Spatiotemporal Traffic Characteristics of Megaregion Mass Evacuations

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16. Abstract

Mass evacuations, particularly those at a statewide level, are among the largest single-event highway traffic events. They can last several days, cover thousands of miles of roadway, and include hundreds of thousands of people and vehicles. Often, they are also marked by enormous delay and congestion and are nearly always criticized for their inefficiency and lack of management. Despite the critical importance and the potential to impact lives and safety, there are no recognized methods to systematically quantify traffic characteristics at statewide scales. This paper documents the development and application of an analytical method to measure statewide mass-evacuations. The proposed approach sought to be both practical and cost-effective.

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Chapter 1. Introduction

Mass evacuations, particularly those at a statewide level, represent the largest single-event traffic movements that can occur. These complex transportation events can last several days, span thousands of miles of roadway, and include hundreds of thousands of people and vehicles traveling with vital urgency. Often, evacuations are plagued by enormous travel delay and congestion and are nearly always criticized for their inefficiency and lack of management. However, few studies quantitatively examine such events to objectively assess what travel conditions were actually like. Typically, opinions are based on media reports that tend to sensationalize poor operations and focus strictly on areas that are performing poorly.

There are many reasons why mass evacuations have tended not to be comprehensively studied. Obviously, they are large and complex, but another reason is the lack of standardized methods by which to systematically quantify traffic characteristics at the proper scale. Few indicators, apart from a lack of fatalities and the amount of vehicles moved, determine if any evacuation was "effective" or not. Instead, outside of media reports, emergency managers and transportation professionals often work under a general assumption that an evacuation was effective if people were able to get out of danger and no one drowned in their homes.

To provide a basis of measurement and comparison, this paper describes research to examine and assess evacuation characteristics. More importantly, the paper attempts to create and apply a method to measure and quantify evacuations in an unbiased, practical, and repeatable fashion that is both intuitive and beneficial to state officials. The research methods are based on simple, yet widely available, and easily understood traffic count datasets.

Traffic volume counts serve as a fundamental parameter of traffic measurement, but they can yield enormous insights into the ebb-and-flow of daily commutes and when, where, how much, and how fast people are able to move during an evacuation. These wide area, long term vehicle counts can also be used to illustrate the movement of evacuees *after* the hurricane to better understand how many vehicles were impacted, when the recovery began, and even how long it took based on when the traffic patterns returned to normal.

Building on these concepts, the objectives of the research were to spatially and temporally quantify key aspects of the evacuation and reentry process in Florida during the record-setting 2017 and 2018 hurricane seasons, specifically:

1. When did the auto-based evacuation make a measurable impact on traffic (when did it noticeably start)?
2. What were the loading characteristics of the evacuating traffic on the network?
3. What was the peak evacuation volume and when did it occur?
4. When did the auto-based evacuation conclude?
5. How many vehicles were used in the evacuation?
6. When did reentry begin?
7. When did reentry effectively conclude?

These objectives were achieved through the observation and analysis of roadway volumes collected from ground based sensors (predominately, magnetic-loop detectors) during the hurricanes Irma (2017) and Michael (2018) evacuations and reentries in the State of Florida. These two events provide a unique opportunity to study the evacuation phenomenon because they are among the largest in the history of the United States; they affected nearly all of the major metropolitan population centers of the state; and traffic volumes are recorded on a geographic scale and at levels of fidelity rarely achieved in prior evacuation studies.

The scientific contribution of this work is its demonstration of a straightforward and reproducible methodology to measure the auto-based evacuation response and reentry of an area. The methods demonstrated in this paper also have a significant practical value for state transportation and/or emergency management agencies seeking to quickly and accurately assess evacuation characteristics. This research also expands the literature by providing insights into the less-often-studied topic of evacuation reentry timing and participation. Finally, it creates a set of aggregate evacuation parameters that can be used to calibrate evacuation planning and simulation models making the paper a valued reference for future research studies.

1.1. Event Background

The 2017 evacuation from Hurricane Irma has been referred to as the largest evacuation in the history of the United States. Approximately 6.5 million Floridians were placed under either mandatory or voluntary evacuation orders [1]. The overwhelming response to Hurricane Irma was fueled by several factors that were unique to the storm: 1) Hurricane Irma had already devastated a number of Caribbean islands, including the U.S. Virgin Islands and Puerto Rico, resulting in several known deaths at the time [1]. 2) At one point, Hurricane Irma was the fifth strongest hurricane ever recorded in the Atlantic Ocean. 3) The storm's path and "cone-of-uncertainty" threatened nearly the entire state of Florida. 4) Fluctuations in the storm's path indicated possible devastating storm surge to nearly all of Florida's coastal areas, where the majority of residents live.

The National Hurricane Center's (NHC) storm path prediction for Hurricane Irma 67 hours before landfall suggested a Saffir-Simpson scale Category 4 hurricane making landfall in Southeast Florida and continuing up the eastern coast. However, 21 hours later the NHC's revised storm path predicted a landfall on the Florida Keys and a northern approach along the western coast [2]. It can be surmised that the storm's path generated evacuees from both the eastern and western portions of the state as well as coastal regions in the south from Key West, north to Jacksonville, FL.

Ultimately, Hurricane Irma made two landfalls within the state of Florida. The first was near Cudjoe Key in the lower Florida Keys, on September 10th 2017 at approximately 9:10 AM ET as a Category 4 hurricane with sustained winds of 130 mph (209 kph). The second landfall was at approximately 3:35 PM ET near Marco Island, just south of Naples, FL as a Category 3 hurricane with winds of 115 mph (161 kph) [3]. The storm left approximately 6.7 million homes (65 percent of the state), without power [4]. Hurricane Irma was attributed to taking the lives of 75 Floridians and costing an estimated $49 billion [5]. The lower Florida Keys remained closed to non-residents for approximately three weeks following the storm [6].

Hurricane Michael was a Category 5 hurricane that made landfall near Mexico Beach, Florida on October 10th, 2018 at approximately 12:30 PM. With sustained wind speeds of 155 mph (250 kpm), Hurricane Michael was the strongest storm by wind speed to strike the mainland U.S. since Hurricane Andrew in 1992 [7]. However, initial reports suggested Hurricane Michael would make landfall as a Category 3 hurricane, which may have had an impact on evacuation participation rates leading up to landfall [8]. Hurricane Michael's intensity projections 54 hours before landfall forecast a Category 1 or Category 2 storm [9]. Ultimately, Hurricane Michael was directly responsible for 16 deaths and approximately $25 billion in damage. In total, 21 counties issued evacuation orders, of which 12 held mandatory orders in place [10].

