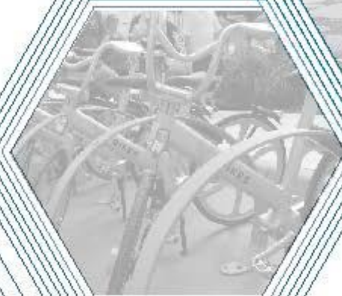
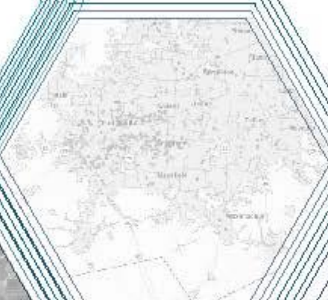


Measuring Transportation Network Performance During Emergency Evacuations: A Case Study of Hurricane Irma and Woolsey Fire

Nikhil Menon, Ph.D.

Brian Staes, E.I.

Robert L. Bertini, Ph.D.



FINAL REPORT

Center for Transportation Equity, Decisions & Dollars

MEASURING TRANSPORTATION NETWORK PERFORMANCE DURING EMERGENCY EVACUATIONS: A CASE STUDY OF HURRICANE IRMA AND WOOLSEY FIRE

FINAL PROJECT REPORT

By:

Nikhil Menon, Ph.D.

Brian Staes, E.I.

Robert L. Bertini, Ph.D.

University of South Florida

Sponsorship:

CTEDD

For:

Center for Transportation, Equity, Decisions and Dollars **(CTEDD)**

USDOT University Transportation Center

The University of Texas at Arlington

601 W.Nedderman Dr. Suite 103

Arlington TX 76019-0108 United States

Phone: 817-272-5138 | Email: C-Tedd@uta.edu

In cooperation with US Department of Transportation-Research and Innovative Technology Administration (RITA)

April 2020

Acknowledgments

This work was supported by a grant from the Center for Transportation Equity, Decisions, and Dollars (CTEDD) funded by U.S. Department of Transportation Research and Innovative Technology Administration (OST-R) and housed at The University of Texas at Arlington.

Disclaimer

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Measuring Transportation Network Performance During Emergency Evacuations: A Case Study of Hurricane Irma and Woolsey Fire		**5. Report Date** April 9, 2020 **6. Performing Organization Code**
7. Author(s) Nikhil Menon, Brian Staes, Robert L. Bertini		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Center for Transportation, Equity, Decisions and Dollars (CTEDD) USDOT University Transportation Center The University of Texas at Arlington 601 W.Nedderman Dr. Suite 103 Arlington TX 76019-0108 United States		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Organization Name and Address United States of America Department of Transportation Research and Innovative Technology Administration		**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

The United States has witnessed several natural disasters in recent memory. Natural disasters such as hurricanes, wildfires, and floods not only cause extensive monetary damages but also lead to spatiotemporal displacement of affected residents. Often, in these scenarios, governments at various levels – state/regional/local – grapple with how to effectively evacuate those affected while ensuring their safe relocation, and minimal risk. Major roads such as the interstates often suffer from heavy gridlock during such evacuations leading to bottleneck formulation and slow traffic speeds due to the high volume, and demand of vehicles. Resource shortages such as fuel and water further intensify the risk of evacuations. During an impending hurricane or wildfire, it is critical that public authorities have a complete understanding of the traffic characteristics before deciding to execute emergency evacuations. This project will utilize 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. An examination of the evacuation traffic patterns, and travel time during said events will serve as an important baseline to benefit emergency planning and management in areas with similar circumstances. This study is timely due to the nature of these natural disasters and their widespread impacts in the states of Florida, and California.

17. Key Words Evacuation Traffic, Hurricane, Wildfire, Traffic Management, Performance Assessment		**18. Distribution Statement**	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 117	**22. Price** N/A

Table of Contents

List of Figures

List of Tables

Abstract

The United States has witnessed several natural disasters in recent memory. Natural disasters such as hurricanes, wildfires, and floods not only cause extensive monetary damages but also lead to spatiotemporal displacement of affected residents. Often, in these scenarios, governments at various levels – state/regional/local – grapple with how to effectively evacuate those affected while ensuring their safe relocation, and minimal risk. Major roads such as the interstates often suffer from heavy gridlock during such evacuations leading to bottleneck formulation and slow traffic speeds due to the high volume, and demand of vehicles. Resource shortages such as fuel and water further intensify the risk of evacuations. During an impending hurricane or wildfire, it is critical that public authorities have a complete understanding of the traffic characteristics before deciding to execute emergency evacuations. This project will utilize 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. An examination of the evacuation traffic patterns, and travel time during said events will serve as an important baseline to benefit emergency planning and management in areas with similar circumstances. This study is timely due to the nature of these natural disasters and their widespread impacts in the states of Florida, and California.

1. Introduction

1.1. Background & Motivation

The United States of America has witnessed several natural disasters in recent memory. Natural disasters such as hurricanes, wildfires, and flash floods not only cause extensive monetary damages but also lead to spatiotemporal displacement of affected residents. Often, in these scenarios, public authorities at all levels – federal, state, regional, or local – grapple with how to effectively evacuate those affected while ensuring their safe relocation, and minimal associated risks. There is always a tendency to conduct evacuation using the major roadways (interstates) but these roadways often suffer from heavy gridlock leading to bottleneck formulation and slow traffic speeds due to the high volume and unprecedented demand of vehicles (Wolshon & McArdle, 2010). Resource shortages, such as fuel and water further intensify the risk with evacuations. During an impending hurricane or wildfire, it is critical that public agencies have a complete understanding of roadway traffic characteristics before deciding to execute emergency evacuations.

