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**Assessment of Evacuation Network Performance Under Different Evacuation Scenarios  
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## **Abstract**

The goal of this research is to better understand the evacuation of a coastal community, the Florida Keys. This will aid in the planning, mitigation, response, and recovery of this community when a hurricane threatens to destroy their homes. To achieve this, a model of the Florida Keys was built in VISSIM, a microscopic traffic flow simulation software, to experiment with different improvement strategies. This process will include collecting data about the Florida Keys, building the roadway network of the Florida Keys, calibrating and validating the model, modeling recommendations, and analyzing the outputs when imploring the different improvement strategies. In addition to the current evacuation plan, evacuation by zone, the following strategies were modeled: flashing yellow signals, conflict elimination, contraflow, and emergency shoulder use. From this, it was determined that the modifications to the intersections with traffic control devices – flashing yellow signals and conflict elimination, did not drastically alter the evacuation process. Adding travel lanes reduced delay and the travel time for both individual vehicles and the entire population. Ultimately, it was determined that emergency shoulder use would be the most effective recommendation to implement.

## 1. Introduction

Every year, it is expected that \$54 billion is lost due to destruction caused by hurricanes and the flooding that often accompanies these storms (Congress of the United States, 2019). In 2019, 82,697,827 people were affected by hurricanes in the United States and its territories (US Census Bureau, 2019). These storms not only have a financial impact, but these citizens of these coastal areas spend a significant amount of time preparing for these storms, evacuating to be out of harm's way, waiting the storm out, for utilities to be restored, returning to their home, and finally cleaning up and repairing the damages. This process can take more than a week depending on storm speed, travel time to evacuation shelter, and duration of flooding and rain after the actual storm passes. Schools, from colleges to local elementary schools, are shut down, grocery stores are closed, and residents are asked to stay home. Because of this, hurricanes and their associated evacuations can be drawn out processes.

Evacuations have been a part of life since the beginning of time. In the first century, the city of Pompeii was evacuated due to the eruption of Mount Vesuvius. From the beginning to the end of 1900s, people were fleeing from war zones. The twentieth century concluded with Hurricane Floyd and three million people moving away from the coast and path of the storm. In the 2000's, evacuation orders were issues for Hurricane Frances, Katrina, Rita, and Gustav. In September 2017, at least 700,000 people evacuated from Florida, Georgia, and South Carolina due to Hurricane Irma. Most recently, people have been evacuating from wildfires in the western United States and Canada. Although evacuations are nothing new, little progress has been made in improving their efficiency.

When Hurricane Katrina hit the city of New Orleans, about 100,000 people were stuck inside the city after the storm due to the congestion that still existed on the highways exiting the cities (Sullivan, 2005). Hurricane Irma, the "most powerful Atlantic Ocean hurricane in recorded history" caused almost 7 million people in Florida, Georgia, and South Carolina to evacuate from their home (Florida Association of Counties, 2017). Obviously, this caused very large traffic jams on the main north-south highways in the southern part of the United States. Miami International Airport saw a 30% increase in the number of flights the Thursday before the storm hit (Florida Association of Counties, 2017). The evacuation process overloads the transportation system, leaving very little option other than sitting and waiting for the vehicles further north to move and letting the queue dissipate.

The Florida Keys is an archipelago consisting of many, small islands off the southeast coast of Florida. As of the 2010 Census, the population of this area is approximately 73,043. The evacuation process is critical in coastal, densely populated areas because nearly every member of the community is required to evacuate and use the same transportation facilities. These facilities were not designed to handle the entire area's population. This problem is magnified even further in the Florida Keys because there is only one road, US-1, that connects all the islands and provides access to the mainland. This creates a significant problem because all 73,043 of these people must use the same road and exit point. In addition to this, when US-1 returns to mainland Florida, the outlet is in Miami-Dade County, which is another densely populated area that has evacuation struggles of its own. Residents of the Florida Keys must be especially cautious

when creating their evacuation timeline to make sure they are not still stuck in traffic when the hurricane hits.

The fall 2017 evacuation due to Hurricane Irma is often referenced as the largest evacuation in the history of the United States. 6.5 million of Florida's residents were placed under mandatory or voluntary evacuation orders (Marshall, 2019). People took these orders and Hurricane Irma seriously for various reasons. First, Hurricane Irma had already destroyed many island communities including known deaths from the storm crashing into the U.S. Virgin Islands, Puerto Rico, and other various Caribbean islands (Savransky, 2017). In addition, this hurricane was the fifth strongest storm ever recorded in the Atlantic Ocean. So many residents of Florida had to evacuate because the "cone-of-uncertainty" was inclusive of most of the state of Florida. The storm's path predicted destructive storm surge to nearly all of Florida's coastal areas – the home to a majority of Florida's residents.

As mentioned above, one of the reasons so many Florida residents evacuated was due to the large cone of uncertainty. 67 hours before landfall, the National Hurricane Center predicted that Hurricane Irma would be Category 4 storm when it strikes southeast Florida and then continue up the eastern coast. 46 hours before landfall, the predicted path shifted to make initial landfall in the Florida Keys and then continue moving up the west coast of Florida (United States NOAA, 2017). Because of this uncertainty of the storm's path, it is thought that residents on both coasts of the state evacuated, creating one of the largest evacuations ever in the United States.

Hurricane Irma made landfall in the Florida Keys – near Cudjoe Key – on September 10, 2017 at approximately 9am as a Category 4 hurricane. Landfall on the mainland occurred later that afternoon, right before 4 pm, just south of Naples, FL as a Category 3 hurricane (Jansen, 2017). Hurricane Irma left 65% of homes – 6.7 million homes – in the state of Florida without power (O'Conner, 2017). 75 Floridians died from this storm and cost residents approximately \$49 billion (Wile, 2017). The lower Florida Keys were closed for 3 weeks following Hurricane Irma's initial landfall in their community (Associated Press, 2017).

Because of the unique geographical situation of the Florida Keys and the devastation that can occur in the Florida Keys, additional research needs to be completed to provide recommendations to the local emergency response teams for improvement in the evacuation process. The overall goal is to better understand the evacuation process in the Florida Keys, FL. This will be achieved by building a model of the Florida Keys and modeling various improvements. Analysis of network performance measures, clearance time, and vehicle emissions will be completed. This analysis will be used to determine feasible, effective recommendations for the local governments in the Florida Keys. This research seeks to better understand the evacuation process of Coastal and River Valley communities in the Florida Keys, FL and to assist in the planning, mitigation, response, recovery, and adaptation of these areas from disasters.

## **2. Research Background**

Prior research provides an exploration of many different aspects and parts of an evacuation and the analysis completed to understand this process. The research included varies

by source and date of publication to ensure a variation of information and ideal is included. The following topics will be presented throughout this literature review: Basics of Evacuations, Evacuation Modeling and Decision Analysis, Explanation of Assumptions and Methodology, Recommendations for Network Improvement, and Hurricane Evacuations and the Environment.

## **2.1 Basics of Evacuations**

Hurricane evacuations are an often studies topic, so significant amounts of research has been conducted. This section provides a discussion on critical points for analysis during emergency scenarios, the operations of roadways during evacuations, and the roadway conditions that affect the evacuation. These are all important topics to discuss and consider when conducting research on hurricane evacuations and help readers better understand these traffic phenomena.

Coastal communities face many different threats including sea-level rise, severe weather, and climate change. To overcome these events, communities hope to become resilient, which is defined as “a community’s ability to prepare and plan for, absorb, recover from and adapt to stressors from acute and longer-term adverse events” (Evacuation Behavior and its Mobility Impacts in Coastal Communities from Across the Nation). Orderly evacuations help these communities overcome the negatives of these unpredictable events. Evacuations help “to prevent injury and loss of life and to mitigate property damage” (Evacuation Behavior and its Mobility Impacts in Coastal Communities from Across the Nation). The relationship for evacuees between time and space provide an understanding of the movement of people and their vehicle’s during an evacuation. This project focuses on the travel flow principles that govern the evacuation process and the impact this has on the community. From this information, better plans can be made, and resources can be used to provide a safe and efficient movement of the community’s people and goods. The goal of this paper is similar: to provide recommendations to the improve the evacuation procedure in the Florida Keys.

Researchers from University of South Florida are using big data to “investigate in detail evacuation operations undertaken during Hurricane Irma in FL (2017) and the Woolsey Fire in CA (2018) to analyze temporal and spatial traffic patterns and assess the performance of the transportation network” (Menon et al., 2020). The goal of this research is to establish a baseline of evacuation traffic patterns including major roads with heavy gridlock, locations of bottlenecks and places of low travel speed and the associated high travel time. This will help emergency managers by providing them with the necessary traffic information prior to deciding to issue an emergency evacuation. This study, which was published in 2020, is very timely due to the California wildfires and the intensification of hurricane season that is predicted in the coming years for Florida. This increased intensity and frequency of Florida is one of the reasons the study of the Florida Keys is crucial. In this paper, a baseline will be determined, and recommendations will be provided.

The bottlenecks and slow speed make the evacuations take a long amount of time for vehicles to be running and burning fuel. Because of this, most evacuees attempt to fill their car with gas prior to leaving, causing gas stations to have run out of gas and a fuel shortage. This is

compounded with the need for gasoline to get goods and supplies into the disaster area. The Center for Advanced Transportation Mobility is managing a project that's goal is to create a predictive model of these fuel shortages during a hurricane and its associated evacuation. This model will include, "Compartmental stochastic epidemic spread model for fuel shortages at city and state level, traffic data from past hurricanes (e.g. Irma and Florence), combined with a Monte Carlo fuel consumption model to estimate fuel usage, agent based discrete event simulation model for detailed analysis, and policy analysis based on the above models" (Multiscale Model for Hurricane Evacuation and Fuel Shortage). Ultimately, the policy that is created will aid in getting evacuees the gas they need which provides a safe and efficient evacuation. Fuel plays a critical role in the evacuation process and is especially important in an area like the Florida Keys because there are a limited number of gas stations and no way for additional gasoline to arrive during the evacuation process due to the lack of route choice between the islands.

In addition to the fuel shortage, which can leave motorists stranded, there are other events that can occur that also keep evacuations from running smoothly. One of these is traffic incidents. The goal of this study is to assess the impact of traffic incidents in hurricane evacuations. This was achieved using "scenarios included from 35 to 48 traffic incidents with locations, rates, severities, and durations based on both historical values for peak period traffic and estimates based on total vehicle miles traveled per road segment" (Robinson et al., 2018). The findings of this study show that traffic accidents extend the travel time for individual vehicles but does not extend the overall time needed to clear the evacuation area. This is important to note because the model of the Florida Keys in this project will not include traffic accidents, but this should not alter the results too drastically.

These traffic incidents often cause bottlenecks which limit the network capacity and increase the travel time for evacuees. If the potential bottleneck areas are identified, the efficiency of the evacuation can be improved by reducing or even removing the bottlenecks. To identify the network bottlenecks, the following steps will be followed: "achieve traffic flow state updating and propagation based on the kinematic wave model, estimate the evacuation demand using a hurricane evacuation response curve, and finally identify the bottleneck links according to the mean and variance of the measurement of the degree of congestion" (Lu et al., 2017). This allows the travel time distribution for areas with a bottleneck to be analyzed. From this, recommendations can be made to improve the evacuation. In the model of the Florida Keys, location of bottlenecks will be identified, and recommendations will be chosen that help will help eliminate these bottlenecks.

Because of these bottlenecks and traffic accidents, the route evacuees choose to take can drastically change the travel time for an evacuee. Most evacuees often stay on primary roads and arterials but using the secondary and other low volume roads could provide an advantage. After the Hurricane Katrina evacuation, which had its challenges, "Louisiana transportation and state police officials developed a plan to achieve a maximum utilization of the state's highest capacity evacuation routes" (Wolshon & McArdle, 2011). Wolshon and McArdle hope to perform a similar analysis on the secondary and low volume roadways to determine how traffic was dispersed, how long impacts lasted, and the areas most highly affected. The results from this analysis found that "many Katrina evacuees used roads in the secondary system as their primary routes of egress

to far greater degrees than previously thought” (Wolshon & McArdle, 2011). These secondary roads were often used by evacuees that were traveling to destinations not easily accessible by the highway network. This is valuable information when modeling an area that has many routes to the destination. Evacuees from the Florida Keys only have one route option, which simplifies the model.

During a hurricane evacuation, not only do drivers pick non-regularly driven routes, but they drive in non-normal ways. The Highway Capacity Manual provides methods to determine the level of service and other measures of traffic flow under non-emergency conditions. But traveling during a hurricane evacuation is not a normal condition. This was proven using “data collected during Hurricanes Ivan (2004), Katrina (2005) and Gustav (2008) to compare traffic characteristics during mass evacuations with those observed during routine non-emergency operations” (Dixit & Wolshon, 2014). It was found that there is a “consistent and fundamental difference between traffic dynamics under evacuation conditions and those under routine non-emergency periods” (Dixit & Wolshon, 2014). Therefore, values that indicate the level of operation need to be measured in different ways. Wolshon and Dixit introduce two quantities: maximum evacuation flow rates (MEFR) and maximum sustainable evacuation flow rates (MSEFR). MEFR represents the true capacity of the road during a hurricane evacuation. This is important to note because a modeling software outputting a level of service based on the Highway Capacity Manual standards does not represent conditions accurately. It does still provide a quantitative value to rank different segments, but LOS A on a road under normal conditions is not the same as LOS A under emergency conditions. In both situations, LOS B on respective conditions is worse.

In addition, because the traffic dynamics are different, it is expected that driving behavior is altered during these emergency situations as well. “studies have shown how driving behavior during emergency evacuation is different from that under "normal" conditions” (Yuan et al., 2014). The problem with this is that there is a transition period, between normal conditions and traffic flowing under emergency conditions, that has not really been studied. This phase is complicated because “drivers receive evacuation information and instructions at different levels, which may induce heterogeneous behavioral driving response” (Yuan et al., 2014). This research uses a new open-source microscopic simulation platform where driver characteristics and behavior can be specified and is influenced by the traffic management strategies used. From various simulations of this model, it was found that a short transition period improves the network performance which indicates that “traffic control and management under a proposed guideline can influence driving behavior of evacuees towards such an optimal operation regime to improve evacuation efficiency” (Yuan et al., 2014). This indicates that most modeling software will not represent this transition period effectively. For the Florida Keys model in this project, this is not a huge problem because the only comparisons that will be made will be between simulations of the same model. Problems arise when comparing a model to the real-life conditions.

Prior conducted research provides information about the basics of evacuations, the fundamentals of analysis of these events, operational characteristics, the routes drivers chose to use, and the conditions that can impact these evacuations. This information does not highly affect



this project that will analyze evacuations in the Florida Keys, but it provides insight and background to better understand the process that is occurring. In addition, the research completed on the Florida Keys provides new research because of the unique geographical qualities of the project study area.

## **2.2 Evacuation Modeling and Decision Analysis**

Every family unit decides whether they will evacuate based on many different criteria. Once the decision is made to evacuate, how, when, and where to they will evacuate must also be decided. Prior research, that will be discussed below, provides insight into how and why people make the decisions they do, the variables they take into consideration, and how this affects the evacuation process. Each hurricane and evacuation event provides an opportunity to grow the knowledge base of evacuee decision making and the factors that influence the choices affected individuals make. Emergency planners can learn a lot from studies of this information.

After Hurricane Irma, which made landfall in Florida in 2017, researchers from University of California Berkeley conducted an online survey across the state of Florida, targeting areas heavily impacted by Hurricane Irma. The goal of this survey was to determine “evacuee behavior and the factors that influence a number of complex choices that individuals make before, during, and after a disaster” (Wong et al., 2017). Wong, Shaheen, and Walker analyzed the survey data using descriptive statistics and discrete choice models. It was found that 31% of people who were in a mandatory evacuation zone did not evacuate. 46% of people who were not required to evacuate evacuated. 42% of evacuees leave three or more days before landfall with an even spread of evacuation departure times (Wong et al., 2017). This information provides a good overview for emergency planners. The Florida Keys is often under a mandatory evacuation, so it would be expected that approximately 69% of people will be evacuating. This provides an indication of the number of people that will be evacuating and should be included in the model.