Chapter 2. Literature Review

Available data sources by which to examine evacuations have been rapidly increasing. Examples include geotagged Tweets [11]-[12], travel time predictions [13], and mobile phone location data [14]-[15]. While these sources help address gaps, such as under-representation of the younger population and low participation rates in surveys [16], they have their own limitations, such as the need for geo-locations and use of the social media platform. The advantages of traditional detectors remain, including low cost [17], real time data access for departments of transportation [18], and lack of need for evacuees' active use of a platform, indicating the value of these data sources alone or in conjunction with emerging data sources.

Detectors are most prevalent on high volume, high-capacity roads. This corresponds well with prior survey-based research which found that evacuees have a strong preference for Interstates (e.g., [10]) and highways (e.g., [20]), although familiarity and experience with a roadway also play a role in evacuation route selection (e.g.,[21]-[24]). A few studies have used detector data to investigate different aspects of the evacuation. Wolshon [24] used detector data from Louisiana collected during Hurricane Katrina to assess how well the maximum capacities suggested by the Highway Capacity Manual matched the detector reported flows for different types of roadways. These roadway types included freeways operating in the normal direction, contraflow freeway segments, four-lane arterial roadways, and two-lane arterials. On all of these roadways, the maximum flows were lower than the theoretical values [24].

Li et al. [25] used automatic traffic count data from tollbooths to develop empirical response curves for Hurricane Irene for a single county in New Jersey. They also identified evacuation volumes and compared these to the volumes from the previous week. They identified the evacuation traffic as starting six hours before the mandatory evacuation order for the barrier island and an overall quick response to a mandatory evacuation order, which they suggested could be due to the large tourist population [25]. They later expanded their spatial coverage and data to include weigh-inmotion stations and historical travel time data [26]. This study reported that the evacuation took approximately 36 hours and the evacuation traffic was more obvious near the shore, tending to move west instead of north along the shore. Similar spatial patterns were observed for Hurricane Sandy, although volumes were lower than for Hurricane Irene [27].

These prior studies focused on the pre-impact evacuation. Compared to research into the evacuation process, fewer studies have investigated the length of time people remain away from home [20] or re-entry traffic [28]. However, from survey data, for Hurricane Lili, the average duration of time away from home was 2.33 days [29] and for Hurricane Katrina, the average was 13.8 days [20]. This large range suggests that the amount of time evacuees stay away from home can vary substantially, depending on the hurricane and its effects. Furthermore, some people may permanently migrate (never return).

Managing reentry can be challenging. In contrast to evacuation where destinations are dispersed, in reentry, traffic converges to the area(s) that were evacuated [30]. These areas may have suffered damage and have debris issues and utility outages. Several studies have reported low compliance with official reentry plans: 38% for Hurricane Ike [31] and 46.4% returning on or after the scheduled return date for Hurricane Rita [32]. Considering this relatively low compliance, it is important for researchers to investigate and agencies to understand when evacuees will return and the volumes in which they do so. This study uses aggregate data to improve this understanding.

Chapter 3. Methodology

Broadly, the research methodology utilized traffic count data taken from across the state of Florida to investigate the auto-based evacuation response and reentry of coastal communities from both Hurricanes Irma (2017) and Michael (2018). The first part of the methodology was to process traffic count data used in the analysis. The second part of the methodology discussion demonstrates how this data was used to estimate the start and end of the auto-based evacuation, the traffic loading and peaking characteristics, and the total number of vehicles used in the evacuation process, as well as the effective start and end of the auto-based reentry.

3.1. Data Collection and Processing

The Florida Department of Transportation's (FDOTs) Transportation Data and Analytics Office gathers roadway data from across the State of Florida. Real-time traffic information is provided during emergency such as hurricanes and wildfires. Traffic information, namely volume, speed, and vehicle classification are collected hourly from telemetric monitoring stations located throughout the state. There are 255 data collection sites on Florida roadways at the time of this study; each provides bidirectional hourly counts and speeds. For the analysis of the Hurricane Irma evacuation, data was collected, cataloged, and processed for a 36-day period beginning August 27th, 2017 and ending October 1st, 2017. The analysis of Hurricane Michael encompasses the same locations and included a 14-day period that began October 1st, 2018 and concluded October 14th, 2018.

The evacuation analysis focuses on four general regions: Naples, the Florida Keys, and Southeast Florida were analyzed during Hurricane Irma and regions of the Florida Panhandle were investigated during Hurricane Michael. Naples and the Florida Keys were included in the analysis because Hurricane Irma made landfall in both regions. Southeast Florida was included in the analysis because this region of Florida is the most heavily populated and was directly in the path of Hurricane Irma. Unlike Irma, Hurricane Michael showed a consistent and ultimately accurate storm path projection, leading to the evacuation being focused in the panhandle region. For this reason, only one analysis area was investigated for Hurricane Michael.

The data collection sites were selected to encompass each of the five regions, similar to the way a cordon line identifies the inner and outer limits of an area. A cordon line is an imaginary line drawn around a study area. Traffic data is collected at roads which cross the cordon line. These locations and analysis regions were provided in Figure 1. Given the relative location of each count station, directional counts were classified as "inbound", into the region, or "outbound", out of the region. Drawing a cordon line around a major city, a net increase in the number of inbound vehicles would be expected in the morning, while the opposite would be expected in the afternoon, for a typical commute. As such, it should also be expected that the number of vehicles entering the region in the morning should be approximately equal to the number exiting in the evening. A failure to maintain this equilibrium would result in an overall net increase or decrease of vehicles within the cordoned area. However, during an evacuation, this pattern is broken resulting in the number of vehicle exits significantly outnumbering vehicle entries.

