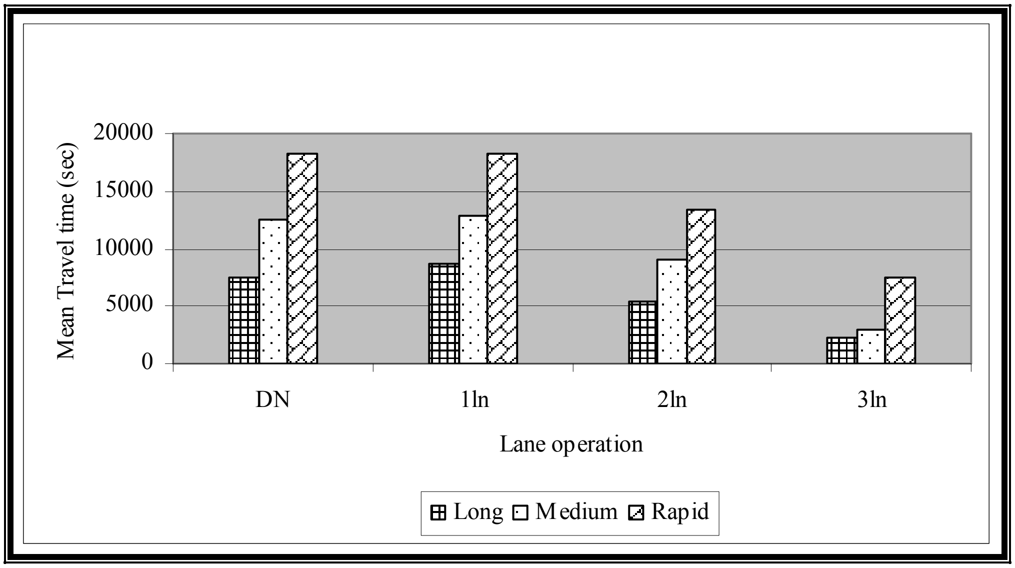


Figure 13 Mean Travel Time and Lane Operation (Existing)

Figure 13 shows the mean travel time for different contra-flow strategies with respect to long, medium and rapid response policies. Rapid response provided the highest travel time in each contra-flow lane operation scenarios. This is attributed to the higher traffic density caused by the greater traffic volume being evacuated within a shorter period compared to long and medium response policies. This demonstrates the importance of response policies on delay caused during evacuation.

Evacuation duration refers to the time required for all the evacuating vehicles to travel through the model. Although the evacuation demand is generated over a 11 hour period for long response, the congestion delays the evacuation duration by over 9 hours, for scenario one with one lane contra-flow and long response.

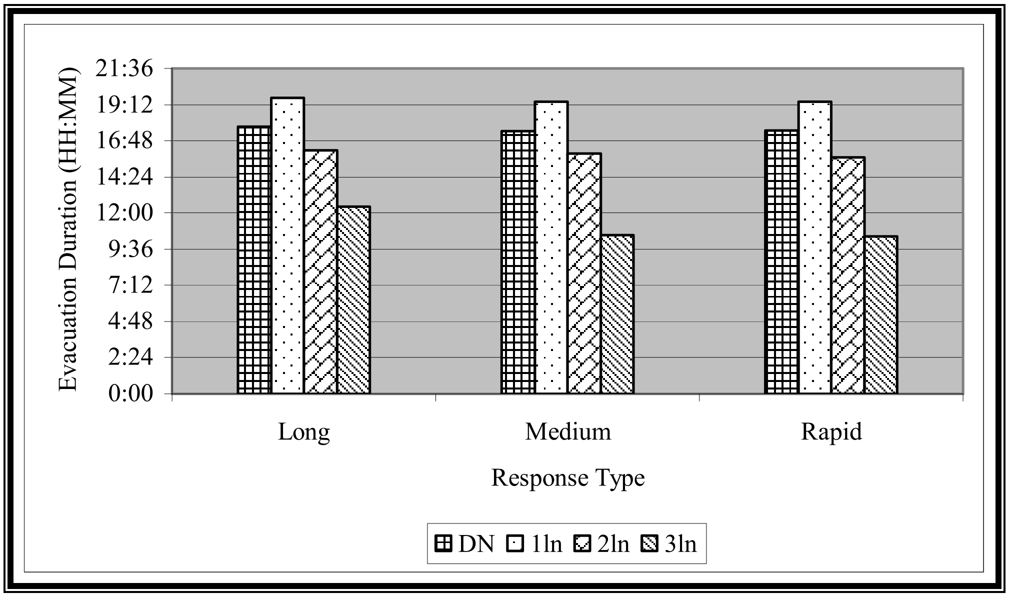


Figure 14 Evacuation Duration by Response Type (Existing)