Yang, Morgul and Ozbay and Kaan, “aimed to explore the association between contributing factors and the evacuation decision choices as well as evacuation destination choices” (2016). This study was unique because it used structural equation modeling to determine the interrelationship between response behaviors. Data from a survey conducted in New Jersey used Bayesian estimation approaches and concluded that “individuals’ preference to evacuate did not significantly affect their choices of evacuation destinations” (Yang et al., 2016). This important to note because whether a mandatory or voluntary evacuation occurs, the destination of the evacuees is the same. This does not majorly affect the Florida Keys because the model likely does not include the final destination.

In 2017, Maghelal, Lu, and Peacock investigated on the “characteristics that influence a household’s decision to evacuate in one or multiple vehicles.” This information would help emergency planners and local government predict how many vehicles are on the roadway and create policy that aid in efficient and timely evacuations. Using a typical least square regression analysis, indicated that “that access to transportation characteristics of a household such as number of registered vehicles in a household and number of eligible drivers was positively and significantly related to evacuating in more vehicles” (Maghelal et al., 2017). The major deterrent

of evacuating in multiple cars was the risk of the entire party not safely reaching the destination. “The time of decision and evacuation did not report any statistical significance” as characteristics that influence a family’s decision to evacuate in multiple vehicles (Maghelal et al., 2017). This is interesting to note because the initial model of the Florida Keys in this project was performed as if each citizen drove a vehicle out of the evacuation. During the calibration and validation process, this will be scaled back to appropriately match the number of vehicles traveling. From this research, no matter when the decision to evacuate is made or the timing of the evacuation do not affect the number of vehicles a family uses.

As the storm’s intensity varies or the path changes, many of the variables discussed above also vary. One of the main variables affected is roadway accessibility. In 2020, a study was conducted that considers both dynamic evacuation demand and the variance of this in relation to the characteristics of a hurricane. Every six hours, the demand in number of vehicles per household in each sub-county is considered with the hurricane’s radius and track. A model was then run with the new data which produced the potential crowdedness index (PCI). This then provides road accessibility in each area (Zhu et al., 2020). This method was applied to the entire state of Florida during Hurricane Irma in 2017. “Results show that I-75 and I-95 northbound have a high level of congestion, and sub-counties along the northbound I-95 suffer from the worst road accessibility” (Zhu et al., 2020). This is expected because both of these roadways are large intersections that flow in the north south direction. It is expected that evacuees from the Florida Keys would take I-95 further north. This is not a part of this project’s study area, but still important to note.

Gehlot, Sadri, and Ukkusuri analyze a similar topic – the relationship between evacuation departure time and travel time. They created a model to estimate both travel times and their related departure time during a hurricane evacuation. Results indicate the importance of the “inter-relationship among the dimensions of evacuation behavior” (Gehlot et al., 2019). In addition, social networks play a significant role on travel times and evacuation departure time during a hurricane. This is important to the Florida Keys evacuation model because it confirms what the model indicates: travel times vary depending on when an evacuee leaves.

To take this a step further, Lindell, Sorenson, Baker and Lehman studied household evacuation time estimates (ETEs) for hurricanes. The study compared data from various surveys analyzing times for various tasks including expected task completion times, actual completion times, and departure delays. From these surveys and analysis, it was found that demographic variables poorly predict preparation times, but rather storm characteristics and personal impacts affect household evacuation preparation times significantly (Lindell et al., 2020). This is important to note because the model that represents the Florida Keys does not need to be shifted to accommodate different demographic areas. If the storm characteristics were to change, this could change the flow of vehicles, but it would shift the entire model – not just one census tract or city limits.

Many of the studies above collected data via survey and used that information to build models or understand the relationship between variables that affect how and when people evacuate. In 2019, Roy and Hasan followed a similar process, but used geo-tagged tweets to

gather this information. More specifically, “The authors develop an input output hidden Markov model (IO-HMM) to infer evacuation decisions from user tweets during a hurricane. To infer the underlying context from tweet texts, the authors estimate a word2vec model from a corpus of more than 100 million tweets collected over four major hurricanes” (Roy & Hasan, 2019). This information was validated by analyzing tweets from Hurricane Irma and comparing it with the outcomes of studies with more traditional data collection methods. From the analysis of Twitter data, information about decisions made and when and where people evacuate to can be concluded. This method is significantly cheaper and can be performed as the natural disaster occurs, changing the process of analyzing evacuee decision making data forever.

Another factor often analyzed when analyzing when, why, and how citizens evacuate is if and when an evacuation order or notice is issued. As in some of completed studies above, models are used to analyze how and when people make decisions. In 2017, Gudishala and Wilmot “develop a model that would predict if and when an emergency manager would issue an evacuation notice when a jurisdiction was threatened by a storm.” A discrete choice model was created and used decisions made in the past by evacuation managers to determine the variables that affect the decisions these people make. Five variables - storm surge, clearance time, time to landfall, hurricane category, and time of day – influence if and when an evacuation manager would issue a mandatory evacuation. This model provides a resource – almost a guide – to emergency managers as to the decision other managers would make. Every area is different, and each manager knows their area, but it would provide guidance and another data point to consider in a high stress situation. This information is beneficial to other researchers because it provides additional insight into the evacuation process and evacuee behavior.

As discussed above, emergency managers have a difficult task of knowing when and how to best issue an evacuation order. Research was conducted to “optimize the issuance of evacuation orders with explicit consideration of (i) the highly uncertain evolution of the storm, and (ii) the complexity of the behavioral reaction to evolving storm conditions” (Yi et al., 2017). This was achieved in a case study of eastern North Carolina via progressive hedging and bi-level programming. The outcomes of this analysis found how important it is to make decisions based on the rapidly changing qualities of the storm rather than static policy. In addition, the relationship between “behavioral models for evacuation decision-making with dynamic traffic assignment-based network flow models in a hurricane context” provides valuable insights (Yi et al., 2017). This information will ultimately help evacuation managers make better decisions and ultimately create safer evacuation for the masses.

All of the information discussed in this section analyzed data from events in the past to better understand the evacuation process. A group of researchers wanted to predict evacuation rates for future events. To achieve this, survey data from 2011 and 2012 in North Carolina to create the prediction model. “The out-of-sample predictive power of the new models are evaluated at the individual household level using cross validation, and the aggregated level using available data from Hurricane Irene (2011), Hurricane Isabel (2003) and Hurricane Floyd (1999)” (Xu et al., 2016). Overall, the model correctly predicts a household’s evacuation behavior about 70% of the time. This can be useful to predict the need for additional infrastructure and could be used by researchers when building models to predict future evacuations.

Significant research has been conducted on hurricane evacuation modeling and the decisions evacuees make. This research provides the needed background information to better understand the evacuation process before masses of people enter the roadways. Every evacuation event takes provides data that can be analyzed. Evacuation managers can learn from this and use models built to help predict if and when evacuation orders should be issues. This research on the Florida Keys will build on the existing information in this field.

### **2.3 Explanation of Assumptions and Methodology**

As read about above, building a model and simulating an evacuation is not uncommon or new. These models provide valuable information for events that occur irregularly. Models are often used to analyze the traffic movements and decision making in a small area. More recently, studies have been performed on using the same modeling techniques on a large, regional scale. The outcomes of these models provide different information and points of analysis. The Florida Keys is a large area, and a microscopic model of the network is being conducted, so information on this process is discussed below.

In 2015, Zhang and Wolshon wanted to analyze an evacuation event than spanned multiple cities, during several days. The goal of this research, Megaregion Evacuation Traffic Simulation Modeling and Analysis, was to analyze the traffic operations and route assignments for the region and even provide recommendations to improve the network's performance. In order to achieve those goals, they "developed a micro-level traffic simulation for a mega region" (Zhang & Wolshon, 2015). After building the model and simulating the evacuation, Zhang and Wolshon concluded that operational qualities shown in the model were both "logical and meaningful...and capture the key elements of the system." In addition to this, the microscopic model of the megaregion was able to "demonstrate benefits of proactive traffic management strategies" (Zhang & Wolshon, 2015). This finding indicates that the model that will be built and analyzed for the Florida Keys is going to produce reliable results. The paper concludes with the idea that "the results and knowledge from this research can be adaptable and transferable for the evaluation of other locations within different road networks, populations, transportation resources, and hazard threats" (Zhang & Wolshon, 2015). This microscopic model of the Florida Keys, a megaregion, will do exactly that.

Parr joined Zhang and Wolshon to further analyze the concept of micro-level analyses being performed for a megaregion hurricane evacuation. The outputs of micro-level models are very specific and provide significant amounts of data for every critical point in the megaregion. Because of this, the goal of this paper by Parr, Wolshon, and Zhang, was to "quantify and describe the operational conditions of evacuation traffic network productivity" (Parr et al., 2017). Maximum production, which is directly related to trip completion, is achieved when the modeled network reaches the largest amount of vehicle-miles traveled in a set time interval. From analysis performed, it was found that "productivity exhibited a peaking characteristic" which suggests that it can be maximized on a large scale as a function of demand (Parr et al., 2017). Therefore, if demand is maximized, the network will be performing at its maximum production. Because of this, "emergency planners can develop evacuation management plans which reach and maintain traffic at an optimal demand level" (Parr et al., 2017). When the optimal demand is exceeded,

delays and traffic congestion will occur, increasing the needed travel time to evacuate. If the network is operating below optimal levels, productivity will be decreased, and fewer trips completed for a given time interval. The goal of modeling the Florida Keys in this paper is to find evacuation management strategies that optimize the network model and find maximum production.

Once the model is built, it must be calibrated to reflect the traffic conditions of the actual roadways. Montz and Zhang, in their paper titled “Modeling Regional Hurricane Evacuation Events: Calibration and Validation,” provide a structure and guidelines for the calibration and validation of regional-scale evacuation models. The model built for this project is a regional-scale model, so the calibration and validation techniques discussed are applicable to this project as well. The “two important aspects of the model: traffic assignment calibration and network flow validation” use “observed evacuation data” to achieve this (Montz & Zhang, 2015). Calibrations should attempt to “determine parameter values that would result in the most realistic traffic assignment by comparing assignment results with real-world traffic flows” (Montz & Zhang, 2015). Because of the unique geographical characteristics of the Florida Keys, there is only one option where vehicles can decide which route to take. This will simplify the calibration techniques needed for this model. Validation of the model shows “the importance of including background traffic in the simulation model” (Montz & Zhang, 2015). Background traffic will be accounted for in the validation process using observed traffic counts during an evacuation, just as recommended by Montz and Zhang.

Using a microscopic model to analyze a megaregion is an accepted practice. The maximum production of the model can be found by finding the optimal demand, which ultimately provides guidance to local agencies on conducting the most efficient evacuation. These models must be calibrated and validated to ensure they provide results that mirror the existing traffic conditions during a hurricane evacuation. This information provides guidance and confirms that the modeling decisions used in this project are sound and will produce reliable results.

## **2.4 Recommendations for Network Improvement**

After building a model of the Florida Keys and verifying it using real world data, the model will be altered in hopes of improving congestion and reducing the impact the evacuation has on the environment. The ultimate goal of this research is to provide the local agencies managing the evacuation with ways to improve travel time, reduce bumper to bumper traffic, and improve the safety of this process. In order to do this, the calibrated model will be altered to determine if a method is efficient given the unique qualities of a coastal, island chain community. Research has been conducted about various methods from improving vehicle flow during an evacuation and will be discussed below.

Intelligent Transportation Systems (ITSs) are becoming very popular in the transportation industry right now. These systems are based on the newest technologies including signs that change display and modifying signal timings when different roadway conditions occur. These changes in condition could be caused by the time of day, the weather, locations of accidents or construction, and special events that could cause increase of roadway users. ITS takes the road

from being a stagnant entity to being a living and changing user experience. Incorporating an intelligent transportation system into an emergency evacuation plan “provides us opportunities to improve the effectiveness and efficiency of emergency evacuations” (Real-Time Recommendations for Traffic Control in an Intelligent Transportation System during an Emergency Evacuation – Part 2). If an IT system was implemented in the Florida Keys, after the first hurricane evacuation using the system, the data could be collected and could be put through machine learning algorithms to be “integrated with optimization models to generate initial evacuation traffic control plans” (Real-Time Recommendations for Traffic Control in an Intelligent Transportation System during an Emergency Evacuation – Part 2). Incorporating intelligent transportation systems on a roadway provides real-time condition mitigation and improvement and produces data to be analyzed for similar situation occurring in the future. Adding this type of system to US-1 from Homestead to Key West could provide long and short-term benefit in the many evacuations the Florida Keys face each hurricane season.

Contraflow is the concept of using a traffic lane for traffic to flow in the opposite direction of surrounding traffic lanes. In an emergency evacuation where almost all road users are traveling in one direction (away from the coast or location of danger), using contraflow lanes increases the capacity of the road by providing more space for vehicles. Not many citizens are traveling toward the point of danger, it is not a huge sacrifice to give up travel lanes going in this direction and it makes sense to use them for travel in the opposing direction. Fries, Chowdhury, Ma and Stephen evaluate different contraflow strategies during hurricane evacuations and their findings “support the use of all lanes for contraflow during all evacuations” (Fries et al., 2011). The goal of this study was to determine the best strategy or combination of strategies for evacuating along I-26 in Charleston, South Carolina. A PARAMICS microscopic traffic simulator was used to determine the impact each combination of strategies had on evacuee travel time and duration. The different combinations were various levels of duration of evacuating (long, medium and rapid) and number of lanes used in contraflow (0, 1, 2, or 3). Using any amount of contraflow was found to significantly improve the evacuation duration with the most success being found when using 2 or 3 lanes (Fries et al., 2011). This is important to note when considering turning the southwest bound lane into a contraflow lane in the Florida Keys because there is only one additional lane for a significant part of the evacuation route. If operating only one lane of contraflow operations is not effective, this may not be a realistic recommendation to make. In addition, essentially closing US-1 to southwest bound traffic may be problematic if emergency vehicles are needed further south in the Keys.

A similar option to contraflow lanes that is often employed in an evacuation where the number of vehicles leaving the area is significantly more than the capacity of the road is the use of the emergency shoulder. This makes logical sense because the road, as designed, cannot handle all the cars trying to use it. So, local authorities allow the shoulder to be used as another lane which increases the capacity of the road. This was “implemented in Florida in September 2017 to facilitate mass evacuation before Hurricane Irma made landfall on the shores of Florida. ESU was implemented on the northbound I-75 for about 39 h and eastbound I-4 for about 6 h when the left shoulders were opened for use as travel lanes” (Sharma et al., 2020). Sharma, Faruk and El-Urfali studied of the use of the emergency shoulder in this situation and then compared

with its operation with other alternatives. This study found that “left shoulder ESU could be an effective alternative to one-way operation.” One-way operation, also known as contraflow, is problematic because it cannot be used at night, requires significant number of resources (cones, police officers, electric signs), and limits the movement of first responders driving into the path of the storm (Sharma et al., 2020). Left-hand emergency shoulder use is easy to implement and provides little interference with existing operations. One of the main problems and points of concern for citizens and evacuation managers is safety. So, using the left-hand shoulder as a traffic lane needs to be safe and not increase the number of accidents on this roadway. This study conducted a crash analysis and found that “the observed number of crashes on an urban I-75 segment during ESU operation is commensurate with normal operation with saturated traffic conditions, in contrast a rural segment experienced a higher observed crash rate than the predicted rate with saturated traffic conditions.” In addition, “the predictive analysis of ESU crashes also showed that ESU implementation helped to reduce the expected number of crashes significantly” (Sharma et al., 2020). Overall, using an emergency shoulder is a reasonable way to increase the capacity of the road without creating an unsafe environment for roadway users. Using the model, the benefit of using the emergency shoulder could be seen, but additional analysis of the as-built plans and a field review would be needed to verify that using the shoulder as a travel lane is feasible.

Another possible improvement strategy that could be used on US-1 to improve the evacuation process from the Florida Keys is a gate control strategy. This method is optimal for use when people in a small, localized area, also known as Protective Action Zones (PAZs), must be evacuated quickly and with short notice. Although the entire Florida Key’s population could fit in this category, there are places where the storm surge is worse, the ground is below sea level and flooding could be a huge concern, or the highest wind speeds and risk for injury could occur. These higher risk population areas could be put into these (PAZs). “Nodes are selected on the PAZ boundary with access (to the main roadway) and could be treated as gates for evacuation traffic to be guided through with a higher priority over traffic using the non-gate nodes” (Wang & Bu, 2015). In this research conducted by Wang and Bu, an optimization process was used to minimize total travel cost. The results from this show that “the gate control strategy could improve the performance of an evacuation by reducing the numbers of conflicts in trip routes and traffic movements” (Wang & Bu, 2015). This process was then used in a Case Study in the Mississippi Gulf Coast region and it was found that “the gate control strategy could achieve an effective evacuation operation and improve the performance of the evacuation by reducing average travel time in trip routes and conflicting traffic movements compared with a non-gate situation where evacuation trips are conducted based on “shortest paths” without a gate control strategy” (Wang & Bu, 2015). Because of the success Wang and Bu found with the gate control strategy in this case study, in an environment similar to the Florida Keys, it may be beneficial to implement this strategy in the model of the Florida Keys and compare the effectiveness with other techniques.