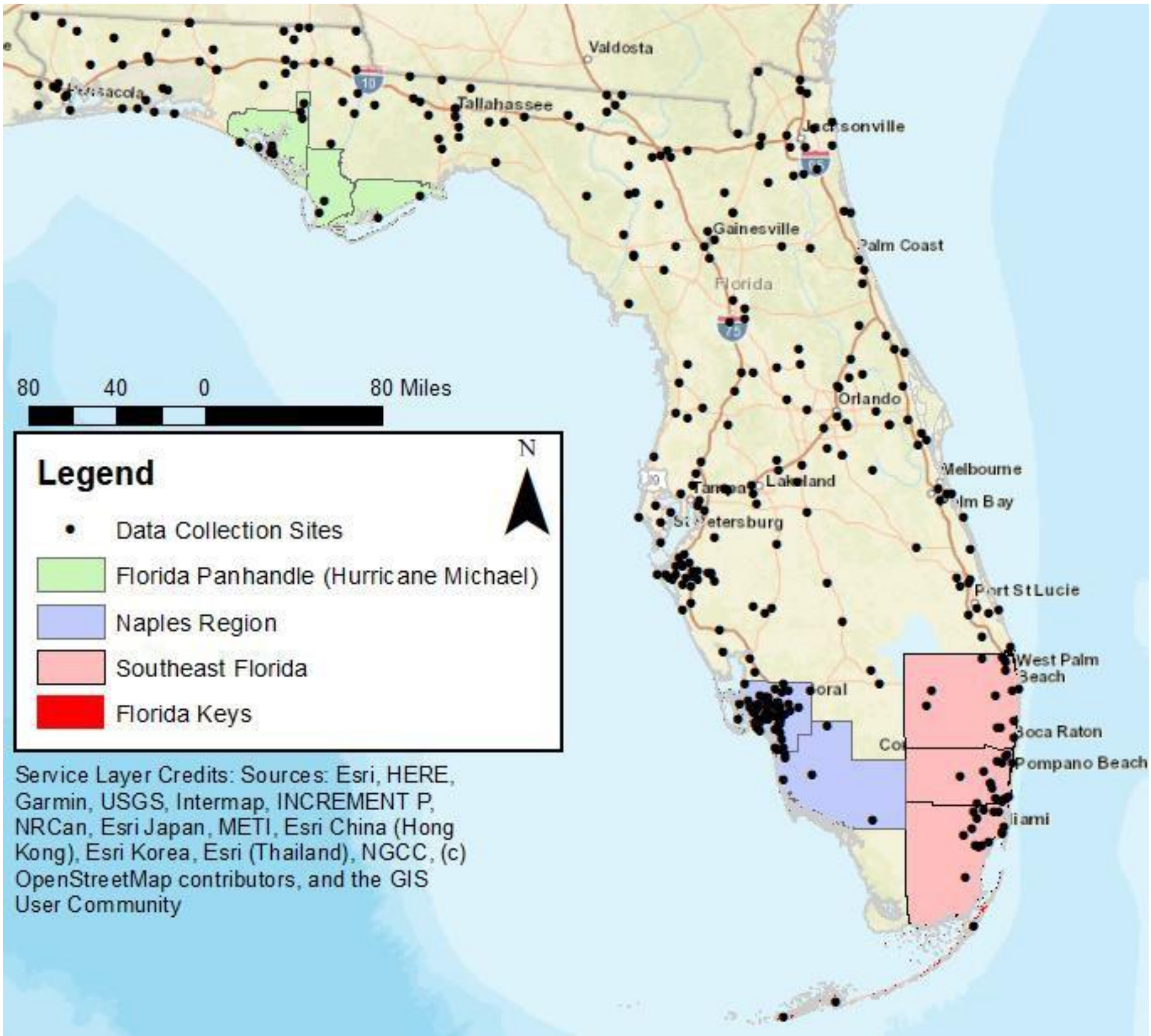

Figure 1 FDOT Data Collection Sites and Analysis Regions [33]

3.2. Evacuation Analysis

Fundamentally, the change in the number of vehicles within a defined cordon boundary can be measured by adding the number of vehicles crossing a cordon line into the area and subtracting the number of vehicles exiting. This simple method can determine the change in the number of vehicles within the boundary area. By establishing a cordon line around an evacuating city or region, it is possible to count the number of vehicles entering and exiting the study area. The number of evacuating vehicles can be estimated by calculating the net change in vehicles crossing the cordon boundary over a period of time. Let the number of vehicles entering an evacuation area A, from location i along the cordon line for area A, over time interval t, be represented by I^{A}_{it}. Likewise, let the number of vehicles exiting A at i, during t, be represented by the variable [illegible]$^{A}_{it}$.

The start of the evacuation is noted as τ and the recovery time, after the evacuation and reentry of *A*, as *T*. The net change in vehicles can be calculated at any time *t*, as Δ_t^A in Equation 1:

$$\Delta_t^A = \sum_{��=1}^{I} (I�_{i��}^A - ���_{i��}^A) \quad (1)$$

In general, daily commuting patterns tend to result in approximately the same number of vehicles entering and exiting a region during a 24-hour period $\sum_{��=1}^{24} {}^A\Delta_t \cong 0$. While seasonal variations or special circumstances often occur that violate this assumption, the daily equilibrium tends to remain relatively in balance. Determining the approximate time an evacuation begins (τ) and recovery ends (*T*) has been a significant challenge for emergency managers. However, as the traffic pattern changes over time, the imbalance caused by the evacuation in favor of outbound vehicles becomes evident i.e. $\sum_{��=1}^{24} {}^A\Delta_t < 0$. While it remains difficult to estimate the precise time at which the evacuation begins and recovery ends, due to the stochastic nature of driving patterns and behaviors, this research shows, to the hour, when the traffic pattern deviated from a typical commuting regimen. For example, Figure 2 (shown later in this paper) represents the cumulative net change in vehicles crossing the cordon line with a thick, dashed line. In a typical situation, this dashed line should return to near zero, daily. That would represent approximately the same number of entering vehicles as exiting vehicles in any 24 hours. The thick dashed line in Figure 2, however, does not return to zero. It instead takes a persistent negative value beginning at approximately 09:00 on Sept. 5, 2017 until landfall. The return to a near zero net change in traffic does not occur until Sept. 17, 2017 at 16:00, several days after landfall. Therefore this research defines the start of the auto-based evacuation τ and the recovery time (the end of the reentry) *T* as the start and end times corresponding to a net loss in vehicles that is inclusive of the hurricanes landfall time, $��_l$.