Figure 14 compares the evacuation duration for long, medium and rapid response policies. As shown in Figure 14, using Scenario 1, which is normal outbound lanes and one contra-flowing lane, is the most prolonged procedure, varying between 19 to 20 hours for long, medium and rapid responses. This extended time is due to congestion on the contra-flowed lane due to its insufficient roadway capacity. As shown in Figure 13, with a rapid response policy in place, the evacuation will require at least 10 hours and 25 minutes with three lanes contra-flowed. This finding is indicative of a relationship between the response time and the evacuation duration, which is further analyzed later in the chapter. This information can aid in selecting suitable traffic management strategies to meet evacuation demand during a hurricane threat.

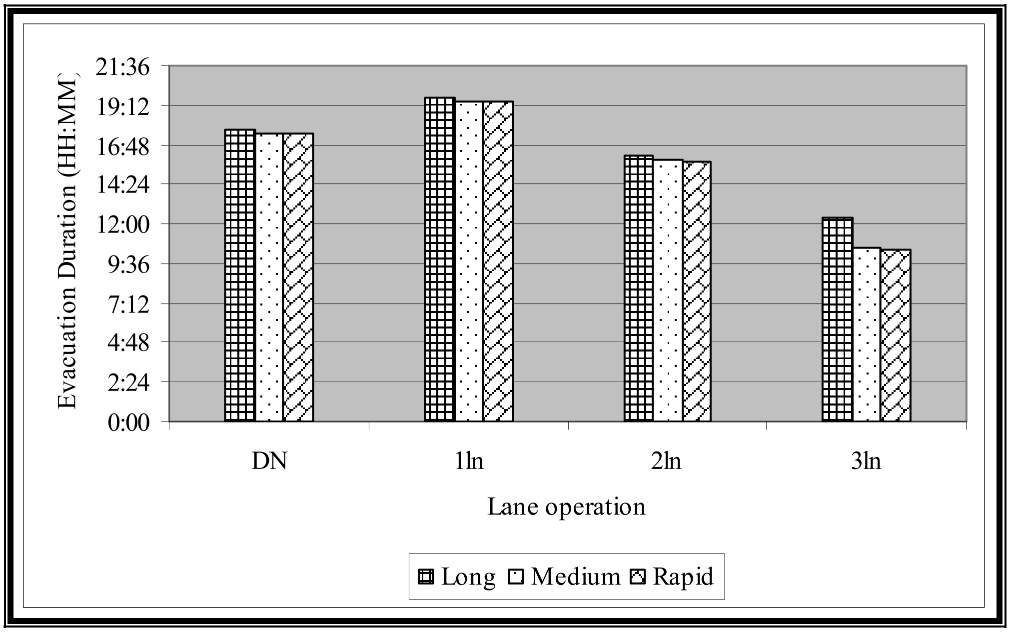


Figure 15 Evacuation Duration by Lane Operation (Existing)

Figure 15 shows the evacuation duration against the four lane operation strategies. As shown in Figure 15, the evacuation duration does not vary significantly between the response policies for each contra-flow strategy.

4.4.Proposed Connector

The next step in the analysis was to determine the travel time and evacuation duration benefits of the proposed connector. This section compares the simulation results of modeling the three contra-flow strategies in combination with the three response types. These values are compared against the normal flow do-nothing scenarios and contra-flow scenarios with the existing roadway geometry.