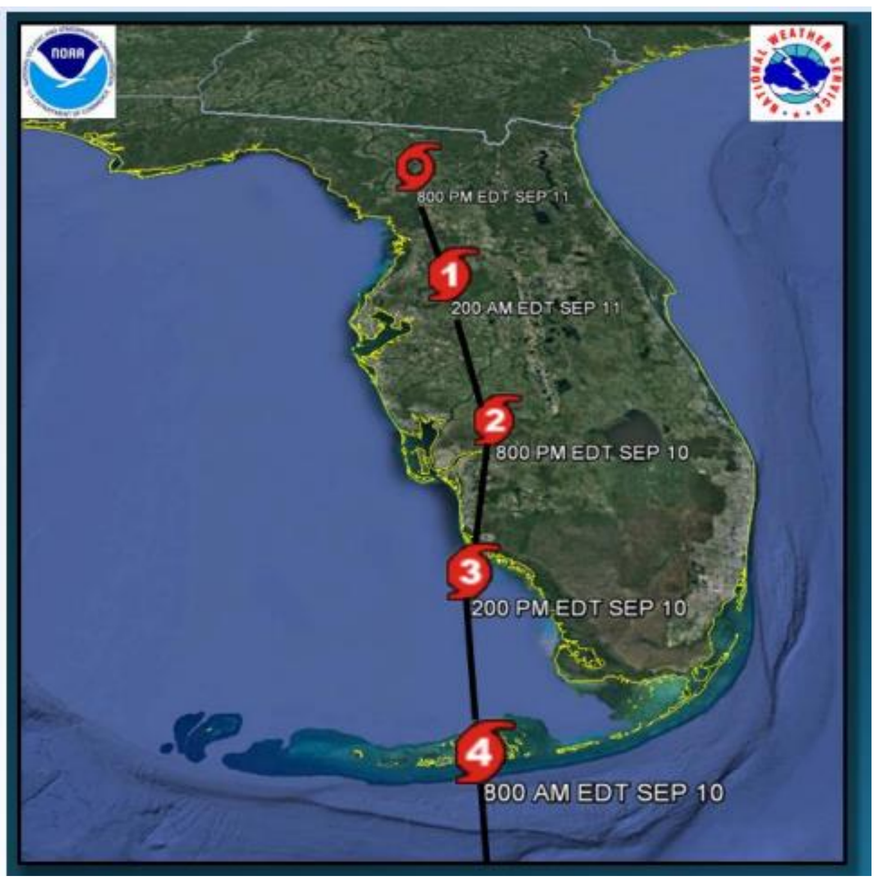


Figure 1 Hurricane Irma Florida Landfall Timeline (Source: NOAA)

In September 2017, Florida and Puerto Rico, recovering from Hurricane Maria a few weeks earlier, encountered yet another hurricane, Irma, which turned out to be one of the worst hurricanes in recorded history. The first warnings of Hurricane Irma were issued by the National

Hurricane Services on the 7th of September, triggering a series of mandatory evacuations initiated in 42 of the 67 Florida counties; 12 other counties issued evacuation orders that were not mandatory – taking the total to 54 out of 67 counties. The Governor of Florida declared a state of emergency soon after and ordered close to 7 million residents to evacuate their homes, making it one of the largest ordered emergency evacuations in the history of the United States (Clark & Bousque, 2018). The evacuation process was carried out in a phased manner with the South Florida counties issuing orders initially followed by their northern counterparts (the evacuation orders lasted from September 6, 2017 to September 17, 2017)[1]. Despite this, there were major gridlocks along the highways – travel times increasing more than two-fold, and roadway capacities, up to four times the average – for the same period.

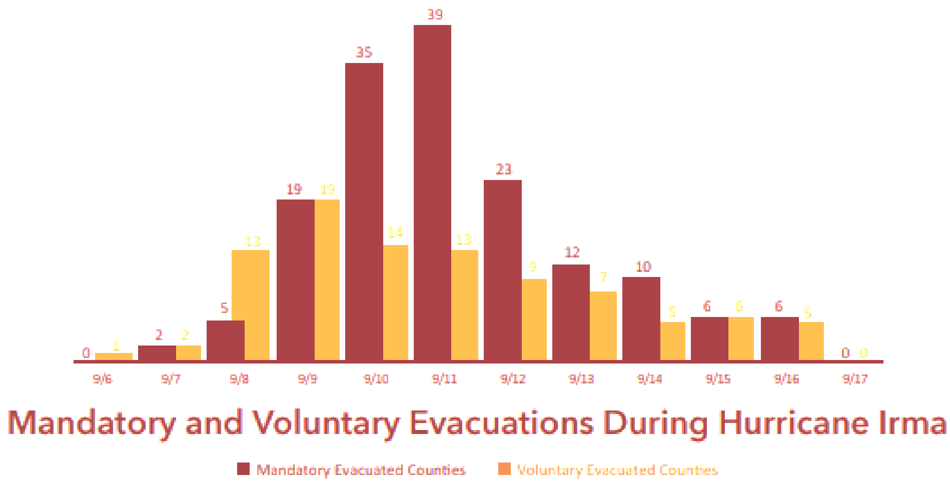


Figure 2 Mandatory and Voluntary Evacuations During Hurricane Irma

The unique geography of Florida poses a big challenge for mass evacuations out-of-state as residents have only few major highways (the I-75, the I-95, and US-1) to travel northward before being able to leave the state's boundaries. While moving westward into Alabama is also an option for evacuating out-of-state, this was not possible to be executed due to the general path of Hurricane Irma (see Figure 1). Preliminary inspections by the research team on select corridors also indicated that while the interstates were experiencing congestion, the adjoining non-freeway sections as well as some toll roads in the vicinity of the interstate were not congested, leading to apprehensions over their utilization during these evacuation periods. Therefore, more analysis is warranted at this stage to investigate some of these initial findings.