The total number of evacuating vehicles for area *A* is calculated as the minimum value of the cumulative Δ_t^A. The clearance point of the auto-based evacuation ($��_{c��}$) is the time at which the cumulative Δ_t^A reaches its minimum value (i.e., when the maximum number of evacuating vehicles have exited the cordoned area). For a hurricane evacuation, the clearance point typically occurs before or at landfall ($\tau \le ��_{c��} \le ��_l$). The clearance time ($��_{c��}$) is the duration between the start of the evacuation and the clearance point ($��_{c��} = ��_{c��} - ��$). The peak evacuation traffic is seen when Δ_t^A reaches a minimum value. The peak evacuation hour $��_p$, is the hour that sees Δ_t^A reach a

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mi ni mu m value. This minimum can then be considered the peak evacuation exit volume of the area. Evacuation peak demand flow rate and evacuation peak hour factor can also be calculated, if detectors report 15-minute count intervals or shorter. Likewise, the same is true for reentry vehicles. The reentry reaches its peak hour (��$_r$) when Δ_t^A reach a maximum value. A similar calculation can be commuted to determine a reentry peak hour factor, as well.

By considering the maximum value of the cumulative Δ_t^A as 100 percent of the auto-base evacuation demand, then ��$_{c}$�� represents the clearance time for 100 percent of the auto-based evacuees. It is therefore possible to estimate the clearance time for any proportion of the auto-based evacuation. For example, the clearance time corresponding to 90 percent of the auto-based evacuation ��$_{c��90}$ is the time at which 90 percent of the cumulative Δ_t^A minimum is achieved. In this fashion, it is possible to estimate vehicle exit rates and if travel time (*TT*) data is available, these exit rates could be adjusted to estimate vehicle-loading rates (*LR*) by subtracting out the average travel time (��$_{c��}$ − ��$_{c��}$ = ����$_{c��}$).

3.3. Methodological Limitations

There are several limitations to the proposed methodology, which warrant discussion before presenting the research findings. The first is that the proposed method is based on the assumption that in any 24-hour period the total number of inbound trips should approximately equal the total number of outbound trips. While the total number of inbound and outbound trips can generally be assumed equal, this does not always occur within a 24-hour cycle. For example, a tourist may travel into a region for several days before exiting. This would result in a net increase in vehicles for several days before canceling out. This is particularly problematic in Florida, which has many desirable tourist destinations. This leads to the next limitation of this study in that the methodology cannot classify trips by purpose. The current method assumes that any vehicle, who exits the cordon and does not return, is an evacuee. For example, a tourist who entered the cordon line before the data collection period and later leaves without returning is counted as an evacuee. This deficiency within the methodology is somewhat mitigated by extending the data collection period, which was done for this study. Another limitation to the methodology results from the intermingling of evacuation origins and destinations. This occurs when a vehicle evacuates from one cordoned area and into another cordoned area. The cordoned area from which the vehicle departed would correctly count this vehicle as an evacuee (-1). However, the area in which the vehicle evacuated to would count this vehicle as a net gain (+1) and would detract from the total number of evacuees departing this area. Furthermore, evacuees who select destinations within their origin cordon area are not counted. The methodology is also limited by the availability of data collection sites. Four out of the five cordon lines used in this study are not true cordon lines, as a number low volume roads were not included in the analysis. However, as the data collection sites were provided by FDOT, the major highways entering and exiting the cordoned regions where included and with them the vast majority of vehicles.

Chapter 4. Results

The results focused on the development and analysis of figures that show the hourly net change in vehicles (Δ_t^A) and the cumulative net change in vehicles (Δ_t^A $\sum_{��=1}^{T}\Delta_t^A$) for the Florida communities affected by hurricanes Irma and Michael. These figures were used to determine the total number of evacuating vehicles ($\sum_t \Delta_t^A$), start of the auto-based evacuation (τ), and end of the recovery ��$_{cp}$

period (*T*), clearance point (��$_{c}$��), the peak evacuation volume (Δ_t minimum) and hour (��$_p$) as well as the peak reentry volume (Δ_t A maximum) and hour (��$_r$). The figures also show evacuation orders and time of landfall. The results further discussed the development of evacuation time estimate curves, which show the cumulative percent evacuating each region over time. From these curves, it was possible to estimate the 90 percent clearance time $��_{c��90}$, 50 percent clearance time $��_{c��50}$, etc.

This figure was also used for the calculation of the 50th-percentile displacement time, the number of hours that at least 50 percent of the evacuated vehicles remained outside the cordoned area.

4.1. Evacuation Figures

Figure 2 shows the evacuation and reentry traffic resulting from the Hurricane Irma evacuation of the Naples, FL region. The primary y-axis displays Δ_t^A, the number of evacuated vehicles hourly. The secondary y-axis displays the cumulative number of evacuating vehicles for all periods. The x-axis is time, in hours. Landfall, $��_l$, is called out in the figure as well as the first mandatory evacuation order given for the region. The figure shows a typical example week of traffic to demonstrate the disparity between the evacuation and routine conditions. In general, the daily traffic shows a morning peak of traffic entering the region ($I�_{it}^A > ���_{it}^A$) and an afternoon peak where vehicles are leaving the region ($I�_{i��}^A < ���_{i��}^A$). Traffic shows net losses in the number of vehicles prior to landfall and net increases, post landfall, representing the evacuation and re-entry, respectively. The maximum traffic demand periods during both the evacuation and reentry are shown on the figure as the peaks and valleys of the evacuation traffic line. It is important to note that the cordon line, which encircled the Naples Region, did not constitute a true cordon, as data for many smaller roads were not available. However, the cordon likely captures the majority of evacuees.

Naples saw a net decrease of 123,202 vehicles in the days leading up to the storm. According to the traffic data, the evacuation of Naples began around 9 AM on Tuesday September 5, 2017. This suggest the vehicular evacuation of the Naples region began approximately 75 hours before the first mandatory evacuation orders were given and 126 hours before landfall on Marco Island. The figure suggest that over 48,000 vehicles had exited the Naples region prior to mandatory evacuation orders being given. That is to say, 38 percent of the vehicles that would eventually leave the region did so prior to governmental directives. The analysis also suggest the evacuation took 122 hours to complete, concluding just 4 hours prior to landfall. Reentry into the Naples region began two hours after landfall, peaking the following day at 1:00 PM (22 hours after landfall). Ultimately, traffic did not return to pre-storm levels until Sept. 17, 2017 at 4:00 PM, over one week after landfall.