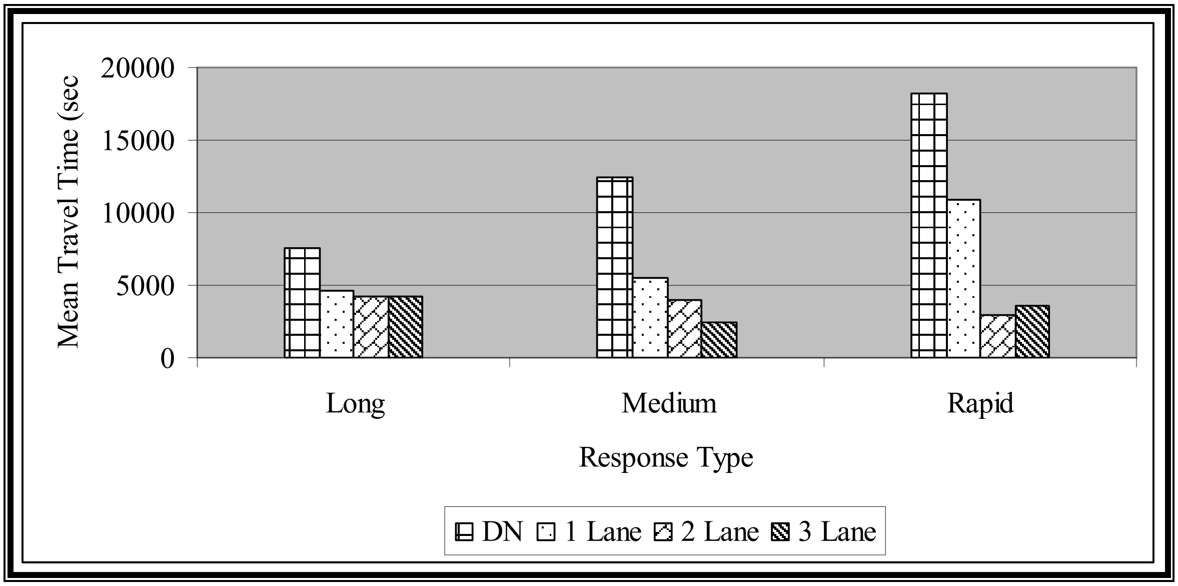


Figure 16 Mean Travel Time by Response Type (Proposed)

Figure 16 displays the simulation results for the contra-flow strategies modeled with the proposed road connector. Tables A-13 to A-21 display the simulation results as data tables The three contra-flow strategies are compared with the normal flow or do-nothing scenario represented by 'DN'. The enormous reduction in mean travel time is obvious from Figure 16. The mean travel time is reduced up to 23% in the two-lane contra-flow assuming a rapid response. This benefit is tremendous considering the small changes in road geometry. It is observed that mean travel time is not considerably different between the two-lane and three-lane contra-flow strategies; this information is useful when there is a need for an inbound lane to remain open.

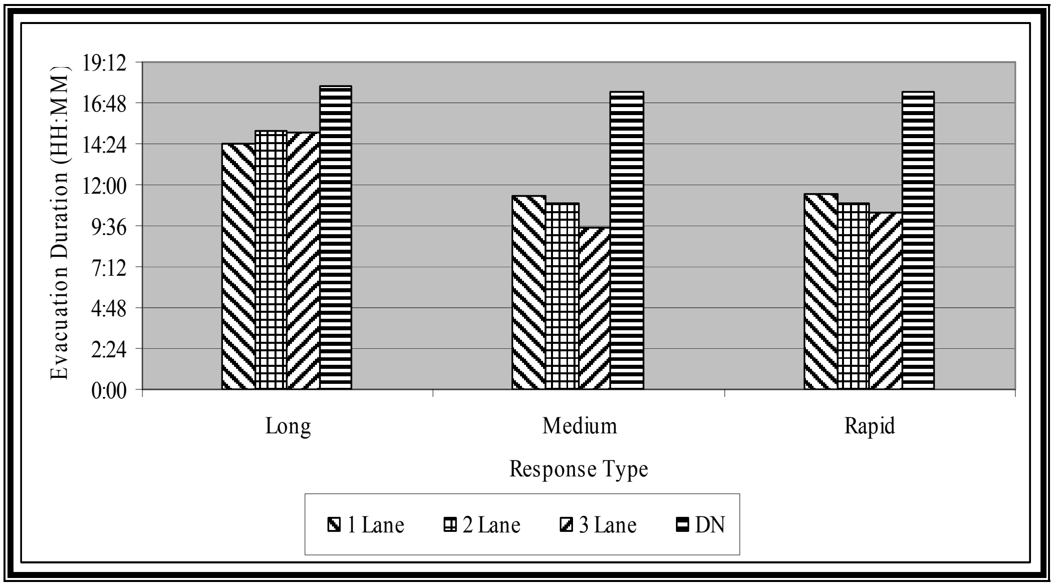


Figure 17 Evacuation Duration by Response Type (Proposed)

Figure 17 displays evacuation duration for each lane operation strategy according to response type with the addition of the proposed roadway connector. As expected, the normal flow scenario presents the highest evacuation duration which is 2-8 hours more than the contra-flow scenarios. As observed in Figure 11 the existing roadway geometry presents higher evacuation duration than with the proposed connector as shown in Figure 17. The maximum delay savings is observed for the one-lane contra-flow scenarios, the reduction in evacuation duration ranges from 5-8 hours.

4.5. Statistical Analysis of Simulation Results

A statistical analysis was conducted on the mean travel time obtained for each scenario. The Factorial Effects Model for a two-factor factorial experiment was used in this study as given in Equation 4.3. The two factors used in this study are the lane operation strategy (0, 1, 2, or 3 lane contra-flow) and the response policies (long, medium, and rapid).