While Hurricane Irma classifies in the literature as a short-notice evacuation, there is another category of evacuations that is worthy of investigation – no-notice evacuations. The authors endeavor to understand through this study, the critical differences in analyzing mass

[1] Hurricane Irma Evacuation Report prepared by the Florida Association of Counties https://www.fl-counties.com/sites/default/files/2018-02/Evacuations%20Report.pdf

evacuations for no-notice, and short-notice events. In order to accomplish this, the authors chose to analyze the Woolsey and Hill Fires in California. On the afternoon of November 8, 2018, a fire broke out west of Thousand Oaks, California in Ventura county, likely caused by a malfunction in one of Southern California Edison's power lines (Cosgrove, 2019). While roughly 400 fire fighters were sent to mitigate this fire named the Hill Wildfire, several hours later another fire broke out 15 miles to the east, near the Santa Susana Pass (Cosgrove, 2019).

By midnight, the Hill Fire had crossed over US-101NB, north of Thousand Oaks and SR-23. In addition to this, the Woolsey Wildfire, which had broken out several hours earlier near the Santa Susana Pass, began to burn quickly down the steep slopes of Agoura Hills, due to strong winds in excess of 40 miles-per-hour (Schleuss & Krishnakumar, 2018; Cosgrove, 2019). By early morning of November 09, 2018, at 5:15 AM, according to Cosgrove (2019), the Woolsey fire had burned across US-101 and continued its path towards US-1 and the coast (Ferreira, 2018). By the time the fires were contained, the Woolsey and Hill Wildfires had destroyed 1600 structures, burned 97,000 acres and took the lives of two people (Ferreira, 2018; Cal Fire, 2018; Cosgrove, 2019). Figure below demonstrates the burn extent timeline for the Woolsey Wildfire.

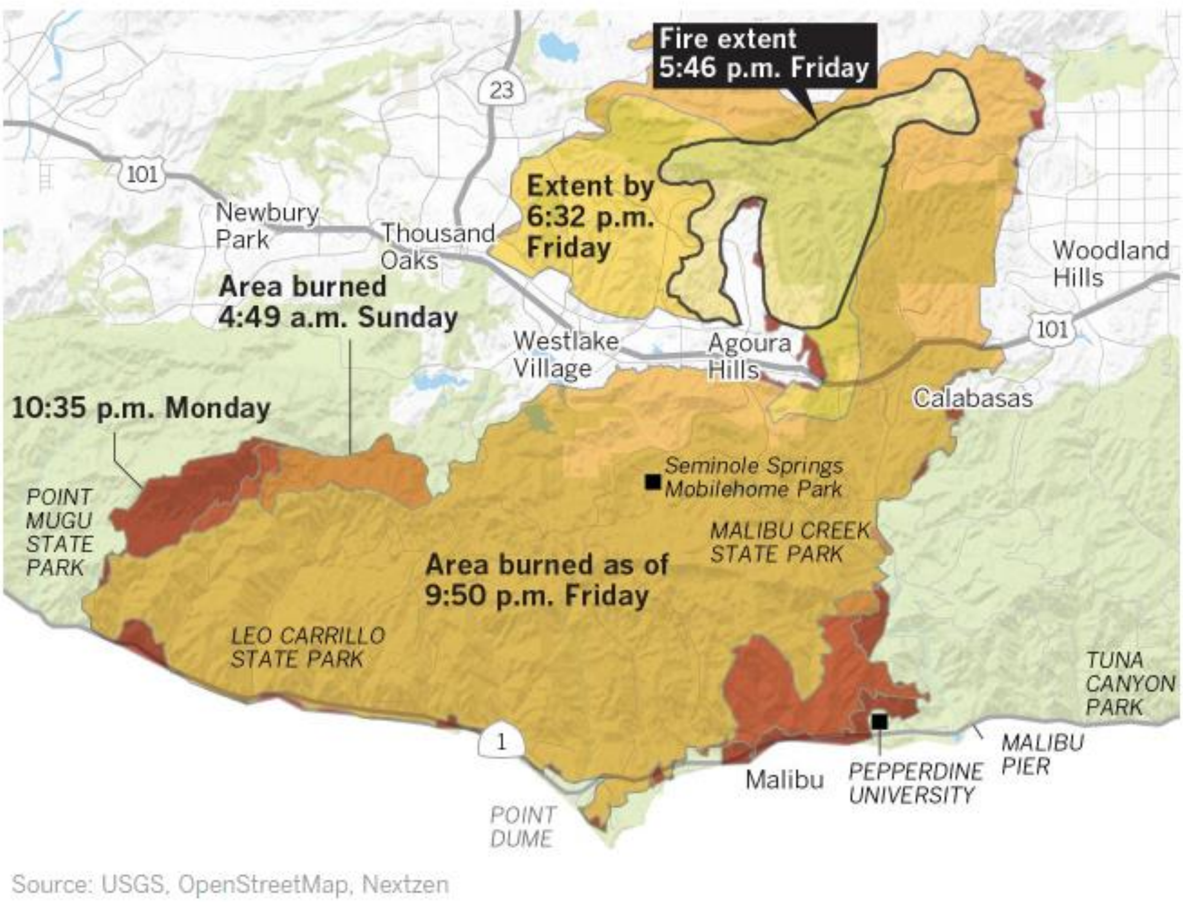


Figure 3 Woolsey Wildfire Timeline (Source: Schleuss & Krishnakumar, 2018)

A significant amount of current research on short-notice evacuations has focused on hurricane-prone states in the Gulf Coast, especially Louisiana along with some limited research on Florida and Texas but not many insights are available when looking at wildfires (Wolshon et al., 2005; Wolshon et al., 2005a; Wolshon & McArdle, 2009; Songchitruska et al., 2012; Harten et al., 2018). The current study utilizes real-world traffic stream data obtained from a selection of different agencies in Florida and California. While previous studies have used simulated travel time to identify spatiotemporal distribution of bottlenecks under evacuation conditions, the current effort will endeavor for use of historic travel time data to improve outputs in terms of realism, accuracy, and reliability (Jha, Moore, & Phashaie, 2004; Zou et al., 2005; Liu et al., 2008; Naghawi & Wolshon, 2012). Using real-world traffic data with observed traffic counts/historical travel time, in place of post-hurricane surveys will add familiarity to the decisionmakers and provide more realistic results (Li & Ozbay, 2015).