Variable speed limit control (VSL) is an adaptive method to improve traffic conditions which reduces safety risks and vehicular emissions. This method imposes changing and different speed limits to each traffic lane based on events happening further ahead in the lane. For

example, if an accident occurred in the right hand lane ahead creating a bottleneck, the speed limit on the clear lanes would reduce allowing the cars in the right lane to merge into flowing traffic without having to reduce their speed significantly. This study conducted by Wu, Tan, Qin and Ran, uses a deep reinforcement learning model to “large number of discrete speed limits in a continuous action space” (2020). Different variables including total travel time, bottleneck speed, emergency braking, and vehicular emissions are analyzed when different speed limits were enforced for different parts and lanes of the segment. From this model, this facet of an intelligent transportation system knows the most efficient way to handle various situations that could occur on the freeway and would change the speed limit signs on a freeway segment as needed to improve operation. Ultimately, the results show that deep reinforcement learning based differential variable speed limit control is able to “improve the safety, efficiency and environment-friendliness of the freeway” (Wu et al., 2020). All of these benefits would make a significant difference on traffic flow operations in an emergency evacuation. In addition, reducing speed on the roadway could be beneficial because slowing road speeds allows for vehicles entering the roadway to need less space to accelerate and become part of the traffic stream. Variable speed limit control could help keep traffic moving and reduce travel time during an emergency evacuation.

Signalized intersections create a challenge in an emergency evacuation because a signal stops a flow of traffic and provides access to the right-of-way to another group of vehicles. In normal operations, this is effective because every stream of traffic has reasonably high demand. In an evacuation, most vehicles are traveling in one direction and the other vehicles want to join this high demand traffic stream. When not operating a signals as it was designed, the three most common methods to use are “manual traffic control (MTC), flashing yellow signals, and crossing elimination” (Parr et al., 2016). MTC occurs when a police officer sits at the intersection and changes the light based on the current situation and demand. Flashing yellow signals provide the main stream of traffic with a flashing yellow light, so they do not have to stop. The minor approach has a flashing red light so vehicles must stop and wait for an opening in the approach before merging with the major approach. Crossing elimination “prohibits right-angle intersection conflicts and allows merging and diverging conflicts only” (Parr et al., 2016). This study found that “MTC was best suited for intersections immediately upstream of a bottleneck or for closely spaced, uncoordinated signals. Flashing yellow signals appeared to work well for intersections with high, unbalanced demand and low volumes on the minor approach. Crossing elimination strategies worked best when demand from nonconflicting directions was high and all other approach volumes were relatively low” (Parr et al., 2016). During a hurricane evacuation in the Florida Keys, there is an unbalanced demand of flow and volume between the major and minor approaches indicating that some of these signal improvements could improve the evacuation patterns of the Florida Keys.

## **2.5 Hurricane Evacuation and the Environment**

Surprisingly, significant research has not been conducted on the impact hurricane evacuations have on the local air pollution due to the emissions from vehicles. There is research that indicates how various traffic management strategies affect the air quality and ultimately public health. A study conducted in Dublin, Ireland found through an emissions model and a



health impact model that by reducing speed limits city-wide, an increase of deaths due to high concentrations of NO<sub>2</sub> would occur (Tang et al., 2020). In a hurricane evacuation, as stated earlier, the volume of vehicles is increased from daily operation and this causes a decrease in operating speed. This natural decrease in speed due to higher capacity would have a similar effect as a decrease in speed due to a change in the speed regulation.

A current solution to the negative impact vehicles have on the environment is electric vehicles. In a hurricane evacuation, where the travel time is unknown and the final destination could be hundreds of miles away, having an electric vehicle is not optimal. One of the main problems comes from the lack of power during these times. One study found that “if the majority of the evacuating vehicles were EVs [electric vehicles], Florida would face a serious challenge in power supply, with its six out of nine main power authorities, especially those in the mid-Florida, being short of power during the evacuation process.” This reliance on electric power to run a vehicle, instead of gasoline, could “induce a cascading failure” throughout the state of Florida (Feng et al., 2020). Solutions to this problem include improving battery performance and public charging strategies. In addition, the use of hybrid vehicles would provide more flexibility in terms of range, power source, and route choice during an emergency evacuation.

This paper analyzes the impact of the current evacuation plan of the Florida Keys on the air pollution levels due to vehicular emissions in the local community. The various alternative strategies that were modeled were also analyzed for environmental impact and reducing air pollution. This will be a consideration, along with other measures of functionality and safety to determine the best alternatives and plan to recommend as part of the evacuation plan. This study provides more understanding of the environmental impacts of an evacuation as there is little research already conducted in this field.

## **2.6 Review Findings**

Research is lacking in the sense that a hurricane evacuation has never been modeled microscopically for the Florida Keys. Other river and coastal communities have been analyzed, but the unique geographical location of the Florida Keys provides an interesting study. There are a limited number of studies that have used a microscopic model of a region, so this study provides additional support that this methodology still produces accurate results. The recommendations that this literature review includes have not been heavily modeled and tested on an environment like US-1 in the Florida Keys, allowing this research to provide new insights into the effectiveness of these methods. As read above, there are few publications that discuss the impact evacuations have on local emissions and the environment. This paper will compare the outcomes from simulations for each of the recommendations in various categories including emissions. This will provide an indication of the environmental impact of these evacuations on the air quality in the Florida Keys.

## **3. Research Methodology**

To provide a basis of measurement and comparison, this research seeks to develop a microscopic traffic simulation model of the Florida Keys to evaluate various evacuation

strategies. More importantly, the research will illustrate methods to measure and quantify evacuations in an unbiased, practical, and repeatable fashion that is both intuitive and beneficial to state officials. Traffic volume counts collected during Hurricane Irma will serve as a calibration and validation parameter for model development. Based on these ideas, the objectives of the research seek to better understand the evacuation process of vulnerable communities in the Florida Keys, FL to assist in the planning, mitigation, response, recovery, and adaptation of these areas from disasters. It is also expected that the findings from this research can be applied to evacuations of any hazard type or location.

In order to achieve this, the following methodology will be completed. First, data collection and analysis of the project study area will occur. This research will set the basic parameters for building a microscopic traffic simulation and the analysis that will occur. Then, the traffic simulation model will be built using VISSIM. This includes building the roadway network, addressing conflict areas, and including proper signals and traffic control measures. Calibration will use population data and traffic counts to accurately portray both the number of evacuees and their appropriate origins. The complete model will be validated and compared to actual travel counts during an evacuation. This verifies that the model is representative of the true physical, operational, and population-based characteristics of the Florida Keys.

Once the model is calibrated, the model can be used for its intended purpose: modeling recommendations for improvement of the evacuation process in the Florida Keys. The first step in this process is to research improvements that could be modeled. This research and analysis will determine which improvements have the potential to be effective in the Florida Keys and ultimately which will be modeled. This process will be conducted in the following steps: research, analyzing the feasibility of different improvements in the Florida Keys, and determination of the improvements that will be modeled in VISSIM. Once these improvements are determined, they will be individually modeled in VISSIM. The existing condition model will be modified to include these changes. Finally, each simulation of the improved evacuation of the Florida Keys will then be analyzed in comparison to the existing conditions and other improvements. The total time of the evacuation, the average travel time for a vehicle evacuating, and the environmental impact of each improvement will be considered.

### **3.1 Data Collection and Analysis of the Project Study Area**

To be able to build a model, calibrate the model, model improvements, and ultimately provide recommendations for improving the evacuation process of the Florida Keys, data collection and analysis of the existing conditions is needed. For this project, that takes many different forms. This process will be discussed below.

When building a model of a roadway, the physical properties of the roadway must be known. Not only must the model have similar geometric design, but the same number of lanes in each direction should be modeled. In addition, the width of these lanes must be known. This information is easily gathered from Google Earth. Using the aerial view, the number of lanes, the location of turn lanes and the width of the lanes can be determined. Because the corridor is 128 miles long, the physical characteristics of the road vary throughout the length of the roadway.

The traffic control devices at each intersection must also match the existing devices. The location of these traffic signals was provided by the Florida Department of Transportation’s Concept of Operations for the Key Connecting Overseas to Advance Safe Travel Project. There are no round-a-bouts or other traffic control devices on this corridor, so if a traffic signal is not used at an intersection, it will be modeled as a stop sign.

The intersections with traffic signals on US-1 between Key West and Homestead were provided by the Florida Department of Transportation, District 6. The Transportation Systems Management and Operations division prepared a concept of operations plan the Florida Keys during normal operating conditions. This report included all the traffic signals in the Florida Keys. Not all of these are on the project site, because Key West has signals further southwest on roads that provide mobility around the downtown area. There are no signals of Card Sound Road. Table 1 below lists the signals from southwest to northeast on the project site. There are total of 16 signals that will be modeled.

**Table 1: Traffic Signals in Project Study Area**

<b>Cross Street Name</b>	<b>City or County</b>
College Road	Key West
Cross Street	Monroe County
MacDonald Avenue	Monroe County
Crane Boulevard	Monroe County
Key Deer Boulevard	Monroe County
33 <sup>rd</sup> Street	Marathon
Sombrero Beach Road	Marathon
107 <sup>th</sup> Street	Marathon
109 <sup>th</sup> Street	Marathon
Sadowski Causeway	Marathon
Coco Plum Drive	Marathon
Woods Avenue	Islamorada
Bessie Road	Islamorada
Ocean Boulevard	Monroe County
Atlantic Boulevard	Monroe County
Tarpon Basin	Monroe County

Population data, along with traffic counts, are needed to know how many people are evacuating from the Florida Keys. The number of users will highly change the time it takes for the evacuation to occur. The best way to determine the population is to analyze census data. This data is provided for each census tracts. A census tract provides the data in small groups of homes

that will be used as the origins for the evacuation model. Because of this, the boundaries of the census tract and the population of that area must be collected for the project study area.

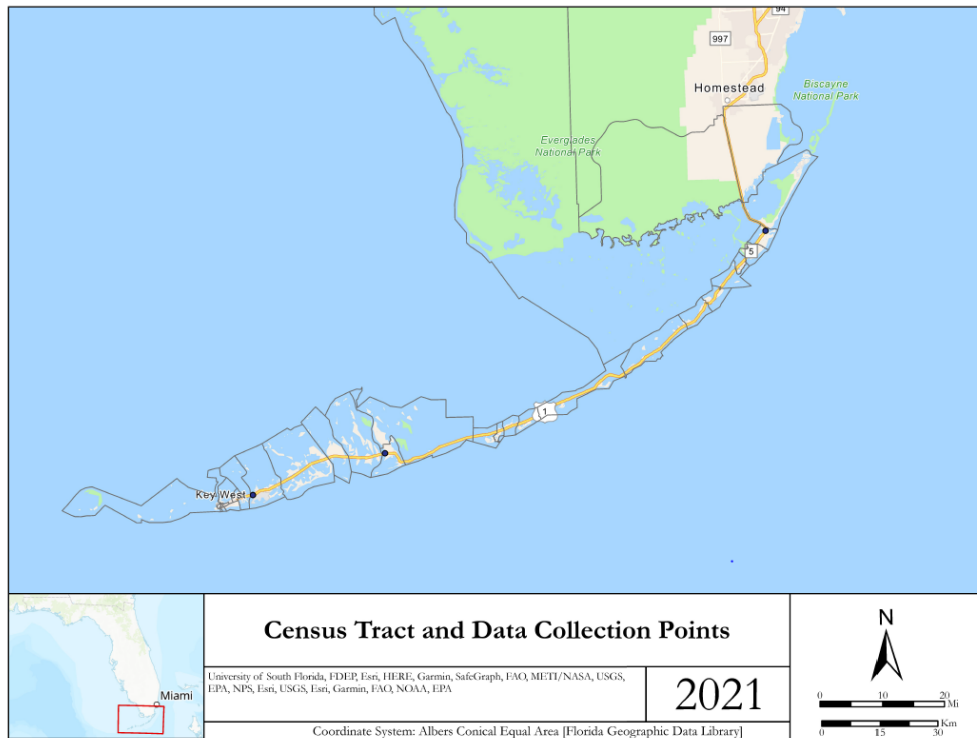
Population data was found on Florida Geographic Data Library Metadata Explorer and provided by the U.S. Census Bureau. This downloadable data produces a shape file with population information for every census tract in the state of Florida. There are 4,245 census tracts in the state, but only 29 are included in the project study area. The information provided by this data includes population, number, and percent of people in each age group, race information, gender statistics, and number and size of households. The information that will be extracted to create the model is the population for each census tract. The population of each census tract can be seen in Table 2. From this information, there is approximately 73,000 people who use US-1 as their evacuation route.

**Table 2: Population for Each Census Tract in the Project Study Area**

Census Tract Number	Population (as of 2010)
9702	1286
9703	2315
9704	3724
9705	2710
9706	1686
9707	2488
9708	3999
9709	1768
9710.01	1389
9710.02	1524
9711	3045
9712	2416
9713	1662
9714.01	3004
9714.02	1333
9715.01	1763
9715.02	2604
9716	1948
9717	2789
9718	4910
9719	5973
9720	4164
9721	3965
9722	2903

9723	2619
9724	3125
9725	1099
9726	838
<b>Total</b>	<b>73,043</b>

The population data collected above, along with traffic counts, will be used to both calibrate and validate the model. Traffic counts provide information on the number of vehicles passing each data collection point. The traffic count data was provided by the Florida Department of Transportation’s Transportation Data and Analytics Office. They are responsible for collecting roadway data – volume, speed, and vehicle classification. This information is gathered hourly from telemetric monitoring stations. Three of the 225 data collection sites statewide are in the Florida Keys and three will be used in this study. The location of these data collection points, as well as the census tracts can be seen in Figure 1 below.



**Figure 1: Census Tract and Data Collection Point Locations**

For this analysis, the bidirectional traffic counts were collected, cataloged, and processed for a six day period from September 5, 2017 to September 10, 2017. This data encompasses the Hurricane Irma evacuation from the Florida Keys. This traffic data was then manipulated to provide information on the number of evacuees and the volume of background traffic for each hour during the evacuation. The use of this data will be further discussed in both the calibration and validation portions of the methodology.

These traffic counts during the Hurricane Irma evacuation reflect the current evacuation plan for the Florida Keys. This plan was found on the Monroe County website. The map that is provided to citizens can be seen in Figure 2. The current plan includes evacuation by zone. This means that a person is encouraged to evacuate at a certain time based on the location of their residence. This process is often a “suggestion” because it is difficult to monitor every entry point onto US-1 in a long stretch of roadway and verify that roadway users are evacuating at the time they are encouraged to do so. The use of traffic counts to calibrate the model will account for evacuees who evacuate at the recommended time and households that evacuate whenever they chose. Because of this, the baseline run of the model will represent the current evacuation plan of the Florida Keys: evacuation by zone.



**Figure 2: Current Florida Keys Evacuation Plan (Monroe County, 2020)**

## 2.2 Build Network Model

The network model is built in PTV VISSIM. This program is the world’s standard for traffic and transportation planning because it provides a realistic and detailed overview of the traffic flow and the impacts this would have on the community. In addition, what-if scenarios can provide a reliable predicative simulation that accounts for driver behavior and decision making in a transportation network. Modeling using VISSIM requires the roadways – both major and minor approaches - to be modeled, defining priority in conflict zones, and adding the appropriate traffic control devices. This will be discussed further below.

VISSIM has a built-in feature that allows you to project a map into the network building area. This allows the roadway network to mirror the exact geometry of the roadway. Because it is only a map view, and not a satellite view, the physical characteristics data of the roadway that was collected in Task 1 is used to supplement this map. The major road is 128 miles long, spanning from the junction of Roosevelt Boulevard and US-1 in Key West to Homestead, where US-1 merges with Card Sound Road to become Dixie Highway. Card Sound Road, also known as County Road 905, splits from US-1 in Key Largo and continues northeast, moving up the archipelago. This

road merges back with US-1 in Homestead. Card Sound Road is a two lane, rural road so there are very few minor intersections. Card Sound Road needs to be modeled along with US-1 because evacuees get to decide which route choice they are going to take.