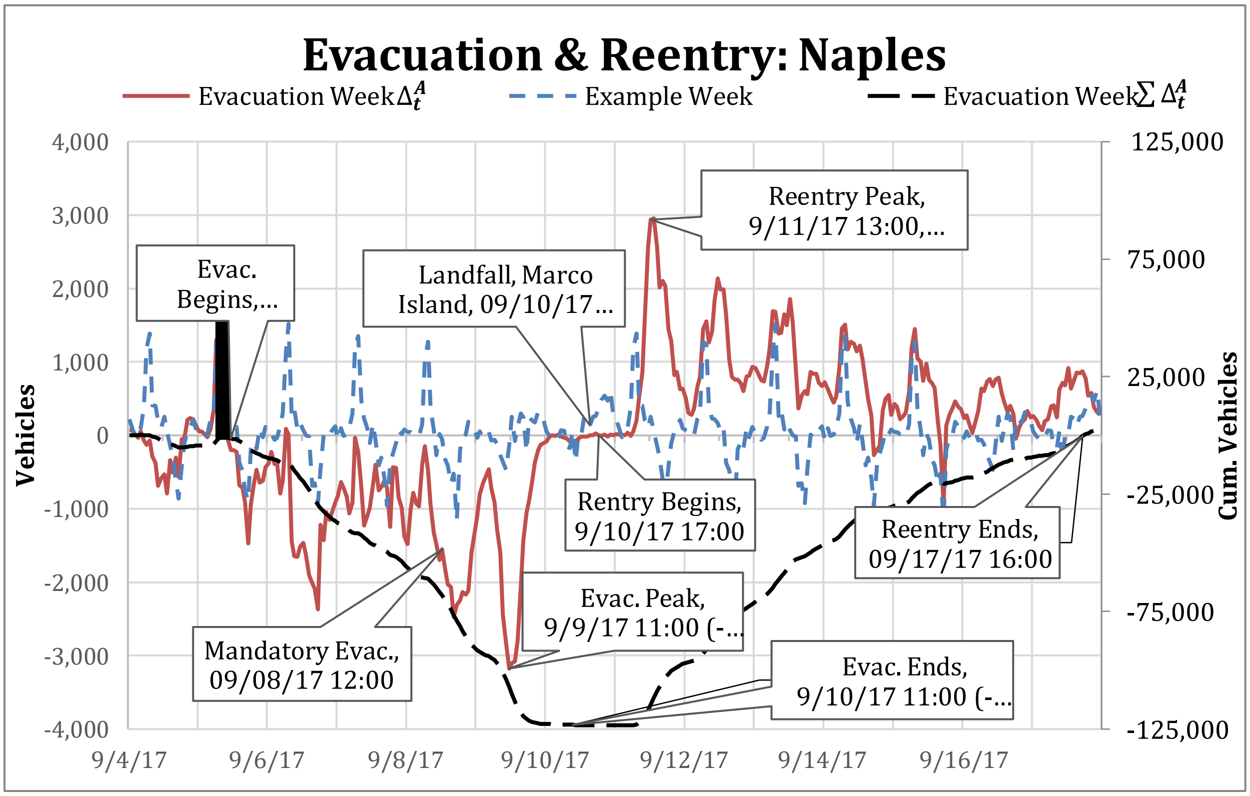

Figure 2 Naples Evacuation and Reentry Traffic Analysis

The figure for the Florida Keys is shown in Figure 3. Unlike the other regions, this portion of the Florida Keys has only one primary evacuation route and therefore the analysis represents data collected from only one detector location. The analysis found that 40,731 vehicles crossed the cordon line, not to return until after the storm. The evacuation began approximately 1 PM on Sept. 5, 2017, two hours before the mandatory evacuation order given for regions of Monroe County and 116 hours before landfall (on Cudjoe Key Sept. 10, 2017 at 9:00). The evacuation peaked 25 hours after the mandatory orders were announced and concluded 102 hours later (12 hours before landfall on Cudjoe Key). The reentry began two hours after landfall, peaking on Sept. 18, 2017 at noon (195 hours after landfall), and required 503 hours (nearly three weeks) to complete.

Figure 4 shows the evacuation of Southeast Florida. This cordon line included nine detector locations along the major highways and freeways exiting the region. Again, it was not possible to conduct a true cordon, as many lower capacity streets were not available for analysis. Southeast Florida saw 276,052 vehicles leave the area along the observed routes in the days leading up to the storm. The first mandatory evacuation orders were given for regions of Miami-Dade County on Sept. 7, 2017 at noon. The evacuation began just three hours later (93 hours before landfall on Cudjoe Key) and peak 66 hours before landfall. The net egress of the South Florida region concluded on Sept. 8, 2017 at 5 PM (40 hours before landfall). The figure shows that at this point 276,052 more vehicles had exited the region than entered. However, in the period between this clearance and landfall, 20,282 more vehicles (7.35 percent) entered the region than exited. That is to say, after the cumulative change in volume reached its minimum value before landfall, over

20,000 more vehicles travelled into and stayed in Southeast Florida, than exited during this 40-hour period. After landfall, vehicles almost immediately began to flow into the region, with reentry traffic peaking 31 hours after landfall. Traffic in the region did not return to pre-storm levels for nearly eight days (223 hours after landfall).