1.2. Organization of the Report

The rest of this report is organized as follows: Section 2 discusses the methodological approach adopted for this study. This section will detail the various approaches currently available to characterize the performance of the transportation network and culminate in a discussion as to why the research team adopted our chosen performance metrics to respectively analyze these mass evacuation events. Section 3 highlights the data collection, data quality, and associated procedures adopted for processing the data for analysis. Section 4 of this report presents the results from the data analyses of the post-processed data and details the evacuation performance at a district-level for Hurricane Irma and provides insights on the chosen approach for analyzing the no-notice Woolsey wildfire event. The final section of this report (Section 5) highlights the conclusions and recommendations that evacuation stakeholders can take away from the findings of this study.

2. Methodological Approach

The methodological framework adopted in the current study can be summarized as follows:

1. We collected real-world transportation, and secondary data for spatiotemporally analyzing traffic patterns before, during, and after Hurricane Irma (FL) and Woolsey Fire (CA)
2. We investigated significant evacuation movements during both mass evacuation events and examined the evacuation traffic patterns for bottlenecks
3. We visualized the observed patterns and provided recommendations for transportation decisionmakers in order to more effectively combat similar circumstances in the future

The study differentiates itself from past efforts due to the significant use of real-time traffic and transportation data to understand spatial and temporal patterns in hurricane and wildfire evacuation. The major sources of raw data are travel speeds, volume, and occupancy that are collected by agencies from roadway sensors (inductive loops) as well as hourly volume counts from toll plaza counts, weigh-in motion (WIM) stations at geographically diverse locations along with historic travel time data made available by a traffic service provider.

The collected data was then analyzed to understand spatial and temporal patterns during both the mass evacuation events. Thereafter, the research team embarked on the identification of performance metrics that would aid in assessing the transportation network during the mass evacuation event. Comparisons were made with data collected pre-evacuation in order to better understand the magnitude of the observed trends and arrive at benchmarks for transportation decisionmakers to consider during similar circumstances that they may encounter in the future.

2.1. Network Performance Methodology

2.1.1. Travel Time Reliability

Daily traffic congestion plagues roadways across the United States. The causes for this congestion can be broken down into six categories: (i) capacity restricted bottlenecks, (ii) incidents, (iii) work zones, (iv) weather, (v) special events, and (vi) daily variance (Cambridge Systematics, 2006). Based on these categories, it is apparent that one, if not several causes, may occur randomly on a given day which can severely increase a roadway user travel time to their destination. This random, yet drastic increase in travel times, may make the daily commuter, or freight vehicle delayed to their destination by an originally unforeseen duration. The randomness of this increase in travel time is also referred to as travel time reliability. It is also mentioned that historical travel times for a region’s roadway network and its reliability can directly infer to the health of that system (Lyman & Bertini, 2008).

To the average driver, having an index which indicates how often this variability may occur and its extent, can give a depiction on how much time they should give themselves to arrive to their destination on-time. In addition to the roadway user gaining applicable information which can affect their commute time decisions, for the Federal Highway Administration

(FHWA), travel time measurements and its reliability are a direct measure of the congestion experienced by the travelers, which is a valid indicator of the operational performance of the facility (Office of Research, 2005).

Several travel time reliability measures were developed to measure this reliability and Figure 4Figure 4Figure 3 demonstrates their interactions on a typical day. Their definitions are as follows:

- 90th and 95th percentile travel time
  - The travel time through a roadway segment each month that corresponds to the highest observed travel times that month, or when 95 percent of the time travel times will be less than this value.
- Travel Time Index
  - The ratio of peak period travel times to free-flow travel times
- Buffer Index
  - The amount of time a roadway user should leave as a "buffer" to arrive on-time 95 percent of the time.
- Planning Time Index
  - The total travel time of the roadway segment that includes the buffer time