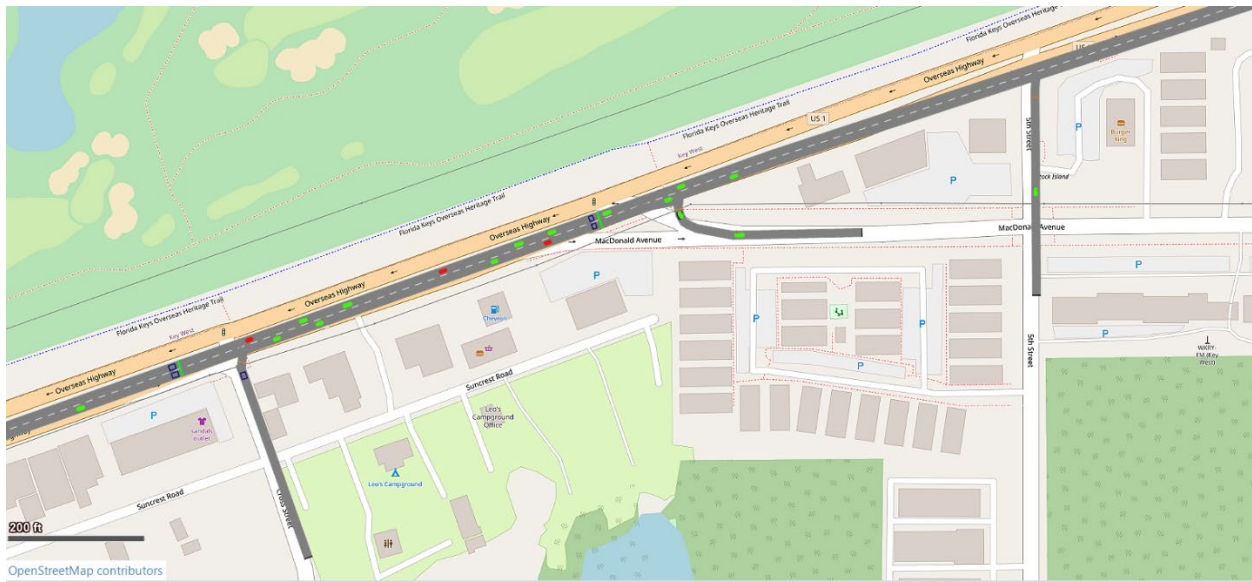
Every intersection with the major road between Key West and Homestead on both routes is included in the VISSIM modeled. There are 512 access points along the 128 mile stretch of road. These minor road approaches are approximately 300 feet long to allow for a queue build up and accurately depict the flow of vehicles during a hurricane evacuation that are attempting to merge onto the only hurricane evacuation route. 300 feet from the intersection of the minor approach and US-1 are where the vehicle inputs are located – the point in the model where vehicles enter the simulation. The number of vehicles entering from each minor intersection is an input provided for each hour of the evacuation. This data, for both evacuees and background traffic, was determined using population data and traffic counts. Additional information about this process will be included in the calibration portion of the methodology.

Connectors provide the connection between the minor road approaches and the major road. These connectors indicate the path a vehicle will make while turning to join the traffic stream. When putting in a connector, a conflict zone is created. A conflict zone is generated by the model as a place where two vehicle paths could meet. The model needs to know which vehicle to give priority to. Assigning this priority defines the conflict zone. For this model, a vehicle on US-1 or Card Sound Road always has priority over a vehicle joining from a minor approach. In addition, the static vehicle route had to be defined. As this is a unidirectional model, with all traffic traveling northeast, the vehicle routes mirror this traffic flow.

Stop bars are then added to each approach. This indicates that the vehicle on a minor approach must stop, look both ways, and then enter onto the roadway. Stop bars are placed on the link, before the connector, because vehicles must stop before beginning to make the turn. Stop signs were placed on the minor approaches that are not controlled by traffic signals.

Signal heads were then placed at the intersections where traffic signals help the flow of traffic. Placing a signal head requires inputting signal timing information and placing detectors and the actual signal head. The signal timing information includes providing the minimum green time, the maximum green time, and the yellow and red time. The signals are modeled after a standard semi-actuated controller. Using a semi-actuated control allows for the signal to receive information about the queue length for each approach and control the signal timing within certain maximum and minimum cycle timings.

Figure 3 below shows a very small portion of the model, as it looks in VISSIM while running a simulation. All of the different components of the model, discussed above, can be seen in this figure and will be discussed below. This segment includes the second and third signal in the network and is near Key West and the far south west part of the network.



**Figure 3: Portion of VISSIM Model Near Key West**

The main road, US-1, is a total of 128 miles long and varies between one and two lanes throughout the network. The main road in this location is two lanes because it is near Key West and a heavily populated area. For this model, the main road is modeled as being a unidirectional roadway because the model will simulate that every roadway user is evacuating – every vehicle will have the same destination at the furthest north point of the model. The green cars represent background traffic that was not evacuating but using the same roadway and route as the evacuees – represented by the red cars. More information about background and evacuee vehicles can be read in the calibration section of the methodology.

The modeling of minor approaches can be seen on Cross Street, MacDonald Avenue, and 50th Street. These links are approximately 300 feet long. There are approximately 512 of these minor approaches along US-1. The black lines at the end of these links are the static vehicle inputs. This is where vehicles enter the roadway network. The connectors are the road or link that connects the minor and major roadways. This can be seen where the minor approach at Cross St. goes off at an angle to connect to US-1.

The intersection on the right, with 50th Street, is a stop-controlled intersection. There are 496 stop-controlled intersections on the roadway network. The stop sign is represented by the orange line. Both intersections on the left are signal controlled. The red lines indicate the signal head and where cars will stop on US-1 to let cars from MacDonald Avenue turn onto the main road. The blue boxes behind these red lines and on the minor approach are the detectors that tell the signal if cars are present. The detectors are needed because the signals are actuated signals.

At each intersection, both signal and stop controlled, are conflict zones. These zones indicate which vehicles priority is given to – the main road or vehicles turning onto it. Obviously,



in this network, vehicles on US-1 have priority and vehicles on the approaches must yield and turn when there is ample space for them to merge into the traffic stream.

### **3.3 Calibration**

Calibration of the model requires comparing the traffic count values provided by the simulation with traffic counts from a real evacuation. As previously discussed, this project will use traffic counts from the Hurricane Irma evacuation as the standard for comparison. The manipulation of traffic counts during an evacuation will be used to determine the number of vehicles in two different classes – background and evacuees - entering the model each hour. This process will be outlined in detail below.

Traffic counts were provided hourly in both the north and south direction at the three applicable sites in the Florida Keys from August 27, 2017 to October 1, 2017 which encompasses normal traffic flow prior to the storm, the evacuation, landfall and storm, and the reentry. For this analysis, traffic counts will be analyzed from Tuesday, September 5, 2017 at 9am to when the storm makes landfall on Sunday, September 10, 2017 at 10am. The beginning date of the evacuation was determined by Parr, Acevedo, Murray-Tuite, and Wolshon in their paper “Methodology to Quantify Statewide Evacuations” by analyzing bi-directional traffic counts to determine when vehicles began leaving the archipelago and would not return until after the storm. This provides a 121-hour period when the evacuation occurs. This entire period will be simulated by the model.

From the provided traffic counts, the number of each evacuees and background traffic passing each data collection point is known. The number of background vehicles traveling in the northbound direction is the number of vehicles that pass the same point traveling in the southbound direction. These vehicles traveled northbound but then returned to their original destination. Reasons for these trips could be commuting to work, gathering supplies to prepare homes and property for the storm, or a last-minute trip to gather necessities from the store. Background vehicles provide friction and represent the vehicles on the road that are not truly leaving the region, but congest the roadway that evacuees are trying to use.

The number of evacuees that leave each hour is calculation by taking the northbound traffic and subtracting out the background traffic. This means that the number of evacuees that leaves each hour is the difference between the number of vehicles traveling northbound and southbound. For the sake of calibration, if this is a negative, the number of evacuees reverts to 0. This does not occur often during this time period, but there are few hours during the middle of the night where the southbound traffic count is larger than the northbound count in this 121-hour evacuation period.

The calibration for this model will occur with the two furthest south data collection points. These points are located just north of Key West and south of Big Pine Key. Because of the large number of input points – 512 – in this roadway network, the calibration needed to occur in steps. This allows the southern part of the model to reflect the true conditions of the Hurricane Irma evacuation before adding additional vehicles further north in the model. Because of this, the Key West data collection point data was used first to calibrate the model.

There are 10 locations where vehicles can join the model before passing over the Key West data collection point. A weighted average, using population and number of entry points for each census tract, is used to calculate the proportion of the total number of evacuees that come from each entry point, each hour. The same proportion is used to determine the number of background vehicles that enter the network at each entry point. The processed used to calculate the weighted average is described below. Each of the census tracts to the south of the data collection point are included.

1. Determine the total number of people who live in the area.
2. Calculate the proportion of people who live in each census tract
3. Divide the proportion by the number of entry points in that census tract. This provides the proportion of both evacuees and background vehicles passing the data collection point that comes from each entry point in that census tracts.
4. Finally, multiply the proportion for each entry point by the total number of evacuees or background vehicles during that hour. This value is the input respectively for each entry point, each hour in that census tract.

Table 1 provides the calculations used to calculate the proportion of the evacuees or background that enters from each census tract’s entry points.

**Table 3: Calculations for Proportion of Total Vehicles from Each Entry Point**

Tract	Population	Proportion	# Entry	Prop Each Entry
9718	4910	0.165901	5	0.033
9719	3584	0.121097	3	0.040
9719	2389	0.08072	2	0.040
9720	4164	0.140695	2	0.070
9721	3965	0.133971	2	0.067
9722	2903	0.098088	2	0.049
9723	2619	0.088492	2	0.044
9724	3125	0.105589	2	0.053
9725	1099	0.037133	2	0.019
9726	838	0.028315	2	0.014
	29596	1		

Census tracts, 9720 through 9726 and a part of 9719 all are further south than the beginning of the network model. Therefore, all vehicles from these census tracts enter the model at the furthest south end. This intersection has two entry points from the main island. From this table, each entry point in Census Tract 18 provides 3.3% of each evacuees and background traffic that pass the Key West data collection point each hour. Each of the south end entry points provide about 35.7% of vehicles each hour.

Because of difference in travel time from each entry point or census tract to data collection point, inputting the exact number of cars as the true data shows does not provide the same

result at the data collection point in the simulation. In some locations, there is queue build up that hinders traffic flow, causing a fewer number of people to cross the data collection point in the simulation than in the traffic counts. During an evacuation it is expected that there will be queues forming at different parts along US-1 but the traffic counts should account for that, so the model should mirror the traffic counts.

To overcome this excessive queueing and to be sure the correct number of vehicles pass over the data collection points, it was decided that an hourly weighted average would help keep the same approximate number of vehicles entering the model and ultimately passing over the data collection point in the simulation as are counted in the real evacuation. After trying various weights, it was found that calculating the total number of evacuee and background vehicle inputs for the hour using Equation 1 below was the most effective, where N is the true number of evacuees passing the point and X is the weighted number of evacuees.

$$X_{hr=3} = (N_{hr=2} * .05) + (N_{hr=3} * .9) + (N_{hr=4} * .05)$$

**Equation 1: Number of Vehicles per Hour**

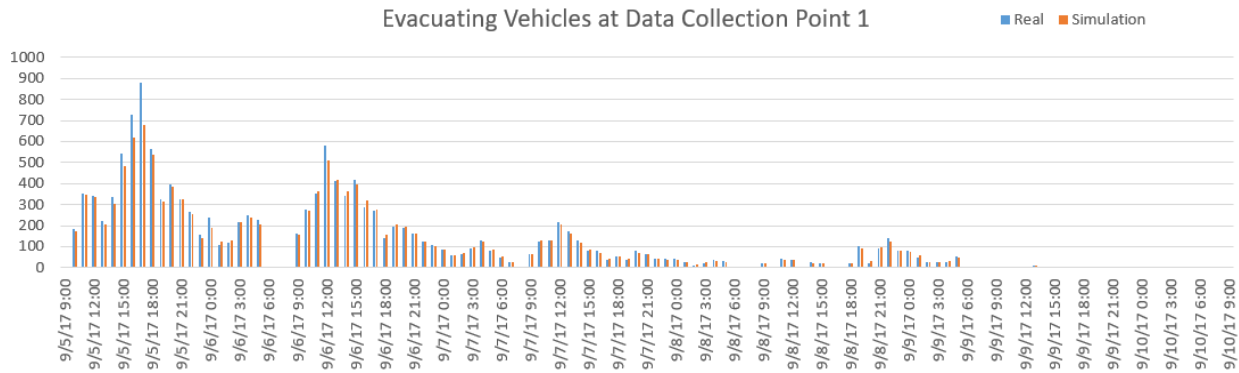
This calculation accounts for the vehicles that left their origin point near the end of the previous hour and did not arrive at the data collection point during the previous hour, the vehicles who leave in the hour and arrive in the hour, and the vehicles who leave in the hour and arrive in the next. The vehicles that leave during the hour and arrive at the data collection point in the same hour is expected to be the largest group because of the relatively short distance between the entry points and the data collection points.

VISSIM provides the number of vehicles that pass over the data collection point – which were placed in same place as FDOT’s data collection site - for every hour and vehicle class – evacuee and background. This data is then taken for the entire 121 hours simulation period for 5 simulations with different random seeds. Using Equation 2, it was determined that a sample size of five is sufficient. Z is representative of the z-score corresponding to the confidence level.

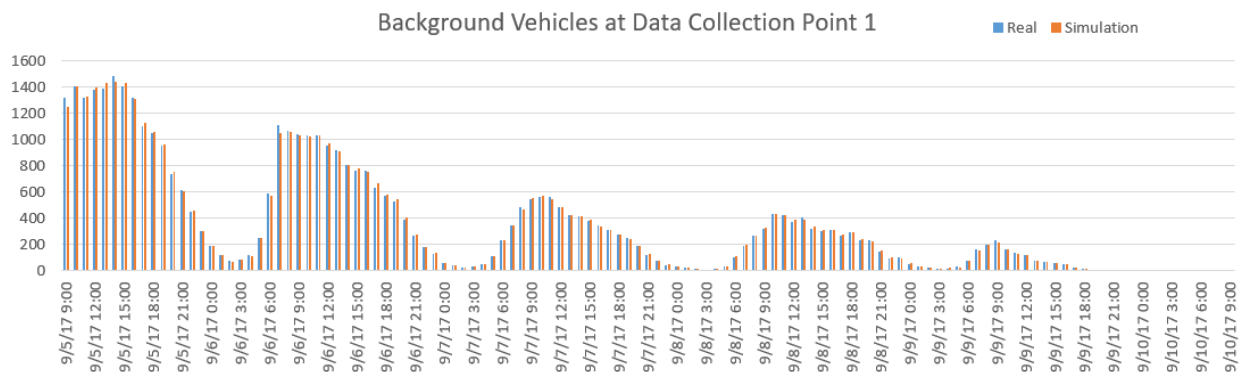
$$n = \left( \frac{Z * \sigma}{E} \right)^2$$

**Equation 2: Sample Size Equation**

The average of the outputs for each hour of each simulation run are average. The graphs below, Figure 4 and Figure 5, show the real and average simulated number of evacuees and background traffic, respectively.