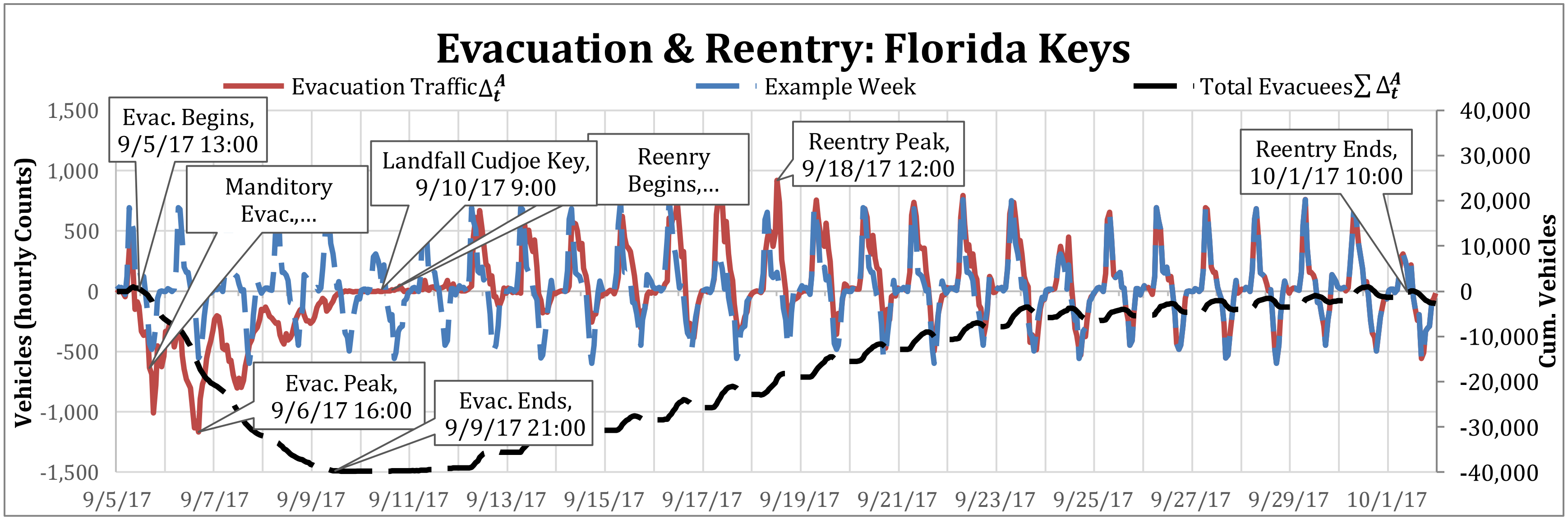

Figure 3: Florida Keys Evacuation and Reentry Traffic Analysis

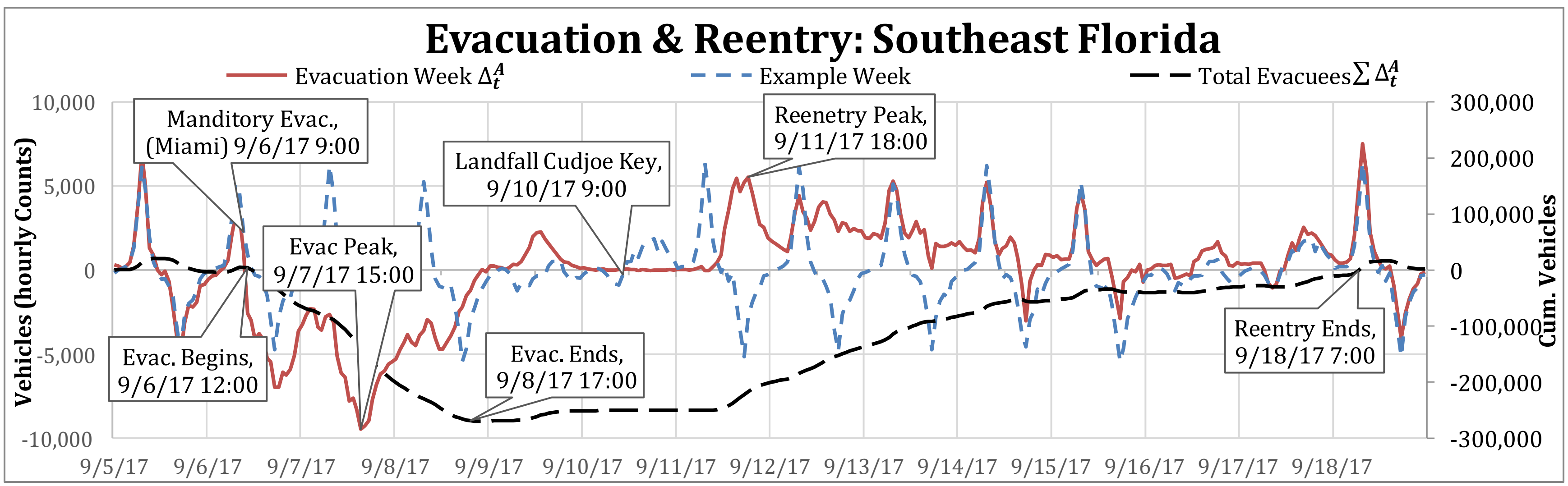

Figure 4: Southeast Florida Evacuation and Reentry Traffic Analysis

Figure 5 shows the evacuation from Hurricane Michael in the Florida Panhandle Region. The cordon line used in the analysis consisted of seven detector locations on the major exit routes of the area. Severe damage to the power grid resulted in the loss of service to many of the data collection sites, leading up to and after the storm's landfall. Detector failure began at midnight of Oct. 10, 2018 and continued (off and on) until the data collection period ended. This period is shown in the figure as a yellow overlay depicting times of poor data quality. The detector failure began 13 hours prior to landfall, at which time, 16,370 vehicles had exited the region. The remaining detectors indicated that 18,302 vehicles had existed before landfall. The evacuation began on Oct. 7, 2018 at 7 AM, 27 hours prior to the first mandatory evacuation orders going into effect. The evacuation traffic peaked nine hours after the mandatory order and 41 hours before landfall. Due to the detector error, it was not possible to determine the exact time of the clearance point. However, the figure suggest this may have occurred just two hours prior to landfall. No estimate for the evacuation reentry time could be determined, as the data collection period of 14 days concluded before the evacuating vehicles could return.

Table 1 provides a summary of the number of vehicles evacuated along the study routes, as well as the dates and times the evacuation began, peaked, and concluded. The table also shows the dates and times corresponding to reentry (beginning, peaking, and concluding), landfall, and first evacuation orders within the respective study regions. That table shows that Southeast Florida experienced the largest net loss in vehicles. This was expected as this region has the highest population and was likely to see the greatest number of evacuees. In general, the evacuations began several days before the storm made landfall. The Florida Keys, Southeast Florida and the Panhandle saw the peak evacuation hour two to three days in advance of the landfall. This is a significant finding because it suggests that hurricane warnings and evacuation notification were taken seriously. However, Naples did not experience peak demand until 28 hours before the storm arrived. Again, this was likely because of the shifting storm track. Naples and Southeast Florida had similar recovery times of just over a week. The Florida Keys required more than 20 days for the traffic patterns to recover. This was likely because the keys were the hardest hit and access was restricted to the lower keys for nearly three weeks.