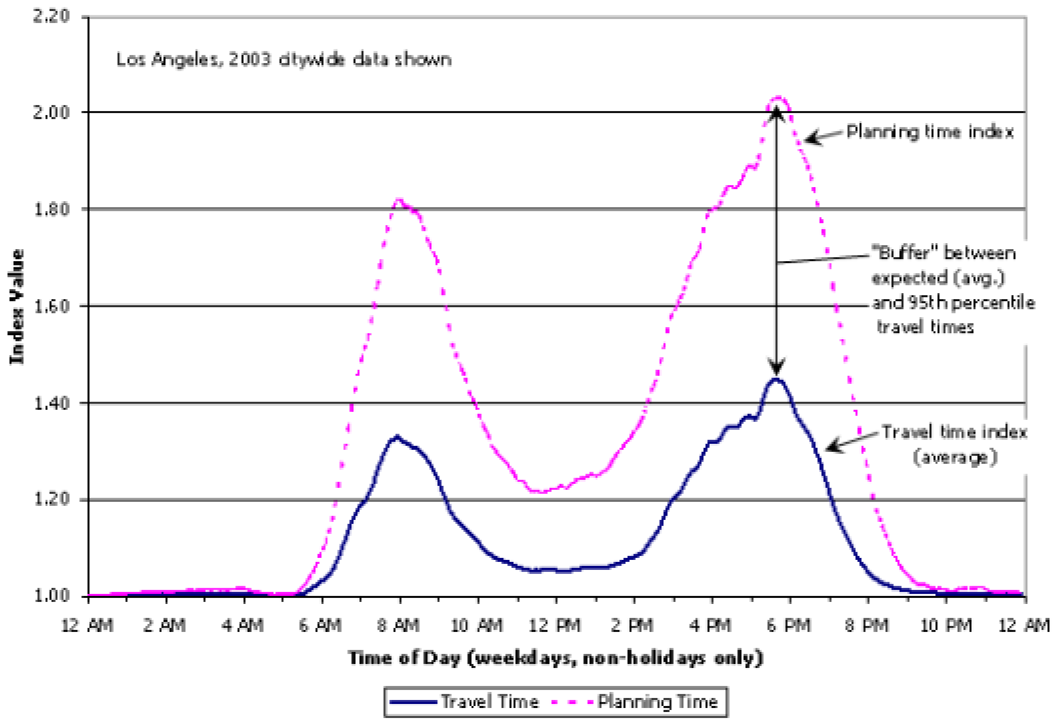


Figure 4 Travel Time Reliability Congestion Measure (Source: Office of Operations, 2007)

Although travel time-based performance measures depict the typical congestion occurring on roadways and the variability in this congestion, in the context of a hurricane evacuation, which has extremely low probabilities to impact the exact same areas as previous hurricanes with the same intensities, using performance measures that are based on normal operating conditions would result in erroneous conclusions. In addition to this, comparing the network characteristics observed from other hurricanes may also lead to vastly different outcomes due to limited observations of hurricanes that are similar spatially and temporally.

2.1.2. Capacity/Mobility-Based Performance Metrics

As mentioned previously, travel time reliability during a spatially and temporally unstable event such as a hurricane draws obvious uncertainties for travel time reliability due to limited observations. Therefore, alternative capacity and mobility-based performance measures, that are employed across the State of Florida, were examined. The combination of capacity and mobility are indicative of quantifying the movement of individuals regardless of their mode and understanding the congestion experienced by these movements through level of service (LOS), capacity thresholds. Issued by Governor Rick Scott in 2017, it is the Florida Department of Transportation's target to have the entire state highway system operate at LOS **D** in urbanized areas and LOS **C** outside of urbanized areas during peak hour traffic (FDOT, 2017). Although this statement was not intended to hold true during mass evacuations, the methodology to determine the performance measures of roadways using capacity-based methods may also see implications for evacuation analysis.

In the context of this study which attempts to analyze auto and truck movements across the State of Florida; the Florida Department of Transportation, depicts four categories of auto and truck mobility measures, below are some examples of each category (FCO, 2018).

- Quantity
  - Vehicle Miles Traveled (VMT)
  - Person Miles Traveled
- Quality
  - Percent Travel Meeting Level of Service Criteria
  - Vehicle Hours of Delay
  - Person Hours of Delay
  - Average Travel Speed
- Accessibility
  - Job Accessibility: Auto
- Utilization
  - Percent Travel Heavily Congested
  - Hours Heavily Congested
  - Vehicles Per Lane Mile

The above mobility measures, desired by FDOT, utilize level-of-service thresholds to indicate both the quality of travel the users sees, and the utilization of the roadway. Inherently, LOS depicts the density of vehicles on the roadway, that is the number of vehicles per mile per lane. Depending on the free flow speed of the facility, and the number of lanes, the density thresholds which indicate each category of LOS alter. Based on the statement made previously, the desire to maintain Florida's major roadways operating at particular thresholds is acceptable under normal operating conditions and indeed demonstrates the mobility of the facility. It is for this reason that some of the capacity-based performance measures will be used, and slightly altered to evaluate the mobility of each facility during the evacuation. In addition to this, previous literature has identified alternate performance measures that have attempted to analyze roadway networks during evacuations.

2.1.3. Evacuation-Based Performance Measures

Similar to the capacity-driven performance metrics used in previous literature (such as FCO, 2018), Wolshon et. al. (2019) utilized percent vehicle miles, and hours traveled while congested during multiple evacuation scenarios. A question arises with this method: how to identify when the traffic stream is congested? The 2010 Highway Capacity Manual utilizes breakpoints to determine this. These breakpoints are identified either with the volume-to-capacity ratio of the facility or a density threshold (HCM, 2010). Other parameters for the determination of congested traffic include speed, density, and occupancy thresholds, or the combination of speed and density/occupancy (Jin, Luo & Ma, 2018). The selection of the parameter to determine if the traffic stream is congested will be discussed in the following section.

Additional evacuation-based performance measures include the use of cumulative evacuation curves to depict the total evacuation volumes and the temporal/spatial characteristics of the volumes across the network (Dixit et al., 2011), destination-based outflow, accumulated macroscopic simulations (Zhang et al., 2015) and maximum flow rates and maximum sustainable flow rates (Dixit & Wolshon, 2014). The current study aims to utilize observed data from the evacuation and describe it using appropriate performance measures which practitioners can use to compare each roadway – not only to its own historical trend but also to other roadways across the state and take necessary actions for future circumstances. For this reason, and the previously mentioned limitations of using travel time reliability, capacity-based performance measures and those used in previous evacuation evaluations (such as percent vehicle miles traveled while congested) will be used as metrics in the current effort. In addition, this study also identifies any bottlenecks observed along the roadway network during the evacuation process.