**Figure 4: Hourly Comparison of Real and Simulated Evacuees at Data Collection Point 1**



**Figure 5: Hourly Comparison of Real and Simulated Background Traffic at Data Collection Point 1**

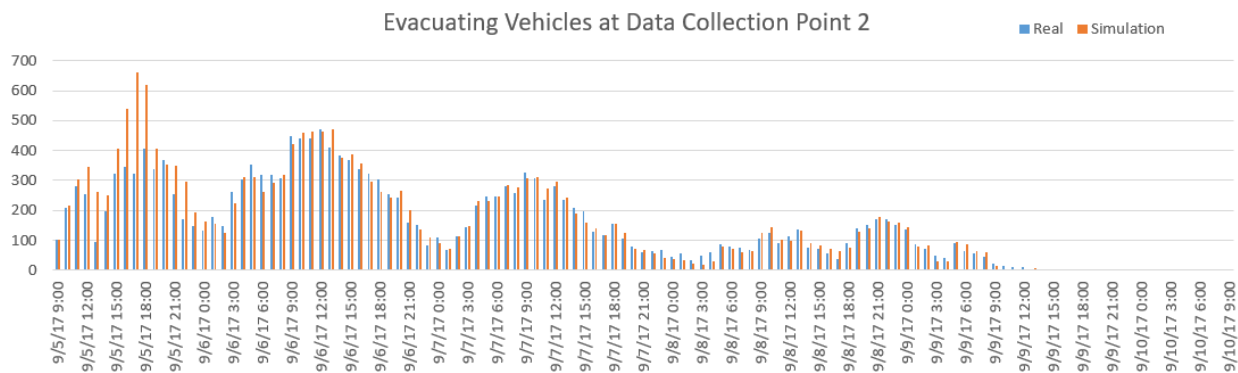
The coefficient of determination, r-squared value, is calculated for each of these relationships. The coefficient of determination provides the extent of the variation of the dependent variable which can be attributed to the independent variable. This value provides a number between 0 and 1. For calibration, an r-squared value of higher than .9 is needed to confirm that the simulation mirrors the true conditions during an evacuation. The r-squared value for the relationship between the number of real evacuees and average simulated evacuees is .99. The r-squared value for the relationship between the number of real background vehicles and average simulated background vehicles is .99. Both of these values are above the required .9 and indicate that the model reflects the real conditions on US-1 in Key West during a hurricane evacuation.

To calibrate the model from the first data collection site to the second, a similar process is followed. An additional step is needed though to account for the evacuees and background traffic passing the second data point that also passed through the first data collection point. The second data collection point was placed before running the calibration for the first portion. From this, the number of evacuees and background traffic passing this point is known. Because of this, the number of evacuees and background drivers will be subtracted out of their

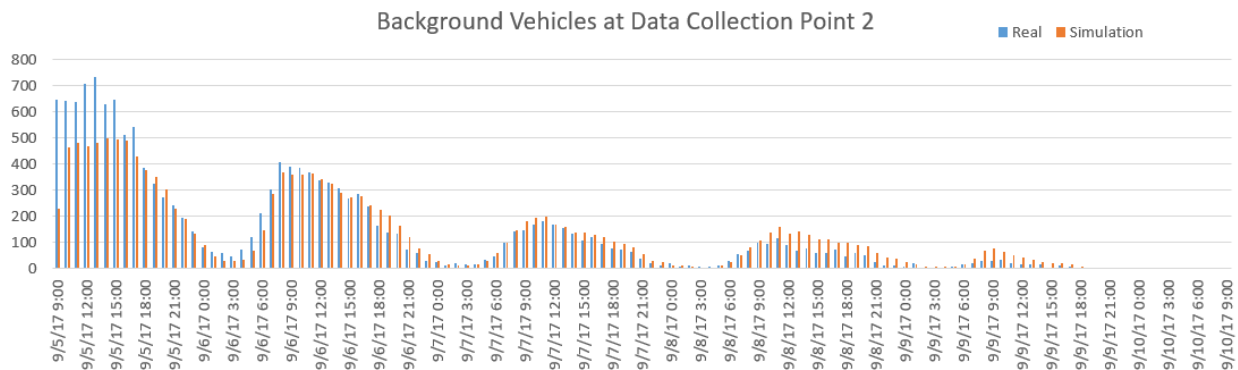
respective categories from the counts at the Big Pine Key data collection point. This new number of evacuees and background traffic will be used to determine the number of vehicles entering the model at each entry point in each census tract.

After analyzing the data, there are significantly more background vehicles passing through the Key West data collection point than there were at the Big Pine Key point. This is expected as citizens leave Key West for work or to gather supplies to prepare for the storm, but do not actually evacuate. Because of this, some of the background vehicles need to be removed from the model. Approximately 65% of background vehicles are routed off of US-1 after the Key West data collection point. This leaves the appropriate number of background vehicles to continue up through the Big Pine Key region and provide the needed friction to keep evacuees on US-1 traveling at a speed that reflects true conditions. Because of this, additional background vehicles do not need to be inputted for census tracts between the first and second data collection point.

The only calculations that need to be made for this segment – from the Key West data collection point to the Big Pine Key data collection point – is the number of evacuees who enter the model per entry point by census tract. This calculation follows the exact same procedure as outlined above – using weighted average by census tract and number of entry points.



**Figure 6: Hourly Comparison of Real and Simulated Evacuees at Data Collection Point 2**



**Figure 7: Hourly Comparison of Real and Simulated Background Traffic at Data Collection Point 2**

The graphs above in Figure 6 and Figure 7 show the real and simulated number of evacuees and background traffic for each hour of the evacuation, respectively. The r-squared value for the relationship between the number of real evacuees and average simulated evacuees is .90. The r-squared value for the relationship between the number of real background vehicles and average simulated background vehicles is .91. Both of these values are greater than or equal to the required .9 and indicate that the model reflects the real conditions on US-1 in a hurricane evacuation.

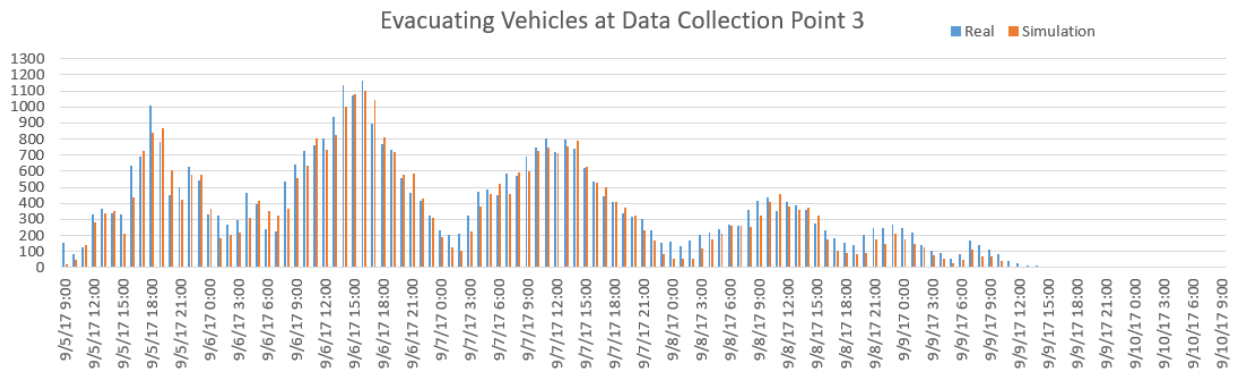
### 3.4 Validation

The same process that was used to calibrate the model at the second data collection point was used to validate the model. This method requires the use of traffic counts from the third point along US-1 in the Florida Keys. This data collection point is located right before the junction of US-1 and Card Sounds Road in Key Largo. The distance between the second data collection point and the third is 78 miles and there are 14 census tracts along this segment.

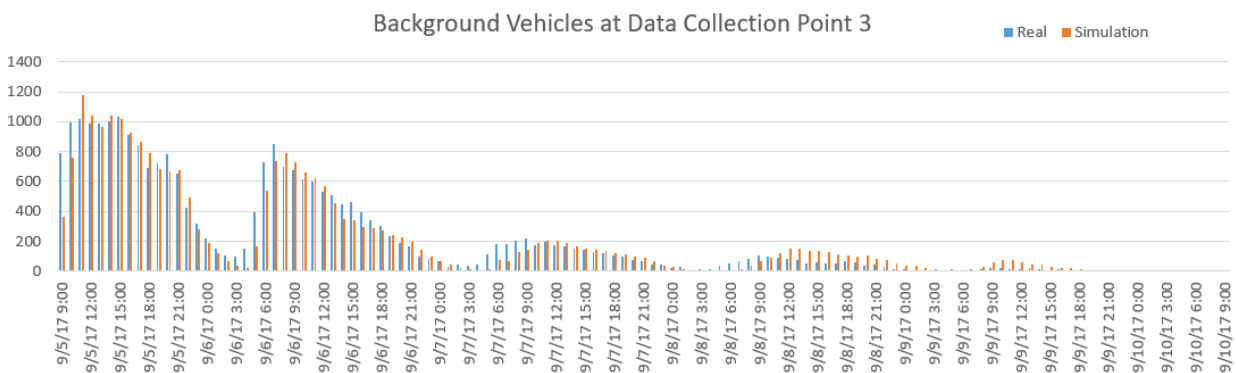
During the final calibration run of the simulation, the existing number of vehicles passing the data collection point of each type (evacuee and background) were known and subtracted from the totals calculated from the raw data. This produces the total additional number of evacuees and background vehicles that needed to be entering the model each hour were calculated using the same equation that was used in calibration. This total number of either evacuees or background vehicles was then multiplied by the weighted proportion per entry point in a census tract, as discussed in calibration. This was calculated for each census tract, for each hour of the simulation.

Although this data collection point is near the end of the archipelago, there are still 15 entry points further north on Card Sound Road that still have people evacuating, but not passing the data collection points. The number of people evacuating and traveling as background traffic each hour is predicted to match the next furthest north census tract. These census tracts have similar number of people per entry point and therefore it would be predicted that the same number of people would be evacuating from the area.

After all of the new inputs are placed in the model, 5 simulations will then be run -with different random seeds. The volumes of both evacuees and background traffic passing the third and final data collection point will be recorded for each hour of each simulation. An average for each hour, for both evacuees and background vehicles, will be computed. An r-squared value of .7 is required in the validation phases. The graphs below, Figure 8 and Figure 9, show the real and average simulated number of evacuees and background traffic, respectively at the third and final data collection point. The r-squared value for the relationship between the number of real evacuees and simulated evacuees is .95. The r-squared value for the relationship between the number of real background vehicles and average simulated background vehicles is .94. This verifies that the model reflects the true conditions of an evacuation in the Florida Keys.



**Figure 8: Hourly Comparison of Real and Simulated Evacuees at Data Collection Point 3**



**Figure 9: Hourly Comparison of Real and Simulated Background Vehicles at Data Collection Point 3**

### 3.5 Model Recommendations

The goal of this task is to determine the improvements that are possible recommendations for improving the evacuation scenario in the Florida Keys. This will require research, analyzing

improvement strategies, and determining which of these strategies will be modeled. Once the strategies are determined, they will be modeled in VISSIM using various techniques.

Research was conducted to help generate and brainstorm possible techniques that could be used to help improve traffic flow during an evacuation. Other research has used models, analyzed different evacuation's travel times where different techniques were used, and investigated the level of improvement when different levels of an improvement were used. Some of the techniques are relatively new due to the technological improvements of the last ten years. This project will build upon prior research and determine if these strategies that were successful in other locations and situations would be effective in the Florida Keys during a hurricane evacuation. This research is summarized in the literature review.

When making this decision, the goal is to find inexpensive, low resource, and safe alternatives that will be effective in helping get all 73,043 residents of the Florida Keys out as quickly as possible. From prior knowledge and additional research, the following improvements will be analyzed for their feasibility in the Florida Keys: contraflow, emergency shoulder use, conflict elimination, and flashing yellow signals. Additional information about these improvement strategies and their effectiveness for the Florida Keys will be discussed below. These improvements will be compared against the current evacuation plan, evacuation by zone, that the model was calibrated from.

Evacuation by zone is the current evacuation plan that the Florida Keys use currently. This can be seen in Figure 1. This strategy focuses on the time component of an evacuation and hopes to reduce the overall travel time of the evacuation process by allowing Zone 1 to begin their evacuation and travel for a significant amount of time before allowing Zone 2 to exit, and so on until all residents have evacuated. This method is especially effective when an area is at a higher risk and needs to evacuate more quickly than another area. In the Florida Keys, by having the furthest south island, Key West, evacuate first, there is a whole bunch of clear roadway until vehicles reach the furthest north zones. Modeling this improvement, which is the current evacuation plan, will provide insight into the strength and weaknesses of the current evacuation plan and the improvements will provide insight on methods to improve this process even further.

Contraflow is the use of a traffic lane to carry vehicles in the opposite direction it was designed to flow. During a hurricane or emergency evacuation, almost all roadway users are driving in the same direction - away from the area of high risk. In the Florida Keys, the evacuation is often deemed as "mandatory" by local governments because of the high risk this island chain faces every time the sea level rises and high winds occur. Because of this, it makes logical sense that using the southwest bound lane of US-1 as a contraflow lane would be productive. The negatives of contraflow are the safety risks it creates. First, if an accident or medical emergency occurs downstream of the first responder's location and both lanes are moving upstream, there is no way for help to get to the citizen. This is especially true in the Florida Keys because there is only one road that connects all the islands, so there is no alternative route for the responders to take. Using a roadway as it was not designed has additional safety risks. In addition, it takes a significant number of resources to operate a



contraflow road like law enforcement, additional signs, and barricades to block turn lanes for directions that are not operating. US-1 in the Florida Keys is primarily a two-lane road, so adding a contraflow lane could significantly improve the travel time during an emergency evacuation even if it takes a significant amount of resource to operate.

The emergency shoulder of a roadway is the paved area on the side of the road which provides additional width to the right-of-way and improves the driving experience for roadway users. In an emergency evacuation, this space, if wide enough, could be used as an additional travel lane. This method was used in September of 2017 during Hurricane Irma on I-75 in Florida. The results of a study that found that crash rates were no higher in an urban setting using the shoulder as a through lane than when operating the roadway at capacity (Sharma et al., 2020). This indicates that using the shoulder in an emergency is not unsafe. Although adding a lane to the traffic flow seems that it would allow the total time to be cut in half, this is not true. When driving in a narrower lane or more closely to other vehicles, it is common for drivers to reduce their speed and drive with more caution, causing a slower free flow speed. By modeling this option, it will be determined how much of an improvement operating an emergency shoulder lane provides.

Conflict elimination is a technique used at traffic signals to eliminate perpendicular intersections and use merging and diverging to join and leave the traffic flow. This creates a situation like a controlled interstate with on and off ramps. This method is most effective when the volume and demand of the major road is very high, and the minor approach volume is low (Parr et al., 2016). This is true in the Florida Keys during a hurricane evacuation because all users are hoping to travel northeast on US-1 to return to the mainland and further north. This method is safe but requires physical space and resources to create the acceleration lanes and merging areas. US-1 in the Florida Keys provides the needed space because similar to contraflow, the opposing direction lane could be used near intersections as the acceleration lane.

Another technique involving the traffic signals that could be used to reduce the total evacuation time is flashing yellow signals. Flashing yellow signals provide the major roadway with essentially a yield sign – they do not have to stop or slow down but should be aware that they are passing through an intersection and should be cautious. The minor approach's signal head would show flashing red. This requires that these vehicles must stop, look both ways, find a place in the traffic flow where they can safely join in with the traffic stream. A flashing yellow signal head operates like a roadway where the minor approach has a stop sign, and the major approach has no control devices at the intersection. This method works the best on intersections with an unbalanced volume and demand between the major and minor approaches (Parr et al., 2016). Similar to the optimal situation for conflict elimination, this obviously occurs during hurricane evacuation in the Florida Keys. This method takes very little resource to implement and is reasonably safe. The only negative is that the line of cars waiting to turn from the minor approach onto the major approach could become very long. Modeling this improvement will indicate if this method is helpful given the number of citizens who would use the signalized intersections to join onto US-1 and the unique traffic flow in the Florida Keys during hurricane evacuation.

From the analysis discussed above, the following improvements will be modeled: contraflow, emergency shoulder use, flashing yellow signals, conflict elimination, and evacuation by zone. The improvements are safe and could be implemented relatively easily in the Florida Keys. The physical demands of each method are met by US-1 in the Florida Keys and should improve the capacity in a safe and efficient manner. Each method has a draw back, but that is expected because evacuating from a hurricane is an emergency traffic pattern, and vehicles just need to move toward the mainland as quick as possible. Because of this, these five methods will be modeled in VISSIM and the outputs of the model will be analyzed to determine the best recommendations. To model each of these scenarios, a change will have to be made to the VISSIM model. The changes that will be made to the base model will be discussed below.

For contraflow, the existing links of the major road, US-1, will be duplicated, so that two lanes are traveling northeast bound. For segments of four lane road, all 4 lanes will be carrying vehicles traveling northeast. In addition to adding lanes, the connectors from the north side of the road will be moved to turn into the closest lane as turning vehicles should. Signal heads will be removed as every lane of US-1 is traveling in the same direction creating a one way road. All approaching vehicles are essentially making a right-hand turn onto US-1 because there is no traffic to cross.