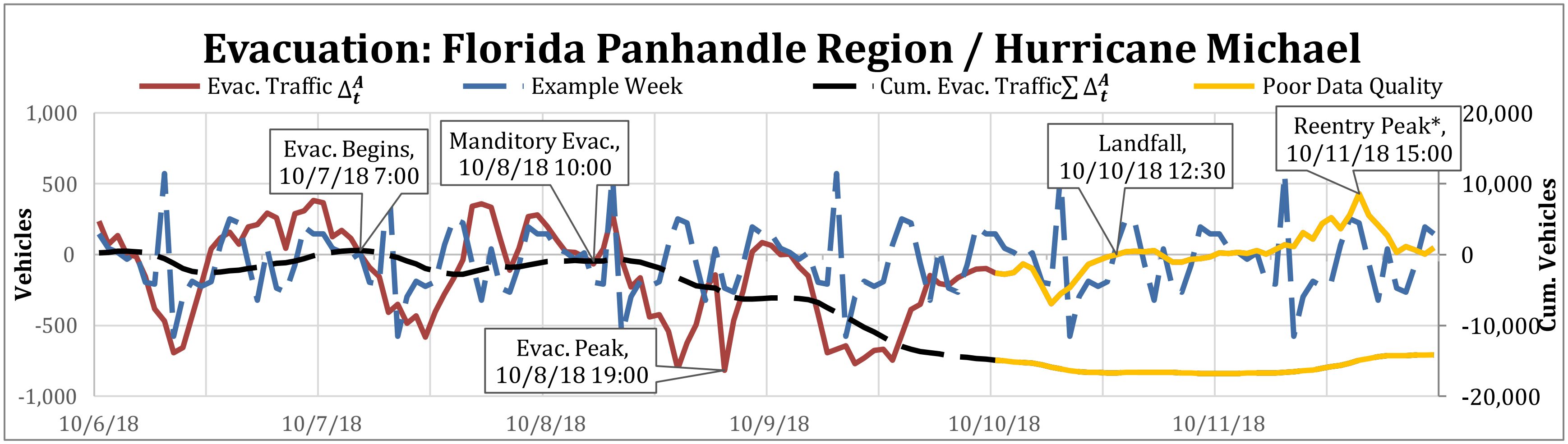

Figure 5 Florida Panhandle Region Evacuation from Hurricane Michael Traffic Analysis

Table 1 Summary of Evacuation Time, Orders, and Reentry

Regions	Total Veh.	Evac. Begins (τ)	Evac. Ordered	Evac. Peak (tp)	Evac. Ends (tct)	Landfall	Reentry Begins (τ)	Reentry Peak (tp)	Reentry Ends (T)
FL Keys	39,804	9/5/17 13:00	9/5/17 15:00	9/6/17 16:00	9/9/17 21:00	9/10/17 9:00	9/10/17 11:00	9/18/17 12:00	10/1/17 10:00
S.E. FL	269,646	9/6/17 12:00	9/6/17 9:00	9/7/17 15:00	9/8/17 17:00	9/10/17 9:00	9/10/17 9:00	9/11/17 18:00	9/18/17 7:00
Naples	123,389	9/5/17 9:00	9/8/17 12:00	9/9/17 11:00	9/10/17 11:00	9/10/17 15:00	9/10/17 17:00	9/11/17 13:00	9/17/17 16:00
Panhandle (Michael)	16,802*	10/7/18 7:00	10/8/18 10:00	10/8/18 19:00	N/A*	10/10/18 12:30	N/A*	10/11/2018 15:00*	N/A*

*Based on incomplete data

4.2. Evacuation and Reentry Time Estimates

An evacuation time estimate provides the approximate time required to evacuate a proportion of the population. The prior analysis measured the time to evacuate 100 percent of the observed vehicles. Based on this, it was possible to estimate the time required to evacuate 50 percent, 90 percent, and 99 percent of the vehicles, as well. Furthermore, the data provided by the evacuation reentry allows for a similar analysis of the proportion of vehicles returning to the region. From there, it is possible to estimate the how long proportions of the evacuees were displaced. Figure 6 shows the evacuation time estimates for the four study regions. The y-axes shows the cumulative percent of vehicles exiting the cordoned area as a proportion of observed vehicles. The x-axis shows the number of hours in reference to landfall. Negative values indicate times prior to landfall, whereas positive numbers are post landfall within the respective region. The period leading up to landfall shows the evacuation. The period after landfall shows the reentry of vehicles into the region.

From this figure, the evacuation clearance time may be estimated for any cumulative percent evacuated. For example, the time needed to evacuate 50 percent of the residents of the Florida Keys was 33 hours. Likewise, 99 percent of evacuees in the Naples Region were able to clear the area within 107, as compared to the last one percent, which required an additional 18 hours. The time of the official evacuation orders is also called out in the figure, along with the proportion of the vehicles, which had exited the region, prior to this order. For example, the Panhandle issued evacuation orders approximately 50 hours before landfall. At this time, over eight percent of the evacuating vehicles had already left the region. Naples also issued evacuation orders approximately 50 hours before landfall. However, over half of the vehicles used in the evacuation had exited the region prior to this order. While it cannot be known for certain, it is likely that many of these earlier evacuees were tourist or other transient populations. The figure also presents a comparison of the exiting rate and by extension the loading rate for each region. The figure suggests that Southeast Florida mobilized quickly as compared to the Florida Keys and Naples Region. However, regions showing slower mobilization began comparatively earlier. The figure also allows for an analysis of the 50th percentile displacement time. Looking at the time lapse between when 50 percent of vehicles evacuated and when 50 percent of vehicles returned, provides insight into how long the typical evacuee was displaced. The figure clearly shows extended reentry times for the Florida Keys, which experienced severe damage resulting from the storm requiring curfews and travel restrictions in the lower keys [6].