2.1.4. Bottleneck Identification

Speeds from raw detector data can be used to identify both congestion and the location of bottlenecks across a roadway facility (Zheng et al, 2011). Although there are alternative methods of identifying the propagation location, extent, and time period for bottlenecks to activate, this research is merely to identify trouble areas across the entire span of Florida's roadway network (Bertini, 2003; Cassidy & Bertini, 1999; Chen et al., 2003; Lindgren, 2005; Zheng et al., 2011). Hence, more specified bottleneck identification techniques, which identify detailed characteristics of each bottleneck were not pursued for this study, although future research may lead to this area. For this reason, speed contours will be used to identify bottlenecks that existed in the network during the evacuation. Next, the location and queue propagation from these bottlenecks that existed during the evacuation will be compared to the five-minute three-month averaged data to inspect the occurrence of the bottleneck at the same location in normal operational conditions.

2.2.Chosen Performance Metrics

2.2.1. Hurricane Irma, Florida

Prior to identifying the characteristics of the roadway segment, a measurement which demonstrates the amount of detector coverage of the facility was needed. A typical measure used is the average spacing of detectors along the roadway segment.

$$Average\ Spacing = \frac{1}{n}\sum_{i=1}^{n} L_i$$

$$L_i = \frac{|(D_i - D_{i+1})| + |(D_i - D_{i-1})|}{2}$$

where n is the number of detectors, L_i, is the length of detector i, D_i, is the location of detector i, D_{i+1} is the location of the immediate detector downstream of i, and D_{i-1}, is the location of the immediate detector upstream of i. Following the performance metric used to identify the data coverage of the roadway, measurements which demonstrated the state of the traffic stream were needed.

The FDOT source book utilizes the measurement of the percent of vehicle miles traveled while congested (VMTC). This is the total vehicle miles traveled versus the total vehicle miles travelled while in a congested state. Certain criteria are used in literature to define congestion – the typical parameters of which are occupancy, speed, and density. This is based on the raw data collected across the state of Florida which, depending on the detector type, collected only vehicle count, and occupancy or vehicle count, occupancy, and speed. For the former detectors, speed is calculated from these readings. Although, the FDOT source book utilizes LOS density thresholds to indicate if the traffic stream is congested, density itself is a calculation derived from vehicle count, and speed from the raw detector data. Moreover, if the detector is calculating speed also, then the density measurements are in a sense two orders from the raw data collected. It is for this reason that detector occupancy measurements were used to indicate the true state of the traffic stream from the raw data. Based on observations made for each roadway, the critical value of occupancy used for the determination of congested ranged from 15 to 20%.

$$VMT\ Congested\ (\%) = \sum_{t=1}^{T}\sum_{i=1}^{n}\frac{N_{tic}L_i}{N_{ti}L_i}$$

where N_{tic} is the number of vehicles observed in the congested state at detector i, in time period t, L_i is the average spacing (defined previously) and N_{ti}, is the total number of vehicles observed at detector i in time period t.

In addition to the percent of vehicle miles traveled while congested, the total hours of delay incurred was also determined for each roadway segment. This utilized the same metric to identify if the roadway segment was congested, however it also considered the difference between the observed speed and the free flow speed of the roadway.

$$Hours\ of\ Delay\ (D) = \sum_{t=1}^{T}\sum_{i=1}^{n} N_{itc}L_i(\frac{1}{V_{it}} - \frac{1}{V_f})$$

where N_{itc}, is the number of vehicles at detector i, during time period, t, and if that time period was congested, c. L_i, is predefined, V_f, is the corresponding mean speed observed for each of the detectors when the occupancy is less than the critical occupancy which was set to fifteen percent. V_{it}, is the average speed of the vehicles for detector, i, during time period, t. This calculation of delay follows a similar equation for delay from bottlenecks (Chen, Varaiya & Kwon, 2008).

Lastly, a measurement of the individual detector coverage for the particular day as a percentage of the total minutes covered, was needed to validate the depiction of the performance measures for the facility. This is displayed in equation X:

$$Day\ Captured\ (\%) = [1 - (\frac{1}{Tn}\sum_{i=1}^{n} K_i)]$$

where T, Is the number of time intervals in a day and is based on the polling interval of the roadway facility. For instance, if the detectors are polling every minute, T would equal 1440-time intervals corresponding to 1440 minutes in a day. Lastly, K_i, is the number of null readings in a day for detector i, and n is the total number of detectors.

2.2.2. Woolsey Wildfire, California

The selection of performance measures for the Woolsey Wildfire evacuation followed a similar thought process as the Hurricane Irma analysis. However, the available data for the roadways affected by this wildfire (via PeMS) did not have speeds recorded in them. Therefore, the total hours of delay *D*, which was used for the Hurricane Irma evacuation was not used in this case.

Additionally, the areas affected by the fire and the pace with which the fire spread throughout Ventura county differ entirely from a hurricane evacuation. This is also a challenge with no-notice evacuation events, in comparison to a short-notice evacuation (as in the case of Hurricane Irma). As seen in Figure 3, the fire began in the afternoon on November 11th, and spread quickly through Agora Hills and across US-101 finally reaching US-1 later that night. As such the analysis needed to go from analyzing vast stretches of roadways (as in the case of Hurricane Irma) to individual ramps and detectors adjacent to the fire, to capture evacuees.

Owing to the vast difference in the magnitude of roadways to be analyzed, the performance metrics proposed by the research team are found to be insufficient for this purpose. Therefore, a decision was made to analyze the graphical illustrations produced by PeMS to demonstrate any reduction and/or sudden increase in traffic flows during the wildfire and the ensuing evacuation. As mentioned in a previous section, the timeline of the fire is pertinent to the evacuation timeline, as such certain detectors including both mainline and ON-ramps will be used and discussed.

3. Data

This section will outline all discussion on the different data sources that were used for this study.

3.1.Hurricane Irma Data

3.1.1. RITIS Probe Detector Data

Table 1 describes the RITIS probe detector data, the definitions of data parameters are as below.