When modeling emergency shoulder use, a lane will be added on the south side of the existing lane on US-1 when the shoulder of the roadway provides the needed space to add a lane. This lane is likely to be very narrow as it is representing the shoulder of the roadway. To determine the exact width and applicable location to implement emergency shoulder use, a virtual field review was conducted. It can be assumed that the narrowest portion of paved roadway in the Florida Keys is the bridges that connect the various islands. Using Google Earth, the width of pavement (current lanes and applicable shoulder) on bridges in the northbound direction in each model segment were measured. The narrowest measurement was used to determine the emergency shoulder lane width and width of driving lanes that would accompany the shoulder length. To minimize the resources needed to implement this method, if a bridge was 20 feet wide with a 12' driving lane in normal operations, an 8' shoulder was added. The table below shows the new lanes widths when implementing emergency shoulder for a hurricane evacuation.

**Table 4: New Lane Widths with Emergency Shoulder Use**

Roadway	VISSIM Link	# of Lanes	Lane Width	Pavement Width	Can EMS be Used?	# of Lanes Using EMS
US-1 (SW)	1	2	12	35	Yes	12', 12', 11'
US-1	5	1	12	18	Yes	9', 9'
US-1	7	2	12	28	Yes	12', 8', 8'
US-1	8	1	12	18	Yes	9', 9'
US-1	9	2	12	37	Yes	12', 12', 12'
US-1	12	1	12	18	Yes	9', 9'
US-1	13	2	12	25	Yes	9', 8', 8'
US-1	15	1	12	18	Yes	9', 9'

US-1	18	2	12	28	Yes	12', 8', 8'
US-1	19	1	12	19	Yes	10', 9'
US-1	21	2	12	35	Yes	12', 12', 11'
US-1	22	1	12	20	Yes	12', 8'
US-1	25	2	12	32	Yes	12', 10', 10'
US-1	27	1	12	26	Yes	12', 12'
US-1	29	2	12	30	Yes	12', 9', 9'
US-1	30	1	12	28	Yes	12', 12'
US-1	31	2	12	28	Yes	12', 8', 8'
US-1 (NE)	33	1	12	24	Yes	12', 12'
Card Sound Rd	4	1	12	14	No	-

In addition to adding a lane and changing the lane widths, signal heads and the needed detectors were added to the additional lanes. The connectors were moved to turn into the closest lane as turning vehicles should.

To model the flashing yellow signals, the signals on the roadway network will be eliminated. A flashing yellow signal represents a yield for the major approach – which requires no stopping or even slowing down. No signal produces the same driving behavior as a flashing yellow signal for the major approach. On the minor approaches, stop signs will represent the flashing red portion of the signal and will be added to the intersections that are normally signalized. This will emulate the same driving behavior as a flashing red signal for those vehicles.

Conflict elimination will be modeled by changing the geometry of the connectors – they will change from being perpendicular with US-1 to looking more like acceleration lanes for merging into the traffic stream. This change will only occur at the traffic signals due to the number of resources – cones, barricades, police officers – this method requires. This decision was made because it is expected that more cars will be using the minor approaches with signals than at the stop-controlled intersections.

Each of these recommendations for improvement will be modeled individually and the outputs compared with the model of the current evacuation pattern and each other to determine which improvement is the best for the Florida Keys region. The analysis of the outputs will be discussed in the final step of the methodology.

### 3.6 Analysis of Model Outputs

After each improvement has been modeled, a simulation of a hurricane evacuation would be completed. This requires that 5 simulations, each with a different random seed, be completed for each recommendation. This guarantees that the results are random and represent the actual conditions of the Florida Keys. VISSIM provides many different data collection options, but this project will focus on 3 different points of output for evacuees: network performance (vehicle miles, vehicles hours, and delay), clearance time, and travel

time. Using these outputs, an outside program will be used to determine the impacts the evacuation recommendations have on the environment.

The network performance evaluation results provide insight into the movements of vehicles in the roadway network. This includes the vehicle miles traveled – the number of miles traveled by evacuees' during the evacuation. It is expected that each recommendation will have a similar number of vehicle miles traveled each hour of the evacuation. If this is not true, it would indicate the queuing is occurring with that recommendation during that hour, but not happening with other recommendations.

In addition, the number of hours evacuees spend driving throughout the entire evacuation will be recorded in vehicle hours. The simulation that takes the shortest amount of time for all evacuees indicates an evacuation with reduced queuing and delay. This would appeal to local emergency management because a lower total travel time indicates a more efficient evacuation. Total vehicle hours will be provided by VISSIM data collection's total travel time.

Delay provides insight into how long vehicles are spending waiting to merge on to the main roadway, sitting in queues on the main roadway, or time spent waiting behind a vehicle wanting to change lanes. The average delay, the delay experienced by vehicles in the hours divided by the number of vehicles in the network during that hour will be recorded for each hour of the simulation. The recommendations with the smallest amount of delay, which likely corresponds to the shortest travel time will be one of the factors that affects which recommendation is the best.

To collect the network performance evaluation results, the proper evaluation parameters must be selected. Because of the importance of these results, VISSIM provides all of this information very clearly for each vehicle class (evacuee or background). The data provided will be averaged for the 5 simulation runs and further analyzed in the results section below.

The second evaluation criteria, clearance time, provides information on when the vehicles leave the roadway network – indicating that they have reached the end of their evacuation in this model. As this model reflects a hurricane evacuation, the goal is to have as many evacuees leaving the area as early in the evacuation period as possible to avoid vehicles being stranded on US-1 during the storm. Therefore, by evaluating clearance time we are hoping to determine which recommendation moves the most vehicles out of the region the earliest.

To collect clearance time information, a data collection point was put at the very end of the roadway network. This will provide the number of evacuees that pass this final point in the model each hour. From this, graphs can be created that show the proportion of evacuees who successfully evacuated by reaching the mainland each hour. For safety reasons, local emergency management agencies want to see many evacuees getting out as early as possible and the clearance time graphs will show us this for each recommendation. The data provided by the data collection point will be averaged for the 10 simulation runs and further analyzed in the results section below.

In addition to collecting network performance evaluation and clearance time data, information on the travel time will be collected. Travel time will provide insight into the periods for each recommendation when evacuating takes the longest and shortest amount of time. When the evacuation takes the longest will indicate the peak hour(s) of the evacuation. This will be helpful to emergency management staff because reducing the peak will make the evacuation safer and more efficient for all affected parties.

Travel time data was collected using the vehicle travel time function in VISSIM. For this analysis, the travel time was collected for evacuating vehicles from Key West in the south to the end of the model when Card Sound Round merges with US-1 in Homestead. The data is collected hourly and is reported based on the hour the vehicle entered the network.

Finally, the emissions produced by the evacuation will be analyzed. For each recommendation, it is expected that the total vehicle miles traveled by evacuees will be similar for all the recommendations. Because of this, the emissions produced by idling vehicles, caused by stop delay, during the hurricane evacuation will be determined for each scenario. By analyzing the emissions, the effect each process has on the environment can be seen. This is important to consider because the ever-changing environment and its pollutants is a possible cause for climate change. In addition, the relationship between evacuation techniques and the effect on the environment is not a well understood and published topic.

To calculate the number of emissions produced by vehicles idling, the total stop delay for all 121 hours of the evacuation will be determined for each recommendation by averaging the result from the five iterations. This number of seconds, provided by VISSIM, will then be converted to number of hours. From there, it was determined by the Energy Systems Division of the Argonne National Laboratory that a passenger car, with a load, spends .6 gallons of gas per hours of idling (2014). Evacuees will have their vehicles weighted down with their personal belongings and needed supplies. According to an idling cost calculator produced by E3 Fleet, each gallon gas burned idling produces 2131 grams of greenhouse gas emissions (2006). From these conversion factors, the total number of green house gas emissions created by the idling of vehicles each recommendation will be calculated and analyzed.

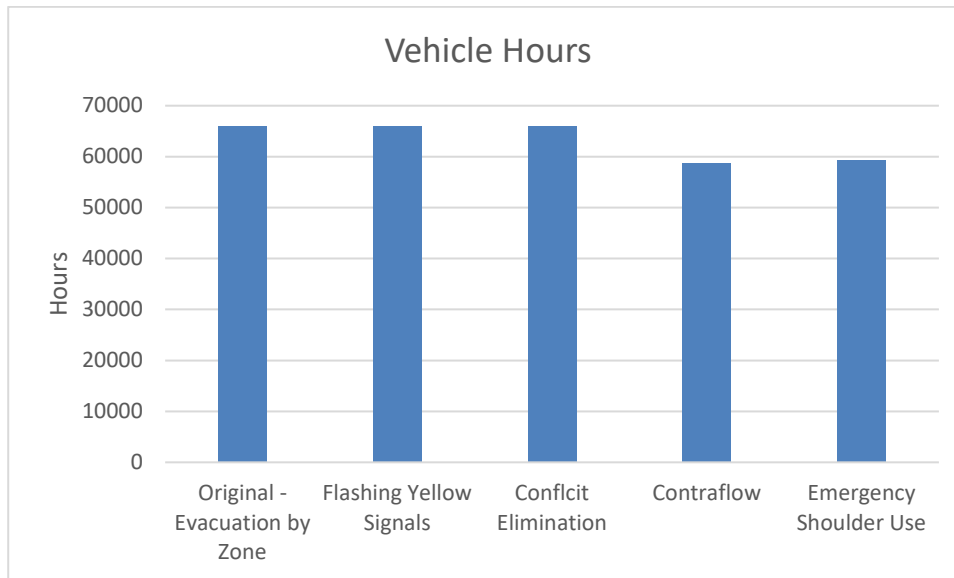
The improvement each modeled scenario experiences for each criterium will be summarized in tables and graphs. From this, a final recommendation will be made to help the local government and emergency operations organizations in the Florida Keys create a safe, more efficient, and environmentally friendly evacuation process.

#### **4. RESULTS**

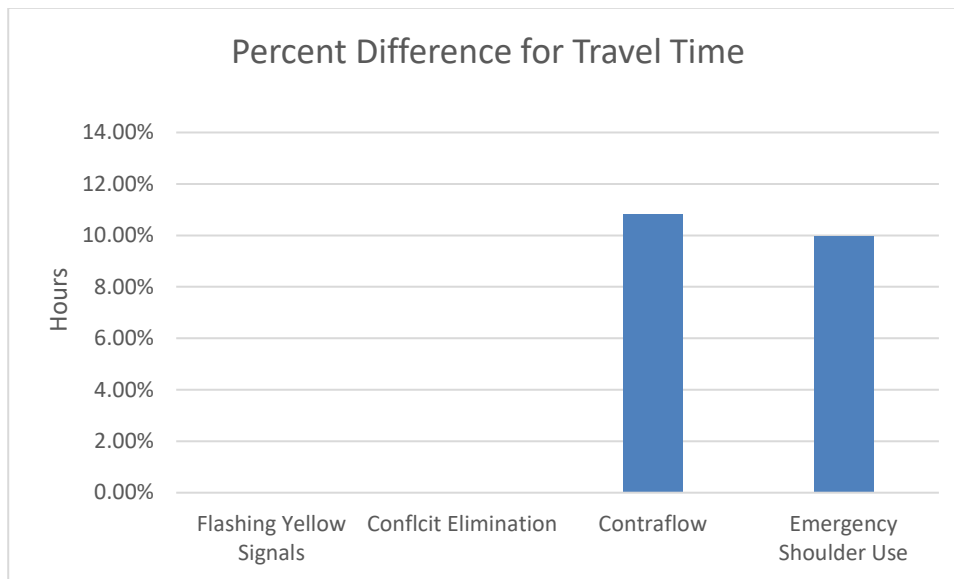
After running the simulation five times for each of the five different scenarios, the results provided by VISSIM can be manipulated and analyzed to better understand the evacuation process of the Florida Keys.

The main goal for emergency management teams during hurricane evacuation is to move people out of the area in possible danger as quickly as possible. Total travel time, in vehicle hours is one way to analyze this. The total number of hours evacuees were driving during the

121 hour simulation period was recorded. Figure 10 provides this data point for each recommendation as well as for the current evacuation plan – evacuation by zone.



**Figure 10: Vehicle Hours for Each Simulation**



**Figure 11: Percent Difference for Total Travel Time**

Given that evacuation by zone is the baseline, it can be seen in Figure 10 above that flashing yellow signals does not significantly change the amount of time that the evacuees, as an entire population, spent driving. The same can be true of the other recommendation that changed operations at the intersections with traffic signals – conflict elimination. Little to no improvement was seen in total evacuation time from the current evacuation plan when using conflict elimination. All three of these simulated evacuations – evacuation by zone, flashing yellow signals, and conflict elimination took approximately 65,900 hours.

Recommendations that change the number of lanes, like contraflow and emergency shoulder use, had a shorter total travel time for evacuee leaving the Florida Keys. This is seen in Figure 11 that shows the percent difference between each of the recommendations and the original model. This is expected because adding lanes increases the capacity of the roadway and allows vehicles to move more quickly and freely during the evacuation. It took evacuees 59,300 hours total to evacuate when implementing emergency shoulder use. For contraflow, the evacuation required 58,800 hours of driving by evacuees. Even shortening the total number of vehicle-hours of the evacuation by more than 1,000 hours can enhance the safety and efficiency of the evacuation.

This total travel time, for the entire population of evacuees, can be further evaluated by analyzing the results from the travel time collection used in the simulation. The time it took evacuees to travel from Key West to Homestead, at the end of the model, was recorded based on when a vehicle entered the model. The graph below shows the average travel time, in hours for each recommendation.