$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{ijk}$ -Equation 4.3

Where,

$\mu_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij}$
μ_{ij} -cell mean
α - Response
β - Lane
$\alpha\beta$ -Interaction term between the two factors α and β

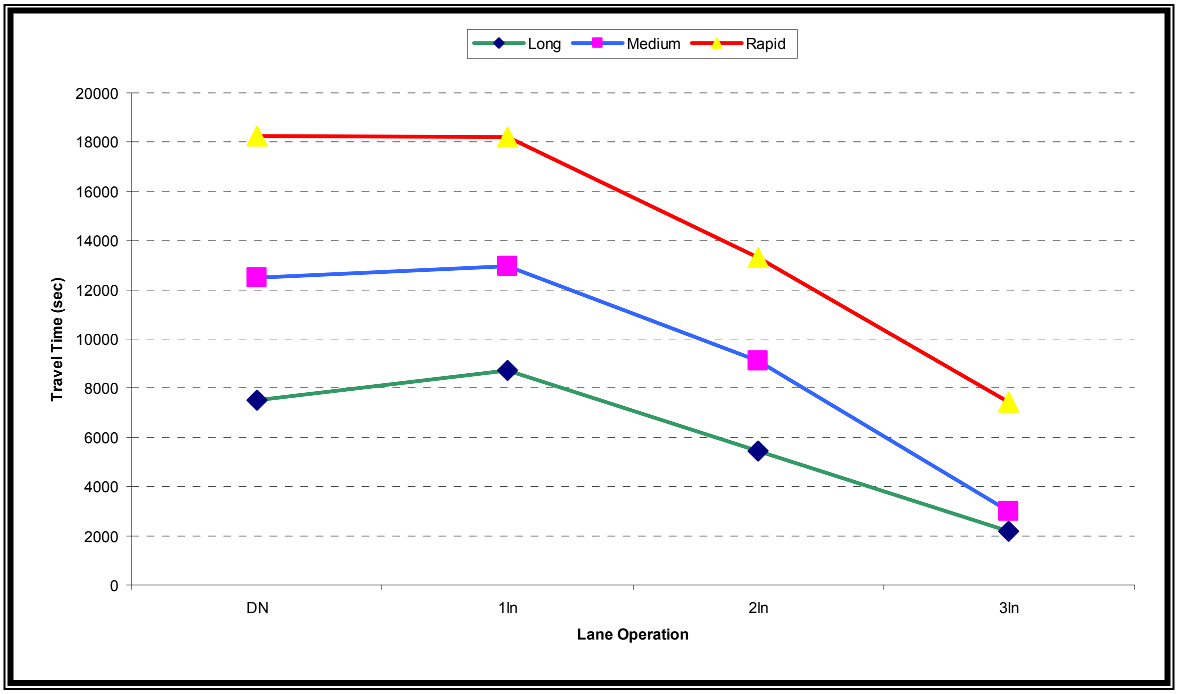


Figure 18 Profile Plots of Travel Time Means and Lane Operation

The profile plot of travel time means, under different lane operation and response type strategies is shown in Figure 18. The three lines are almost parallel to each other, which indicate a general trend of response time for different contra-flow options considered in this study. Additionally, a two-factor ANOVA analysis was conducted using Statistical Analysis Software (SAS) to analyze the trend in more detail. The two factors used are response policies, represented by variable ‘Response’ and number of reversed lanes, represented by variable ‘Lane’.

Test I

The author conducted a hypothesis test to determine if there is an interaction between response policies and lane operation. The SAS program is displayed in Appendix A The SAS output for the hypothesis test is displayed as Table 4.4. The results of the test revealed that there is an interaction between response policies and the number of lanes reversed. This conclusion gives rise to a number of possibilities, which are further examined using additional statistical analyses.

Table 8 SAS Output: The Mixed Procedure-Type 3 Tests of Fixed Effects

Effect	DF	DF	F Value	Pr>F
Response	2	24	7883.86	<0.0001
Lane	3	24	5862.18	<0.0001
Response * Lane	6	24	176.11	<0.0001

Test II

Since response policies and number of lanes reversed are correlated, the author evaluated the actual effect of response strategy on number of lane reversal. A test was conducted by varying the lane contra-flow strategies with each response policy to determine the effect of varying the number of reversed lanes for each response strategy. Table 8 displays the results of this test.

Table 9 Results of Statistical Test comparing number of lanes reversed with response policies

Response Time	Numerator Degree of Freedom	Denominator Degree of Freedom	Critical Value: F_{obs}	P-value	Decision
L	3	24	904.93	<.0001	Reject
M	3	24	2385.08	<.0001	Reject
R	3	24	2924.39	<.0001	Reject

The analysis provided sufficient evidence that there is a significant difference in the travel time for varying the number of reversed lanes for each response policy. This finding indicates that the number of lanes contra-flowed will always impact travel time no matter which response strategy is undertaken.