- Range of Detectors (MM) – the range of the detectors under analyses.
- Total In-District Roadway Distance – the total distance covered by the roadway in that district
- Detector Spacing Per Mile – the average spacing of the detectors along the roadway facility which is equal to the quotient of the range of the detectors to the number of detectors.

Table 1 RITIS Probe Detector Data

Facility	Range of Detectors (MM)	Total In-District Roadway Distance (mi)	Detector Spacing per mile (Number of Detectors)	Detector Type (Polling Interval)
District 6				
I-95	0 - 16.7	16.7	0.53 (33)	Radar (60)
I-95 EL	0 - 12.2	-	0.38 (32)	Radar (20)
SR-821	0 - 34.7	45.0	1.74 (20)	Radar (60)
SR-826	0 - 10.2	23.0	0.34 (28)	Radar (20)
District 4				
I-75	6.50 – 50.7	69.8	0.51 (88)	Radar (20)
I-95	42.8 – 145.0	145.0	1.02 (98)	Radar (20)
I-95 EL	18.4 – 26.1	-	0.54 (16)	Radar (20)
SR-91	114.5 – 188.4	133.4	0.53 (140)	Radar (60)
District 1				
I-75	101.2 - 227.6	183.0	0.77 (160)	Radar (30)
District 7				
I-275	1.5 – 59.3	59.3	0.57 (102)	Radar (60)
I-75	249.9 – 298.2	71.5	1.34 (36)	Radar (60)
I-4 EB	0.3 – 57.7	25.0	1.0 (56)	Radar (60)
Suncoast Parkway	14.8 – 54.1	-	0.55 (72)	Radar (60)
District 5				
SR-91	189.5 – 306.7	117.0	0.67 (174)	Radar (60)
I-4 EB	62.2 – 117.5	74.8	1.46 (38)	Radar (30)
I-95	160.4 – 251.5	138.0	1.0 (91)	Radar (30)
District 2				
I-95	297.4 – 359.7	83.9	0.56 (111)	Radar (20)

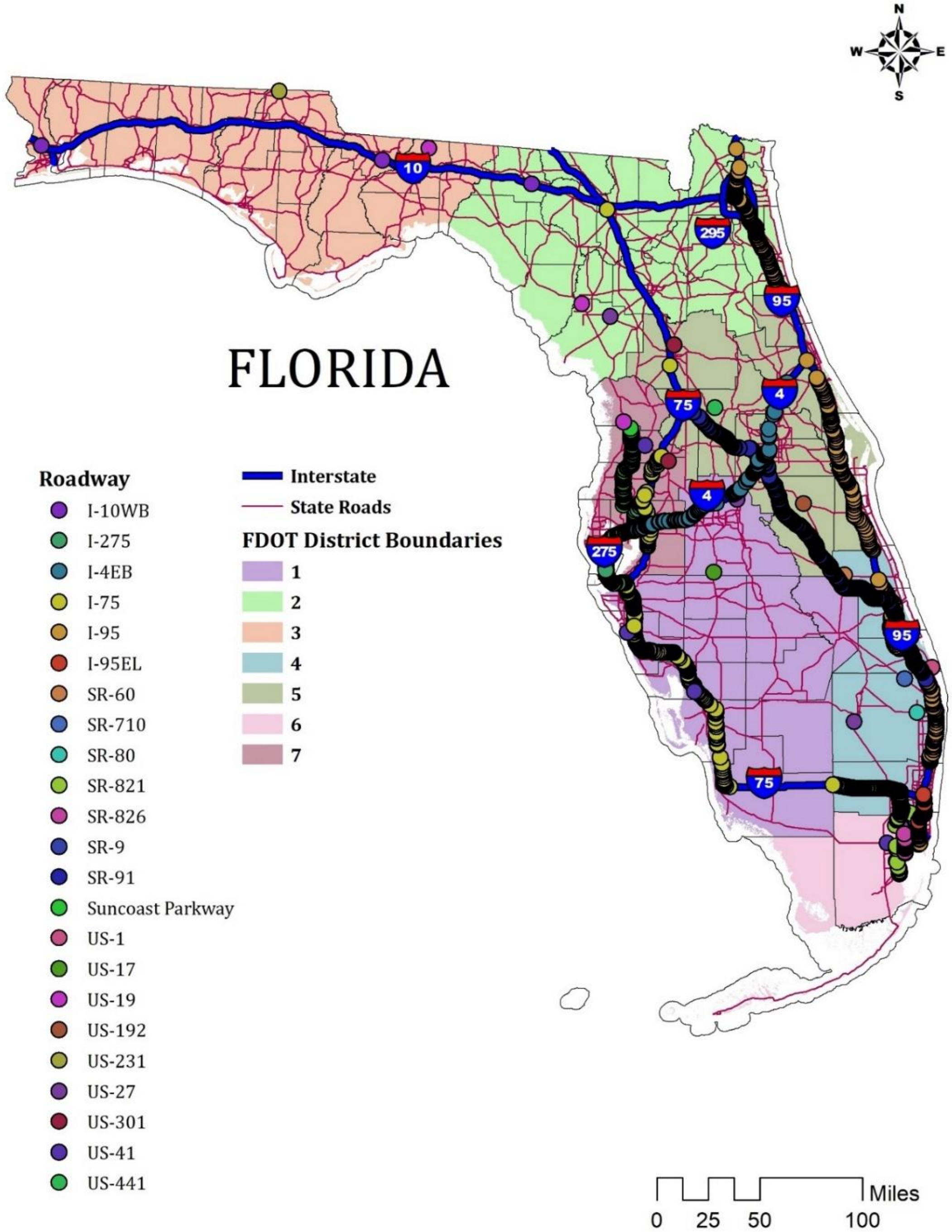


Figure 5 Detectors – Hurricane Irma – Florida

3.1.2. Florida Traffic Online Hourly Continuous Data

The hourly continuous counts from Florida Traffic Online consists of permanent loop detector data spanning across Florida. There are over 600 stations scattered throughout the state.