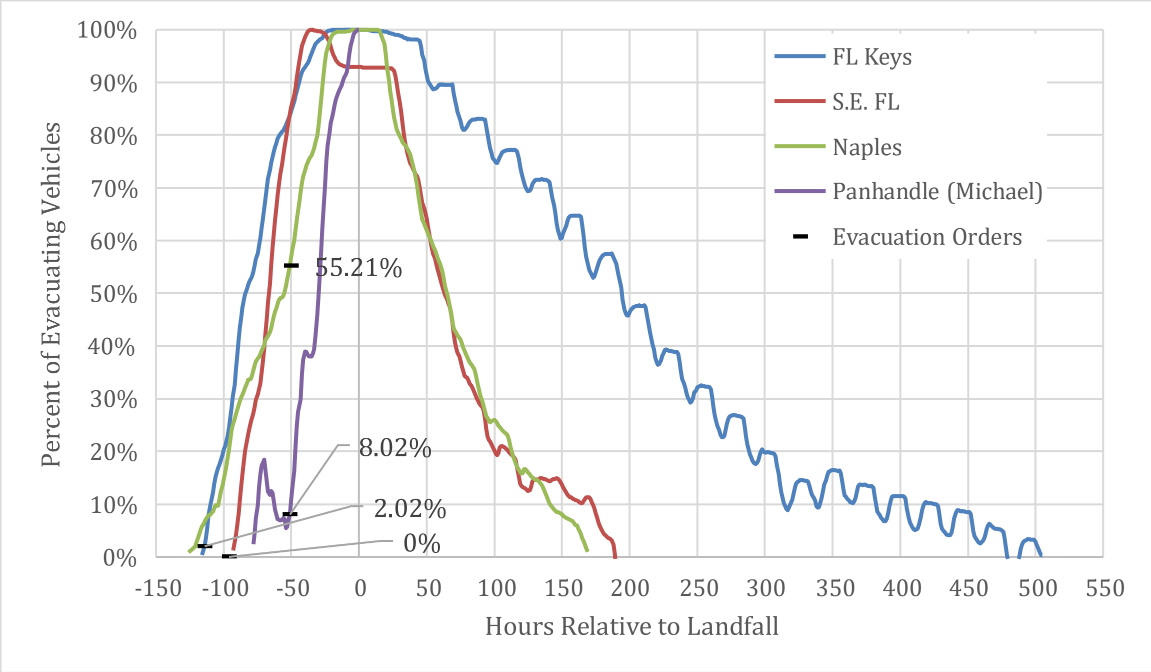

Figure 6 Evacuation and Reentry Time Estimate

Table 2 provides the clearance and reentry times for 50 percent, 90 percent, 99 percent, and 100 percent of evacuees for each region. The table also provides the 50th percentile displacement time. The table shows Naples and the Florida Keys had the longest clearance times. The Keys also experienced the longest reentry time. The evacuation tail, generally considered the last 10 percent of evacuees to exit the region, was also found to be the longest for the Keys and Naples at 32 hours and 25 hours, respectively. It is not likely coincidental that these two regions were also directly hit by the storm. Southeast Florida had significantly shorter clearance times and evacuation tail, despite evacuating more vehicles. This was likely because these areas have more, high capacity roads and freeways and their evacuations started much later when compared to the other regions. The evacuation of the Panhandle in response to Hurricane Michael as also comparatively shorter, and saw an 11-hour evacuation tail.

Table 2 Summary of Evacuation Analysis Results

Regions	Clearance Times (hours)				Reentry Times (hours)				50 Percentile Displacement Time (hours)
	50%	90%	99%	100%	50%	90%	99%	100%	
FL Keys	33	72	91	104	193	424	501	503	278 (11d, 14h)
S.E. FL	27	47	54	59	64	173	189	190	130 (5d, 10h)
Naples	71	100	107	125	63	140	167	167	120 (5d, 0h)
Panhandle (Michael)	49	66	74	77	N/A	N/A	N/A	N/A	N/A

Half of the population of Southeast Florida that evacuated by vehicle did so within 31 hours after the evacuation began. However, it was not for another 130 hours that half of the population reentered. Therefore, the average evacuee from Southeast Florida was displaced for over five days. Using this same approach, 50 percent of the Naples auto-based evacuees were displaced for 120 hours as well. The displacement time for the 50^{th} percentile of the auto-based evacuees for Florida Keys resident was 278 hours, over 11.5 days. It should also be noted the evacuation reentry was more gradual than the evacuation itself.

Chapter 5. Conclusion

Often, the perceived success of an evacuation, or lack thereof, is based on media reports, anecdotal observation or, worse, rumors and social media discussion. In reality, a highly effective evacuation could be assumed a failure because of a few limited but highly visible areas of congestion. This has suggested the need for a better way to describe and assess large statewide evacuations in more systematic and objective ways. Unfortunately, this is not easy to accomplish because there are few, if any, data records or performance measures generated that accurately and effectively describe the conditions of these events. In fact, there is no standardized methodology to quantify the characteristics of an evacuation that is transferable and repeatable between state departments of transportation.

Fortunately, there are many commonly used data measures for analyzing routine transportation conditions. The intent of this work was to adapt and apply them to develop a method capable of describing mass evacuations. In fact, these methods can also be applied to describe evacuation reentry traffic patterns; a historically lightly studied area in practice and research. The results of this effort showed these methods could be quite effective to illustrate statewide temporal and spatial trends of traffic movement as well as infer evacuee behavioral responses and threat interpretation. Results of the application of the research methodology showed that the evacuations from Hurricane Irma and Michael began several days before landfall. Vulnerable residents in the Florida Keys started their evacuations five days before Hurricane Irma's landfall with nearly 20 percent departing prior to the mandatory evacuation order. This observation was unexpected because prior survey results suggested that a two-day loading period was most likely [34]. In general, the evacuations peaked two to three days before landfall and between the hours of 8:00 AM and 3:00 PM confirming prior research that suggested a preference for morning departures [35]. From an emergency preparedness standpoint, these trends are positive and suggest an increased civic awareness of hazard risk perception. The research also found that half of the auto-based evacuees from Southeast Florida and the Naples region were displaced for up to five days. The 50^{th} percentile displacement time for Florida Keys residents, which evacuated by car saw significantly longer displacement times of over 11 days.

This research provides a system for state departments of transportation and emergency management officials to analyze future auto-based evacuations. The method also facilitates parametric comparisons between evacuation events, an area needed to continue to evolve and improve evacuation practice. Standardize measures for hurricane evacuations are needed to facilitate systematic evaluations of performance. Future researchers could build upon methods presented here to develop a level-of-service (LOS) analysis for emergency evacuations. This would be similar to the way the Highway Capacity Manual uses the standardized collection and processing of freeway densities for its LOS evaluations. With additional research, the methods laid out in this paper could also lead to a more comprehensive understanding of evacuation traffic processes and behavioral responses to improve their planning and management. The proposed analysis procedure did not attempt to investigate shadow evacuees. However, it would be possible to do so, if additional cordon lines could be drawn around evacuation zones. The difference between the number of evacuating vehicles between the "inner" and "outer" cordon lines would be the number of shadow evacuation vehicles within the area between the cordon lines. Also, the proposed approach classifies any vehicle exiting the region without returning before landfall, to be an evacuee. This classification approach is blurred by the persistence of background traffic both before and after landfall. The presence of tourist or other transient populations, which may evacuate earlier than residents, also impacts evacuation estimates.

Chapter 6. References

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