Test III

The next statistical analysis conducted was to determine if travel time differs with varying response time for each 0, 1, 2 and 3 reversed lane options. and which configuration presents the lowest travel time. Table 9 displays the statistical analysis results for this test.

Table 10 Statistical test results comparing response strategies with lane reversal options

Number of Reversed La	Numerator Degree of Freedom	Denumerator Degree of Freedom	Critical Value: F_{obs}	P-value	Decision
0	2	24	3219.07	<.0001	Reject
1	2	24	2549.49	<.0001	Reject
2	2	24	1733.88	<.0001	Reject
3	2	24	909.75	<.0001	Reject

The results provide sufficient evidence to conclude that there is a variation in the travel time due to different response time when using each 0, 1, 2, and 3 reversed lane(s) options. This finding suggests that travel time will always be impacted with different response policies no matter with lane reversal option is selected.

4.6.Identifying Bottlenecks

Twenty-four links at 1 mile intervals were selected on the network. The delays on these links were analyzed to identify possible bottlenecks in the system during evacuation. The total network delay over the entire evacuation duration is graphically represented in Figure 20. The higher delay points indicate bottleneck areas. There are three such links with significant delays. They occur near exit ramps or at points where lanes merge.

Figure 19 displays the possible bottleneck areas during full contra-flow operation. The bottleneck areas observed during full contra-flow operation is different from the bottlenecks created during two-lane and one-lane reversal. The major bottleneck area in this case lies immediately after Exit 209 A. This is an area where the number of lanes is reduced due to merging. The area before the Exit 209 A also shows higher delay, which is due to the downstream shock wave. The link numbers in Figure 19 corresponds to the numbers in Figure 20, where their field locations are shown.