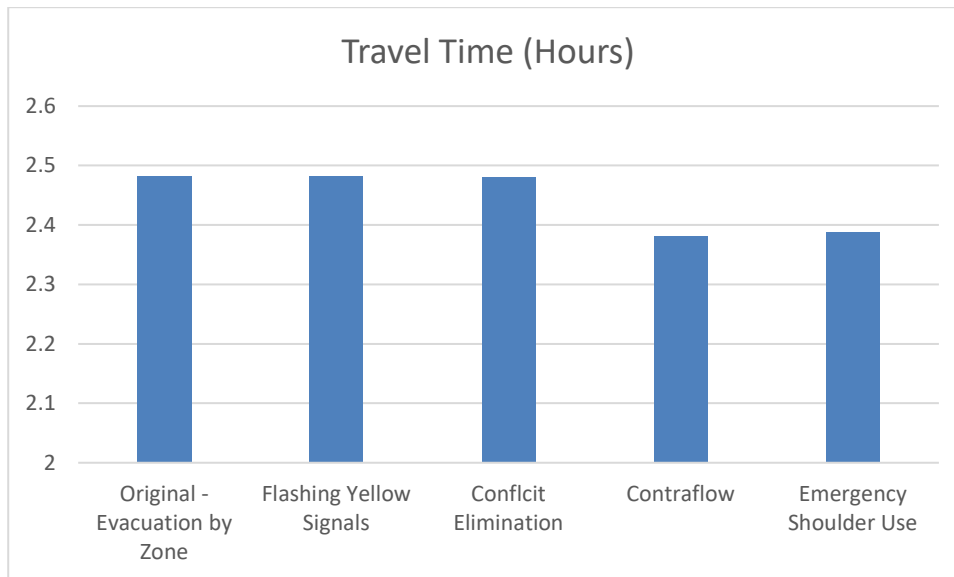


Figure 12: Travel Time from Key West to Homestead

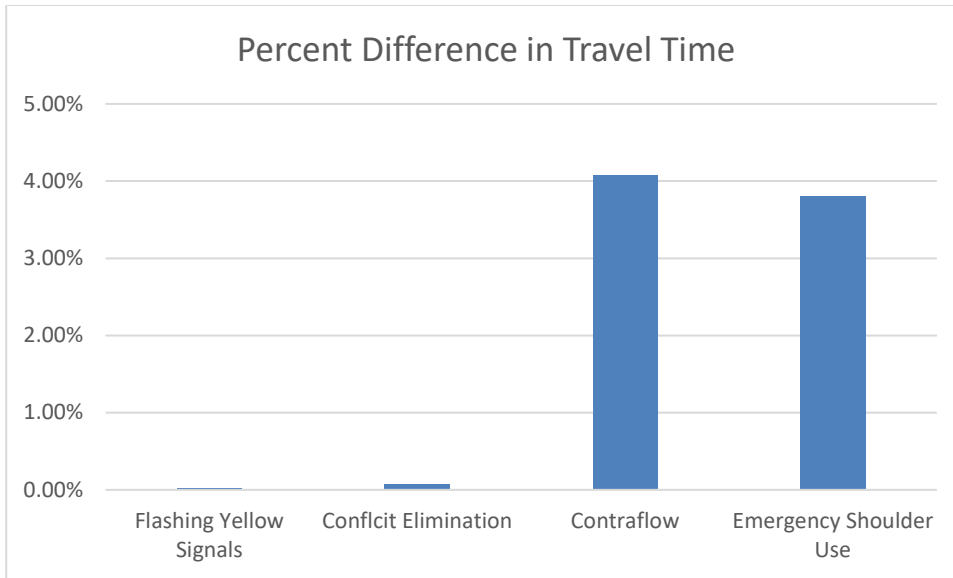
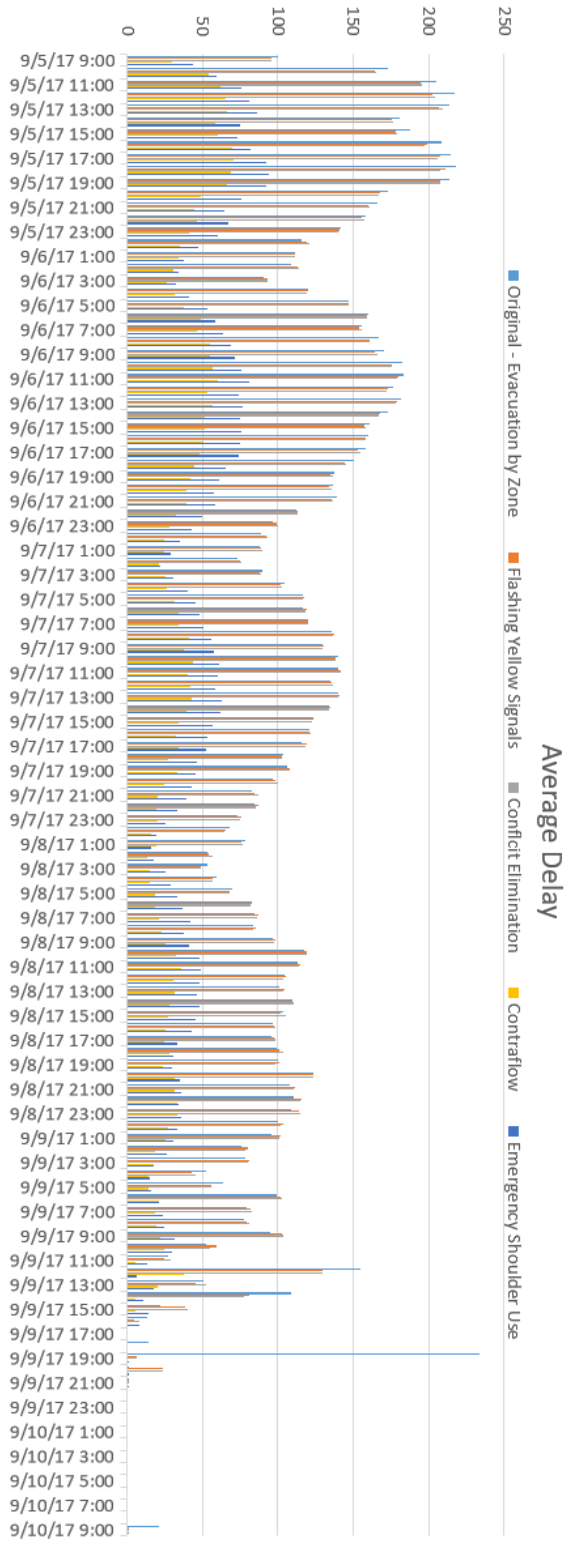


Figure 13: Percent Difference in Travel Time

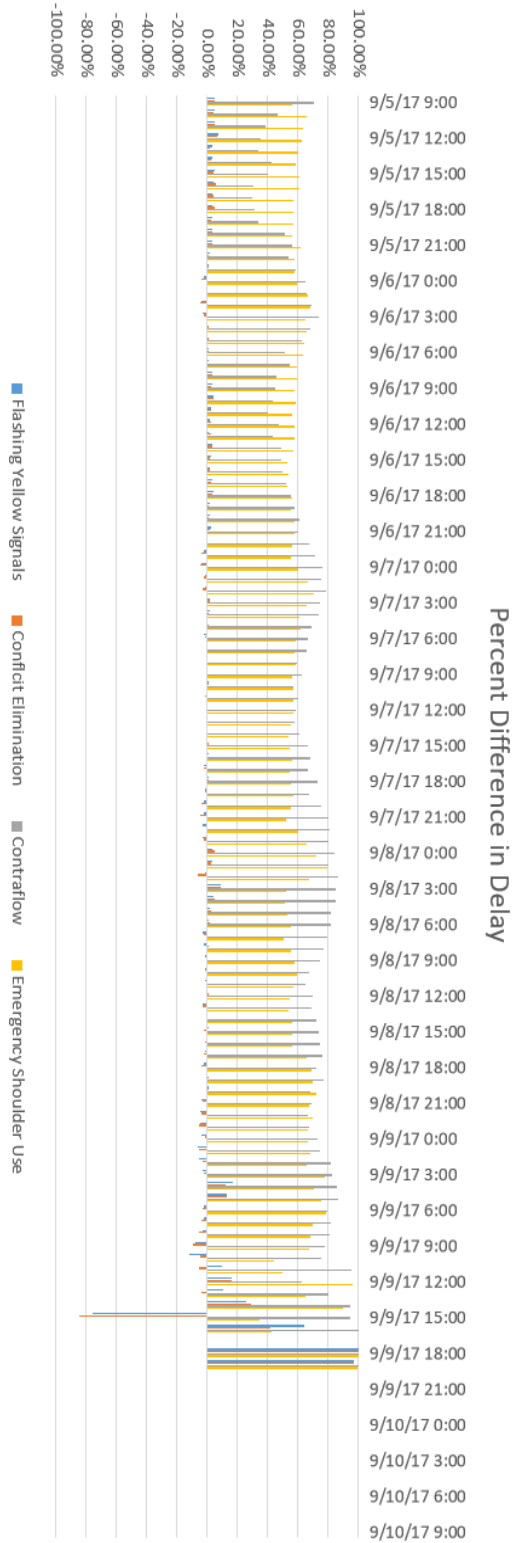
Just as discovered when analyzing the total travel time of evacuees when leaving the Florida Keys, the travel time for each vehicle is similar for evacuation by zone, flashing yellow signals, and conflict elimination. On average, a vehicle leaving from Key West will take approximately 2 hours and 30 minutes to get to Homestead and the main peninsula of Florida for all three of these evacuation strategies. Contraflow and emergency shoulder use have a short travel time. With emergency shoulder, the average vehicle leaving from Key West only takes 2 hours and 20 minutes to arrive in Homestead. Contraflow produces a travel time of 2 hours and 20 minutes as well for these evacuees.

Delay plays a large role in both total travel time and the travel time of vehicles from Key West to Homestead. If vehicles are sitting idle, waiting for a signal to change or for waiting for their turn to merge, the total travel time for the population and the travel time from Key West to Homestead would increase. This can be seen in the figure below which compares evacuee’s average delay – the delay divided by the number of evacuating vehicles active in the model – for each hour.





**Figure 3: Average Delay by Hour and Recommendation Type**



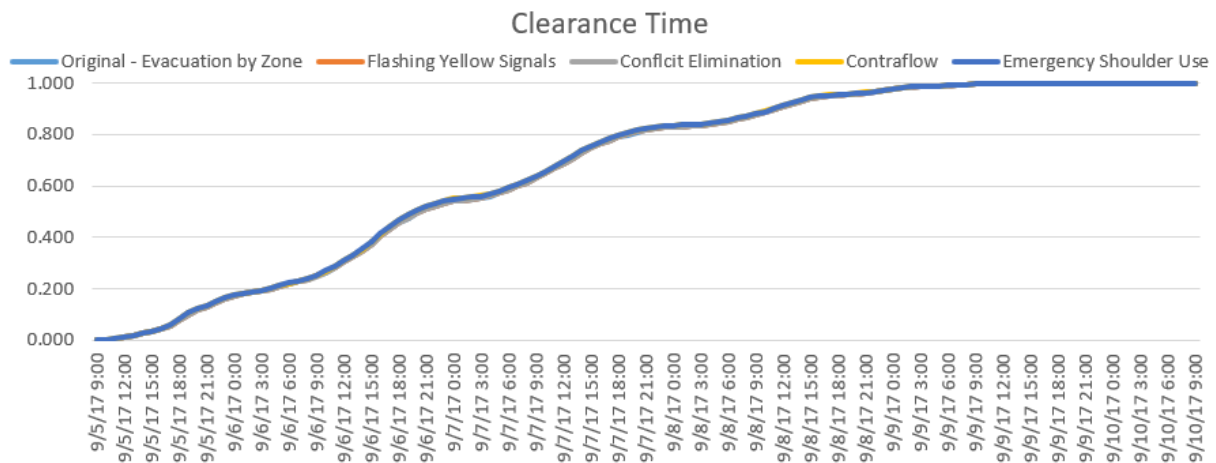
**Figure 2: Percent Difference in Average Delay**

From Figure 14 and Figure 15, implementing flashing yellow signals does not significantly impact the delay when comparing to the baseline of evacuating by zone. The average delay per evacuating vehicle per hour is improved by 2.58% when implementing flashing yellow signal. This would indicate that the time vehicles on US-1 sitting at red lights while vehicles join on US-1 (original model) is comparable to the amount of time vehicles on minor approaches wait at stop signs and signals wanting to join the traffic stream on US-1 (flashing yellow signals). There are very few signals, 16, in this roadway network compared to the approximately 500 stop-controlled approaches where vehicles can turn onto US-1 and this could impact the effectiveness of the flashing yellow signals in this area. The same could be true of conflict elimination which was only implemented at the intersections with traffic signals due to the large number of resources this method requires. The average delay was reduced by 2.00% when average over the 121 hours evacuation period.

Emergency shoulder and contraflow however significantly reduce delay. For emergency shoulder use, delay is reduced on average by 61.35% per hour during the evacuation for evacuating vehicles. Contraflow reduces delay by 66.58% per hour during the evacuation.

The significant reduction in delay by implementing these two methods indicates that delay when evacuating is caused primarily by queue formation along US-1. Adding lanes to the roadway increases the capacity and allows more vehicles to move at a higher speed. If large amounts of delay were caused by vehicles being forced to wait to turn onto US-1, these methods would not have been as effective, and the signals modifications would have made a larger impact.

In addition to the amount of time it takes to get evacuees out of the Florida Keys, it is important to understand this data in relation to the full length of the evacuation. To get a better understanding of the effectiveness of each recommendation in getting evacuees out of the Florida Keys, clearance time, the time when 90% of evacuees have left the archipelago, will be determined. This can also be seen in Figure 16. For every recommendation, 90% of evacuees have arrived on the main Florida peninsula by 11 am on September 8. It is important to note that the simulated evacuation began on September 5 at 9 am and the hurricane made landfall on September 10 at 9am. Because the modeled roadway is a maximum of 128 miles long, approximately a 3 hour drive, it was not expected that an improvement strategy would greatly change the shape of it curve; a recommendation would have to reduce the travel time by one third of the total travel time, almost an hour, to change the shape of the curve. If this data was collected for every 5 minutes, it may have been possible to see the recommendations that move vehicles more quickly through the network.



**Figure 16: Clearance Time**

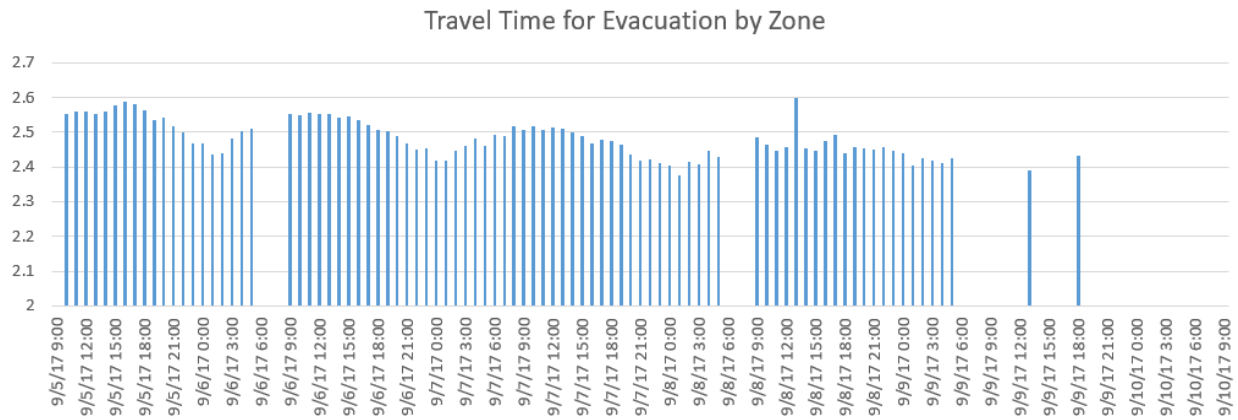
In addition to clearance time, determining the peak hour of the evacuation provides insight into the movement of evacuees during this evacuation period. Each recommendation corresponds to a graph below that shows the travel time to Homestead based on when the evacuee left Key West, by hour. This information will help emergency management teams see when the evacuation takes the longest and hopefully mitigate this potential for danger.

From Figure 17 the peak evacuation hour when only using evacuation by zone is on September 8, at 1pm. Leaving during this hour is the longest it would take for someone leaving Key West to reach the mainland – taking 156 minutes, more than two and a half hours in the evacuation conditions. For flashing yellow signals, the maximum evacuation travel time is 2.58 hours, or 154 minutes. This occurs twice during the evacuation – at 8am on September 7 and at 1pm on September 8. This can be seen in Figure 18. Figure 19 provides the travel time by hour for conflict elimination. The maximum travel times occur at the same times of the evacuation - 8am on September 7 and at 1pm on September 8. The maximum travel time is slightly lower at 2.55 hours, or 153 minutes.

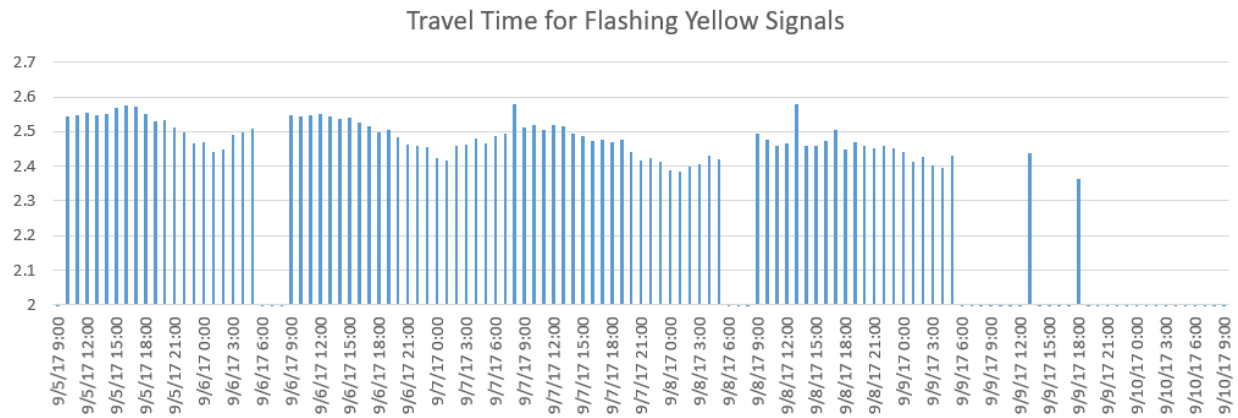
When implementing emergency shoulder use along US-1, the maximum travel time still occurs on September 8 at 1pm, but the time it takes an evacuee is less – 2.48 hours or 149 minutes. There is also a spike in travel time on September 7 at 8am but it is not as long of a travel time as leaving right after noon on September 8. When comparing this graph, Figure 21 to the current evacuation plan, by zone, this graph is less volatile – the travel time is similar no matter when an evacuee leaves their house. This is positive because this indicates that evacuees can leave at the time that fits their schedule best and will not experience a significant difference in travel time.