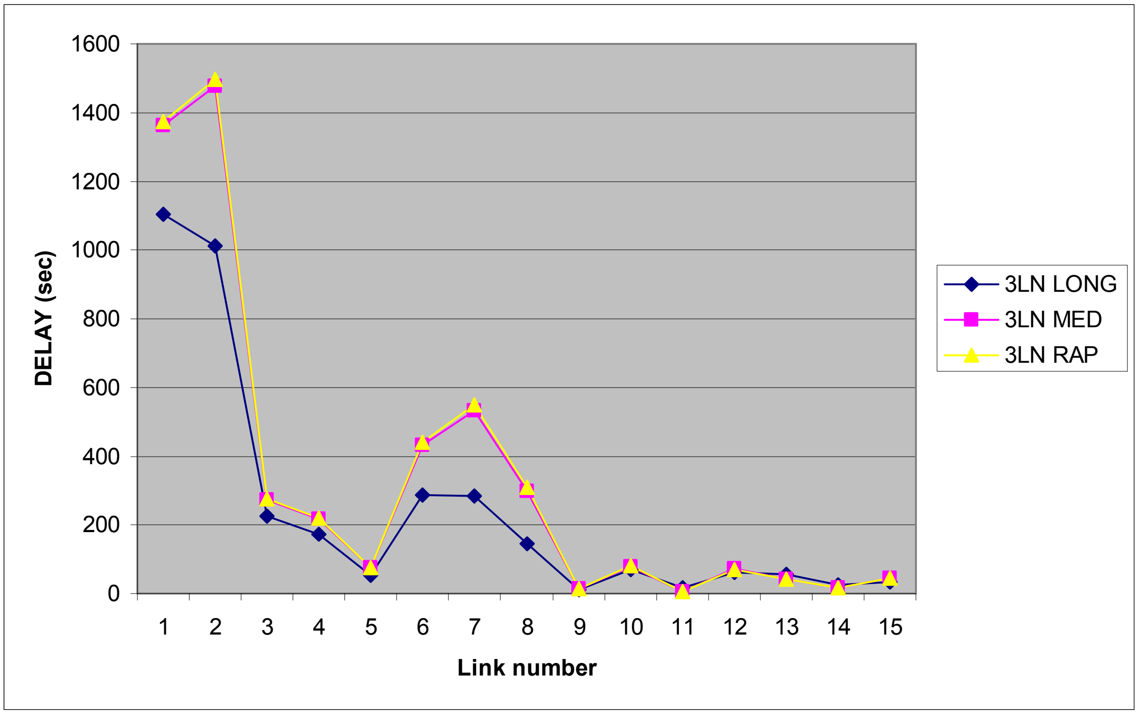


Figure 19 Bottlenecks with 3-Lane Contra-flow Operation

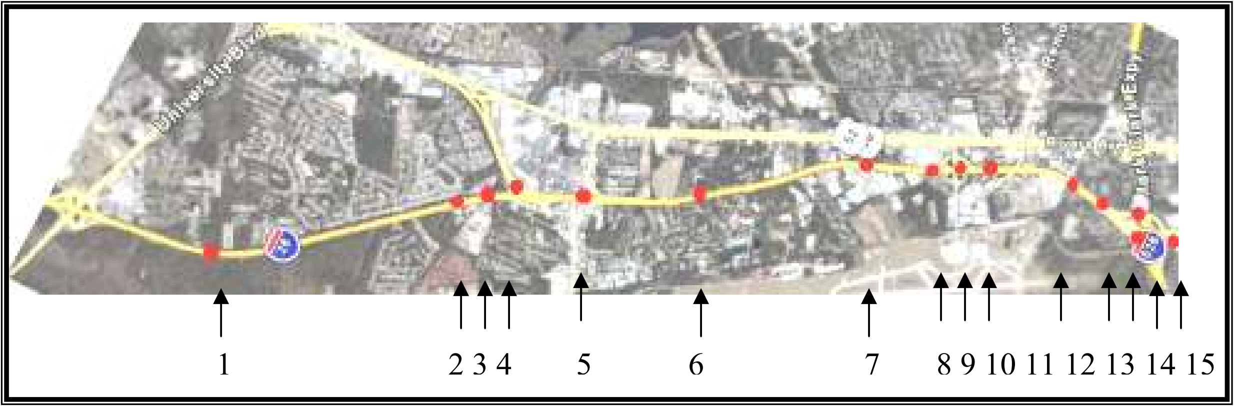


Figure 20 Key showing Link Locations

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1.Conclusions

During the approach of Hurricane Floyd, public agencies experienced enormous traffic problems while trying to evacuate the at-risk population from Charleston. One of the primary problems was caused due to the absence of any prior traffic planning and a resultant failure to accommodate the huge increase in traffic demand on the main evacuation route, which is I-26 West. SCDOT's current plan involves a contra-flow of traffic for the use of all six lanes of I-26 during evacuation. This study evaluated two geometric layouts; the existing evacuation layout, and a proposed design with an additional ramp for evacuating traffic from Charleston using 1-26. For each condition, three contra-flow strategies, and three mobilization response types were tested. This study employed the microscopic traffic simulation tool PARAMICS to provide a decision support tool for use in this traffic evacuation.

Simulation analysis revealed that the proposed design presents lower travel time than the existing geometric layout. Long, medium and rapid response strategies display similar evacuation duration for both existing and proposed designs. However, long and medium responses exhibited faster travel time than rapid response, with long response allowing vehicles to travel almost 58-70% faster.

In the existing design, the use of three-lane contraflow reduces travel time up to 76% for a three lane medium response evacuation, also allows vehicles to travel at speeds three times higher than the “do nothing” scenario. Total evacuation time is reduced upwards of 40 % when using three-lane contraflow in comparison with the do nothing scenario.

The scenarios that present the maximum savings in evacuation duration is the two-lane medium response type for the proposed road connector. The findings indicate that next best scenario is the full contraflow operation under rapid response for the proposed connector. The duration increases by approximately 54 minutes for this scenario. The minimum travel time for the existing and proposed road geometry scenarios differ by barely five minutes. However, overall each scenario presents a lower travel time than for the existing network.

The research found that earlier identification of the evacuation needs and informing decision makers earlier in the process significantly reduced evacuation times out of the threatened area. As expected, three-lane contra-flow provided the minimum delay, although it was found that it was necessary to leave one lane open for in-bound traffic such as emergency vehicles. Still, contra flow reduced to two-lanes was also an optimal choice as it still reduced delays by 27%.

5.2.Recommendations

The author recommends the following:

- SCDOT should use the results of this study as an input to revise their plans regarding traffic distribution between contra-flow and normal lanes.

- SCDOT should perform additional simulation to identify the optimal distribution of traffic between normal and contra-flow lanes.
- SCDOT should perform periodic evaluations of the evacuation strategies as changes in the population distribution between different areas in Charleston will affect the impacts of selected strategies.
- Future research should evaluate other traffic management strategies, such as the use of the shoulder as a traffic lane, and different evacuation plans, such as a phased evacuation strategy.