Contraflow produces a maximum travel time of 2.58 hours or 154 minutes, on September 9 at 1pm. Travel time when leaving Key West on the same day at 6pm is also a longer travel time. This can be seen in Figure 20. Similar to emergency shoulder use, the travel times are all

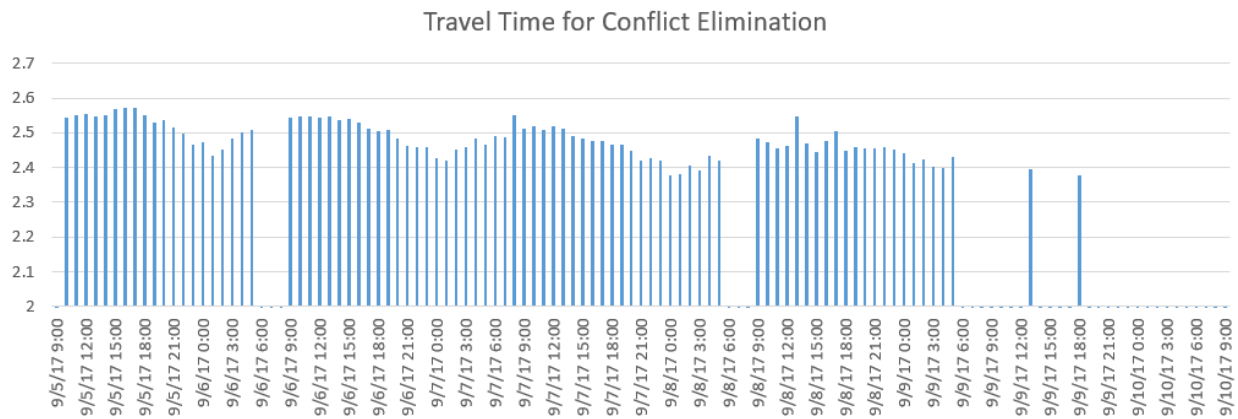
approximately the same – hovering around 2.40 hours. This is helpful because there is less pressure on evacuees to leave at a certain time when their travel time would be reduced.



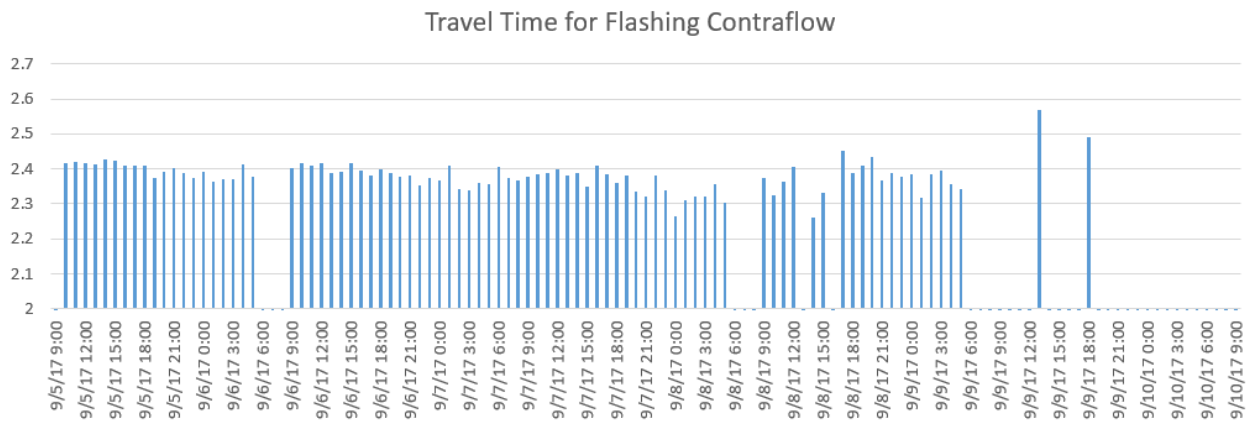
**Figure 17: Travel Time for Evacuation by Zone**



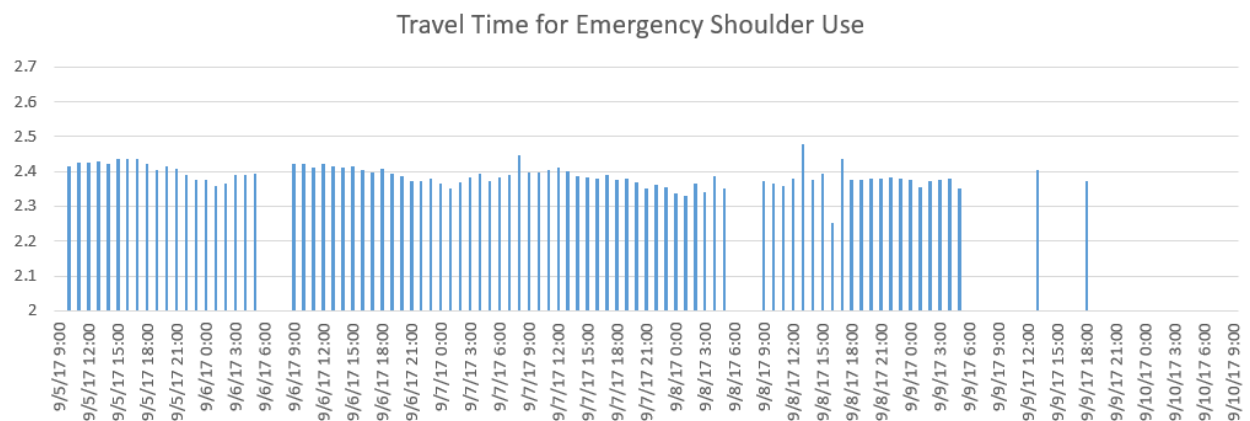
**Figure 18: Travel Time for Flashing Yellow Signals**



**Figure 19: Travel Time for Conflict Elimination**



**Figure 20: Travel Time for Contraflow**



**Figure 21: Travel Time for Emergency Shoulder Use**

The peak hour of the evacuation, for all the recommendations but contraflow, is on September 8 at 1pm. This is important to note because this occurs just three hours after 90% of evacuees reach Homestead. This indicates that the longest travel time occurs for the “last minute” evacuees. This makes sense because a majority of the population had exited, creating a large queue and therefore these last-minute evacuees faced the end of the most traffic and therefore the slowest travel time. This is problematic because these evacuees are at the highest risk of experiencing the beginnings of severe weather, power outages, and fuel shortages. In addition, from these graphs it can be determined that the shortest travel time often occurs at night. This is expected because very few people will be beginning their evacuation after midnight, especially given that Homestead is likely not evacuees’ destination.

Finally, the greenhouse gases produced by vehicles idling during each simulation was calculated and analyzed. As discussed in the methodology, Equation 3 was used to convert the number of total stop delay hours, which was provided by VISSIM, to grams of greenhouse gas emissions.

Table 5 provides the total stop delay, as well as the greenhouse gas emission for each of the recommendations. In addition, the percent difference was calculated.

$$94.3 \text{ hours} * \frac{.6 \text{ Gallon}}{1 \text{ hour}} * \frac{2131 \text{ grams}}{1 \text{ Gallon}} = 120,571.98 \text{ grams of GHG Emissions}$$

**Equation 3: Calculation for Grams of Greenhouse Gas Emissions**

**Table 5: Summary of Emissions Analysis**

<b>Vehicle Hours</b>	<b>Total Stop Delay [hr]</b>	<b>Greenhouse Gas Emissions [grams]</b>	<b>Percent Difference</b>
Original - Evacuation by Zone	94.30	120,571.98	-
Flashing Yellow Signals	16.33	20,879.54	82.68%
Conflict Elimination	15.64	19,997.30	83.41%
Contraflow	5.40	6,904.44	94.27%
Emergency Shoulder Use	53.53	68,443.46	43.23%

From this, all four recommendations reduce the greenhouse gas emissions dramatically. The recommendations that improve emissions by more than 50% - flashing yellow signals, conflict elimination, and contraflow – all remove traffic signals from the roadway network. This is important to note because this indicates that a majority of stop delay during the evacuation process is due to vehicles sitting idle at traffic signals.

Emergency shoulders use still uses traffic signals as the traffic control device, so the reduction in stop delay and emissions must come from the reduction of idling in queues. This is further supported by contraflow’s extremely low total stop delay and greenhouse gas emissions. Contraflow does not have traffic control devices on US-1 and a doubled capacity, which should reduce stop delay at traffic signals and in queues, producing such a low number of emissions from idling.

**Table 6: Analysis Summary Table**

		<b>Flashing Yellow Signals</b>	<b>Conflict Elimination</b>	<b>Contraflow</b>	<b>Emergency Shoulder Use</b>
Vehicle Hours	Total	65897.5	65888.74	58770.08	59317.77
	Percent Difference	0.02%	0.01%	10.80%	9.97%
	Rank	3	4	1	2
Average Delay	Average Percent Difference	2.58%	2.00%	66.58%	61.35%
	Rank	3	4	1	2
Clearance Time	Time at 90%	9/8/17 at 11 am	9/8/17 at 11 am	9/8/17 at 11 am	9/8/17 at 11 am
	Rank	-	-	-	-
Travel Time	Average Travel Time	2.48	2.48	2.38	2.39
	Percent Difference	0.01%	0.08%	4.07%	3.80%
	Rank	4	3	1	2
Emissions	Greenhouse Gas Emissions	20879.54	19997.3	6904.44	68443.46
	Percent Difference	82.68%	83.41%	94.27%	43.23%
	Rank	3	2	1	4
<b>Total</b>		<b>13</b>	<b>13</b>	<b>4</b>	<b>10</b>

Table 6 provides a summary of the previous data discussed. The percent difference shows the improvement from the current evacuation plan, evacuation by zone. Rank orders the recommendations for each analysis category, with 1 being the best and 4 being the worst. The final row provides the total score for each recommendation. Contraflow received a 1, as the best in each category. Emergency shoulder use received a score of 10, as the second best in the three categories relating to time and vehicle movement. Conflict elimination and flashing yellow signals both received scores of 13, making them the least effective.

As evidenced by the numbers in the summary table, contraflow and emergency shoulder use were the two recommendations that had the lowest total and therefore the largest positive impact on the evacuation process in the Florida Keys. Further discussion on each of these methods will be provided below to aid in making a final recommendation for local emergency management officials.

Contraflow, although it reduced delay significantly, produced a very small amount of greenhouse gases, and improved the efficiency of the evacuation, is an evacuation technique that requires significant resources and would be considered risky. If operating in contraflow conditions on US-1 in the Florida Keys, there is no way for hurricane-essential supplies, like

gasoline, non-perishable food, and bottled water, to reach the southwest islands. In addition, emergency vehicles and first responders would have no way to reach homes and people in danger. In other geographical locations, there are other routes that supply trucks and first responders could take to reach their destination, but this is not true in the Florida Keys. There is only one road, US-1, that connect the islands. In addition, implementing contraflow on US-1 would require significant amounts of resources – signs, police officers, and barricades that would be needed. This creates additional challenge because prior to a hurricane, local resources are focused on preparing the area for the disaster. There are also safety risks that could occur when operating a roadway in a way that it was not designed to handle. Because of all of this, it is not reasonable to put citizens at additional risk because supplies and assistance could not reach them even though contraflow provided the best results.

Emergency shoulder use provided significantly improved results when compared to the current evacuation plan, evacuation by zone, just as contraflow did, but comes with less risk. Emergency vehicles, supply trucks, and non-evacuating citizens will still be able to travel freely along US-1 in the southbound direction, unlike with contraflow. In addition, operating emergency shoulder does not require significant resources during the evacuation. Often, signs are used to indicate that the shoulder is open for use in an emergency. This does not require a significant number of law enforcement officers or time to set up the roadway for use. One of the largest risks with operating emergency shoulder is maintaining a safe driving experience. Emergency shoulder use was used on I-75 in Florida as a part of the Hurricane Irma evacuation. A study found that crash rates were no higher when using the shoulder as through lane (Sharma et al., 2020). This indicates that emergency shoulder use is a safe and beneficial technique to improve operations in an evacuation.

The Florida Department of Transportation has begun implementing emergency shoulder use on many of their interstates that provide routes northbound and away from the coasts that are heavily used during evacuations. Table 5 provides the locations where FDOT implements emergency shoulder use during a hurricane evacuation. They began implementing this strategy in 2017 and it replaced their former “one-way plans, also known as contraflow” (Florida Department of Transportation, 2017).

**Table 7: FDOT Emergency Shoulder Use During Evacuation (Florida Department of Transportation, 2017)**

<b>Road</b>	<b>Bounds</b>	
I-4 Eastbound	US41 – Hillsborough County	SR417 – Osceola County
I-10 Westbound	US301 – Duval County	US319 – Leon County
I-75 Alligator Alley (both directions)	SR951 – Collier County	US27 – Broward County
I-75 Northbound	SR951 – Collier County	SR143 – Hamilton County
I-95 Northbound	SR76 – Martin County	I-295 – Duval County
	Airport Rd – Duval County	Florida-Georgia Line



Florida's Turnpike Northbound	SR50 – Orange County	US301 – Sumter County
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Because of the Florida Department of Transportation's preference for emergency shoulder use and the risks related to contraflow, it is recommended that emergency shoulder use be implemented along US-1 in the Florida Keys. Implementing emergency shoulder use reduces the delay each hour by an average of more than 60% and the total travel time for evacuees in the region by almost 10%. The travel time for each vehicle is improved by almost 4% and provides a more consistent travel time throughout the evacuation process. Emitted greenhouse gases would be reduced by more than 40% if emergency shoulder use were implemented. All these things indicate that implementing emergency shoulder use will help move evacuees out of the Florida Keys more quickly and safely. This decision and the results from this analysis will ultimately help with the planning, mitigation, response, recovery, and adaptation of the Florida Keys from hurricanes and other natural disasters.

## 5. CONCLUSION

The Florida Keys is a unique archipelago with one roadway connecting the islands and the main peninsula of Florida. This creates different challenges for the region when facing a natural disaster like a hurricane. Because of this, comparing evacuation techniques and standards of other regions can provide a baseline but additional research and understanding is needed to best advance the evacuation process.

The goal of this research is to provide recommendations to the local emergency response teams and other stakeholders for improvement in the evacuation process in the Florida Keys. A methodology, including data collection, building a model of the roadways in the region, calibrating and validating the model, modeling recommendations, and analyzing the results, was completed to achieve this. Relevant research was analyzed and discussed in the literature review to gain a better understanding of the evacuation process, the difficulties surrounding evacuations, and possible improvements that could be implemented.

Data collected included the number of lanes and their widths for each segment of US-1, population by census tract, and the location of traffic control devices in the corridor. A unidirectional model was built in PTV VISSIM, which included the 128 miles of roadway between Key West and Homestead, 512 approaches where evacuees may be turning onto US-1, the appropriate traffic control devices, and other modeling features. The vehicle inputs were then calculated from traffic counts from the Hurricane Irma evacuation and inserted into the model in the calibration phases. Adjustments were made to the inputs until the model reflected the real traffic counts at two different data collection points. During validation, the traffic counts at the final data collection location in real life were compared to the simulation, further verifying the legitimacy of the model.

Changes were then made to the base model to reflect the different recommendations: flashing yellow signals, conflict elimination, contraflow, and emergency shoulder use. This required adding lanes, making changes to the traffic control devices at intersections, and modifying

connectors. These models were then run 5 times and the results averaged for analysis. Network performance data, travel time, and clearance time were all analyzed to better understand the evacuation process with each recommendation better.

Both flashing yellow signals and conflict elimination were not highly effective. It is predicted that this was caused by the low proportion of signalized intersections where these techniques could be implemented. The recommendations that change the capacity of the roadway, contraflow and emergency shoulder use, were much more effective in improving the evacuation for residents of the Florida Keys.

Ultimately, emergency shoulder use is the best recommendation to implement in the Florida Keys. Emergency shoulder use reduces total travel time and the average delay a vehicle faces while evacuating. Emergency shoulder differs from contraflow in the sense that it does not require as many resources to operate and still allows vehicles to travel in the opposing direction. The favoring of emergency shoulder use over contraflow can be seen in policy changes made in recent years by the Florida Department of Transportation, as they implement emergency shoulder use on the major evacuation routes in the state.

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