APPENDIX

Table 11 Long Response One-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-1 lane	19:34	8636.5	158398	158398				
2	19:29	8607.3	158127	158263	36747.60499	191.7	265.678	0.17%
3	19:38	8699	159209	158578	316969.313	563	637.0948	0.40%
4	19:32	8647.9	157889	158406	329991.977	574.4	562.9603	0.36%
5	19:46	8904.4	163247	159374	4934283.932	2221	1947.077	1.22%
6	19:50	8906.2	163470	160057	6743889.231	2597	2077.953	1.30%
Mean values	19:38	8733.55	160057					

Table 12 Long Response Two-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-2 lane	16:14	5516.5	100755	100755				
2	16:05	5389.2	98340	99548	2917295.97	1708	2367.18	2.38%
3	16:12	5468	100346	99814	1671392.392	1293	1462.967	1.47%
4	16:07	5386	98480	99480	1559172.828	1249	1223.695	1.23%
5	16:08	5421.4	98860	99356	1246303.027	1116	978.5497	0.98%
6	16:15	5497	100880	99610	1383884.464	1176	941.305	0.94%
Mean values	16:10	5446.35	99610					

Table 13 Long Response Three-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-3 lane	12:28	2221.5	40736	40736				
2	12:25	2148.9	39298	40017	1033116.877	1016	1408.691	3.52%
3	12:28	2196.6	40376	40137	559502.02	748	846.4402	2.11%
4	12:27	2195	40193	40151	373778.5482	611.4	599.1468	1.49%
5	12:21	2152.7	39286	39978	429779.1628	655.6	574.6372	1.44%
6	12:28	2213.6	40651	40090	419255.8725	647.5	518.1077	1.29%
Mean values	12:26	2188.05	40090					

Table 14 Long Response Do Nothing (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-DN	17:43	7451.8	163090	163090				
2	17:42	7619.9	167225	165157	8545887.504	2923	4051.536	2.45%
3	17:42	7553.1	165841	165385	4428781.773	2104	2381.429	1.44%
4	17:51	7387.4	161546	164426	6637993.24	2576	2524.902	1.54%
Mean values	17:44	7503.05	164426					

Table 15 Medium Response One-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Medium-1lane	19:27	13063.8	238998.5	170723.9				
2	19:26	13083.2	239523.6	131882.1	137859.75	371.2947	514.5882	0.39%
3	19:21	12835.4	234217	130807.1	8549692.9	2923.986	3308.801	2.53%
4	19:36	13098.2	239857.9	130756	6997321.3	2645.245	2592.34	1.98%
5	19:10	12704.6	232921.9	207513	10713081	3273.084	2868.985	1.38%
6	19:20	12898.2	235595.9	281740.5	8949405	2991.556	2393.743	0.85%
Mean values	19:23	12947.23	236852.5					

Table 16 Medium Response Two-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Medium-2 lane	15:55	9127.8	167139	167139				
2	15:58	9121.5	166972	167055.5	13952.851	118.1222	163.709	0.10%
3	16:00	9129.8	167215.6	167108.8	15519.895	124.5789	140.9743	0.08%
4	15:50	9041.9	165176.1	166625.7	944207.91	971.7036	952.2695	0.57%
5	16:07	9330.8	171621.1	167624.8	5699105	2387.28	2092.543	1.25%
6	15:50	8958.2	163885.6	167001.6	6889443.8	2624.775	2100.257	1.26%
Mean values	15:56	9118.333	167001.6					

Table 17 Medium Response Three-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Medium-3 lane	10:38	3035	55886.03	55886.03				
2	10:31	2959.7	54155.12	55020.58	1498024.7	1223.938	1696.292	3.08%
3	10:25	2926.6	53485.11	54508.75	1534896.6	1238.909	1401.958	2.57%
4	10:36	3087.1	56737.24	55065.88	2264802.6	1504.926	1474.828	2.68%
5	10:28	2952.6	54061.3	54864.96	1900436.1	1378.563	1208.364	2.20%
6	10:29	2952	53954.76	54713.26	1658426.3	1287.799	1030.454	1.88%
Mean values	10:31	2985.5	54713.26					

Table 18 Medium Response Do Nothing (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-DN	17:27	12235.4	268019	194383.3				
2	17:30	12162.4	265336.4	555370.5	3598198.2	1896.892	2628.958	0.47%
3	17:21	13042	286363.3	520048.4	130972529	11444.32	12950.47	2.49%
Mean values	17:26	12479.93	273239.6					

Table 19 Rapid Response One-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Rapid-1 lane	19:26	18274.2	335819.2	135757.3				
2	19:09	17962.2	328878.61	136068.1	193261.7	439.6154	609.2758	0.45%
3	19:25	18272	335093.98	136496.5	647120.6	804.438	910.3073	0.67%
4	19:20	18131.9	332942.39	136120.9	995850.4	997.923	977.9646	0.72%
5	19:36	18481.7	338318.17	136033.5	785082.4	886.0488	776.656	0.57%
Mean values	19:23	18224.4	334210.47					

Table 20 Rapid Response Two-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Rapid-2 lane	15:46	13332.5	244314.97	244315				
2	15:37	13201.6	241710.1	243012.5	3392674	1841.921	2552.773	1.05%
3	15:46	13409.5	245639.41	243888.2	3996494	1999.123	2262.221	0.93%
Mean values	15:43	13314.53	243888.16					

Table 21 Rapid Response Three-Lane Contra-flow (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Rapid-3 lane	10:24	7438.3	135757.28	116852.7				
2	10:27	7459.1	136378.99	163741.1	193261.7	439.6154	609.2758	0.37%
3	10:29	7502	137353.23	182003.3	647120.6	804.438	910.3073	0.50%
4	10:21	7380.9	134993.92	214192.4	995850.4	997.923	977.9646	0.46%
5	10:26	7420.7	135683.85	229992.3	785082.4	886.0488	776.656	0.34%
6	10:26	7468.3	136504.19	236518.3	664998	815.4741	652.5152	0.28%
Mean values	10:25	7444.88	136111.91					

Table 22 Rapid Response Do Nothing (Existing)

Scenario	Time of exit of last vehicle from network	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-DN	17:32	18282.4	399779.82	194383.3				
2	17:15	18209.8	398000.8	593157.7	1582456	1257.957	1743.44	0.29%
3	17:41	18239.6	398617.31	3412247	816071	903.3665	1022.255	0.03%
Mean values	17:29	18243.93	398799.31					

Table 23 Long Response One-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-1ln	14:18	4521	82601.65	82601.65				
2	14:18	4515.7	82833.59	82717.62	26898.08	164.0063	227.3012	0.27%
3	14:32	4627.3	84470.25	83301.83	1037353	1018.505	1152.547	1.38%
Mean	14:22	4554.67	83301.83					

Table 24 Long Response Two-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-2ln	15:10	4282.9	78872.14	78872.14				
2	15:21	4342.6	80278.25	79575.2	988572.7	994.2699	1377.988	1.73%
3	15:02	4199.1	76852	78667.46	2966217	1722.271	1948.933	2.48%
Mean	15:11	4274.87	78667.46					

Table 25 Long Response Three-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Long-3ln	15:02	4167.3	76338.48	76338.48				
2	15:06	4139	75844.37	76091.43	122072.3	349.3885	484.2278	0.64%
3	15:06	4203.6	77246.27	76476.37	505591.8	711.0498	804.6286	1.05%
Mean	15:04	4169.97	76476.37					

Table 26 Medium Response One-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Medium-1ln	11:22	5582.3	102033.6	102033.6				
2	11:23	5559.8	101639.5	101836.6	77653.46	278.6637	386.2082	0.38%
3	11:24	5563.5	101987.4	101886.9	46410.46	215.4309	243.783	0.24%
Mean	11:23	5568.53	101886.85					

Table 27 Medium Response Two-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Medium-2ln	10:54	4069.8	74818.19	74818.19				
2	10:58	4079	74513.35	74665.77	46463.71	215.5544	298.7432	0.40%
3	10:46	3920.1	71586.7	73639.41	3183456	1784.224	2019.04	2.74%
Mean	10:52	4022.97	73639.41					

Table 28 Medium Response Three-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Medium-3ln	9:28	2523.7	46264.76	46264.76				
2	9:29	2454.7	44849.15	45556.96	1001976	1000.987	1387.298	3.05%
3	9:29	2473.4	45272.9	45462.27	527883.7	726.556	822.1755	1.81%
Mean	9:28	2483.93	45462.27					

Table 29 Rapid Response One-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Rapid-1ln	11:21	10904.4	199211.6	199211.6				
2	11:25	10956	200668	199939.8	1060594	1029.852	1427.301	0.71%
3	11:28	10951	200722.2	200200.6	734318.3	856.9238	969.7005	0.48%
Mean	11:24	10937.13	200200.61					

Table 30 Rapid Response Two-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Rapid-2ln	10:52	4034.5	74001.16	74001.16				
2	10:53	4008.2	73306.43	73653.8	241324.9	491.2483	680.8354	0.92%
3	10:52	995.6	73157.75	73488.45	202682.7	450.2029	509.4525	0.69%
Mean	10:52	3012.77	73488.45					

Table 31 Rapid Response Three-Lane Contra-flow (Proposed)

Scenario	Evacuation duration	Average travel time	VHT	Mean	Variance	SD	Margin of error	% of mean
Rapid-3ln	10:22	3551.8	65156.15	65156.15				
2	10:19	3443.5	62867.67	64011.91	2618570	1618.2	2242.71	3.50%
3	10:33	3624.6	66613.55	64879.12	3565462	1888.243	2136.748	3.29%
Mean	10:24	3539.97	64879.12					

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