The research team identified key stations which would capture significant movements moving out, and away from the urban locations in Florida. Therefore, the stations chosen from Florida Traffic Online were in locations at the edges of each district moving north and east/westward out of the state. During preliminary investigations, in the southern districts (D6, D4, D1, D7, and D5), vehicles were traveling north, and east. In the case of the northern districts (D2, and D3), it was found that predominant vehicular traffic was moving westward. The variables of interest that identified the location of each permanent count station were tabulated and are as shown in Table 2. The definitions of the data parameters are as shown below:

- Nearest Intersection – the output from Florida Traffic Online which gives the distance to the nearest roadway crossing, and the county in which the detector is located
- Mile Point – the distance from the start of the county that the detector is in, to its location within the county
- Florida Traffic Online Site ID – the site ID is used to identify a detector station through the Florida Traffic Online website and on each of the maps based on the district in which the detector is located.

Table 2 Florida Traffic Online Hourly Continuous Count Data

Facility	Nearest Intersection	Mile Point	Florida Traffic Online Site ID
District 6			
US-41	SR-90/US-41/SW 8TH ST, 0.36 MI. W OF SW 157TH AV, DADE CO.	1.7	870383
US-27	US-27, 2.1 MILES N OF PALMETTO EXPWY, MIAMI-DADE CO.	8.1	879447
SR-9	SR-9, 0.4 MI SW OF BISCAYNE CANAL BRG, DADE CO.	12.5	870096
District 4			
US-27	SR-25/US-27,0.46 MI. N. OF CR-827, PALM BEACH CO.	22.8	930268
SR-60	SR 60-1.5 MI E OF BLUE CYPRESS LK RD INDIAN RIV CO.	6.1	880139
SR-710	SR-710/BEELINE HWY,3.6 MI SE OF SR-706, PALM BCH CO.	4.7	930140
SR-80	SR80/SOUTHERN BLV,1 MI W OF SR7/US441, PALM BCH CO.	10.9	930101
US-1	MARTIN COUNTY	1.93	890374
US-1	SR5/US1, @ N END OF ROOSEVELT BRG., STUART, MARTIN CO.	-	890332
I-75	SR93/I75,2 MI W OF US27,.6 MI W OF TOLL, BROWARD CO.	20.2	860357
I-95	SR 9/I-95-0.6 MI S OF SR 68/ORANGE AV, ST LUCIE CO.	17.0	940260
SR-91	SR-91, N OF OKEECHOBEE RD/SR-70	15.6	970421
District 1			
US-17	SR-35/US-17,0.3 MI N OF BILL BRYAN RD, POLK CO.	1.7	160319
US-27	SR-25/US-27,280' S OF S HOLLY HILL TANK RD, POLK CO.	20.5	160310
US-41	SR-45/US-41,4.6 MI N OF LEE CO LINE, CHARLOTTE CO.	4.6	010367
US-41	SR-45/US-41,600' NW OF SPRINGFIELD DR, SARASOTA CO.	10.4	170181
I-75	SR-93/I-75,0.7 MI N SR72@PROCTOR RD OP, SARASOTA CO.	35.4	170225
District 7			
US-19	SR-55/US-19,0.2 MILES NORTH OF CR-480, CITRUS CO.	2.13	020044
US-41	SR-45/US-41, N OF CR-485/MONDON HILL RD, HERNANDO CO.	10.7	080294
US-301	SR-35/US98&301,0.2 MI S OF US301 & 98 JCT, PASCO CO.	20.3	140079
I-75	SR-93/I-75, 1.0 MI N OF SR-56, PASCO CO.	2.64	140190
I-275	SR-93/I-275,900' S OF SKYWAY TOLLBOOTH, PINELLAS CO.	6.9	150183
District 5			
US-301	SR-25/US-301,0.3 MI N OF SR-326, MARION CO.	3.8	360118
US-441	SR-500/US-441,0.3 MI E OF CR-44, LAKE CO.	8.6	110177
US-192	US-192,2 MI W OF SR-15, HOLOPAW, OSCEOLA CO.	22.2	920065
I-75	I-75, 0.23 MI N OF WILLIAMS RD/SW 66TH ST O/P, MARION CO.	12.2	360317
SR-91	SR-91, S OF CR468	3.4	979931
District 2			
US-19	SR-55/US-19,2 MI S OF SR-26, CHIEFLAND, LEVY CO.	3.2	349909
US-27	SR-55/US-27A,158' SE OF CR-339A, LEVY CO.	20.2	340278
I-75	SR-93/I-75, BETWEEN I-10 AND US-90, COLUMBIA CO.	22.4	290320
I-10WB	I-10, 1.81 MI EAST OF CR-53, MADISON COUNTY	24.6	359902
I-95	SR-9/I-95, 2.5 MI N OF HWY A1A, JAX., NASSAU CO.	5.6	749923
District 3			
US-319	SR-61/US-319,4.1 MI S OF GEORGIA STATE LN, LEON CO.	14.2	550349
US-231	SR-75/US-231,.7 MI S OF ALA. STATE LINE, JACKSON CO	17.7	530050
I-10WB	SR-8/I-10,250' W OF CR-268 OVERPASS, GADSDEN CO.	23.9	500220
I-10WB	I-10, 0.6 MI W SR-297 U/P, @ST LN, ESCAMBIA CO.	6.4	480156

3.2. Woolsey Wildfire Data

The figure below shows the extent of the Woolsey wildfire, and the neighboring Hill wildfire along with the location of the roadway detectors analyzed for the purpose of this study.

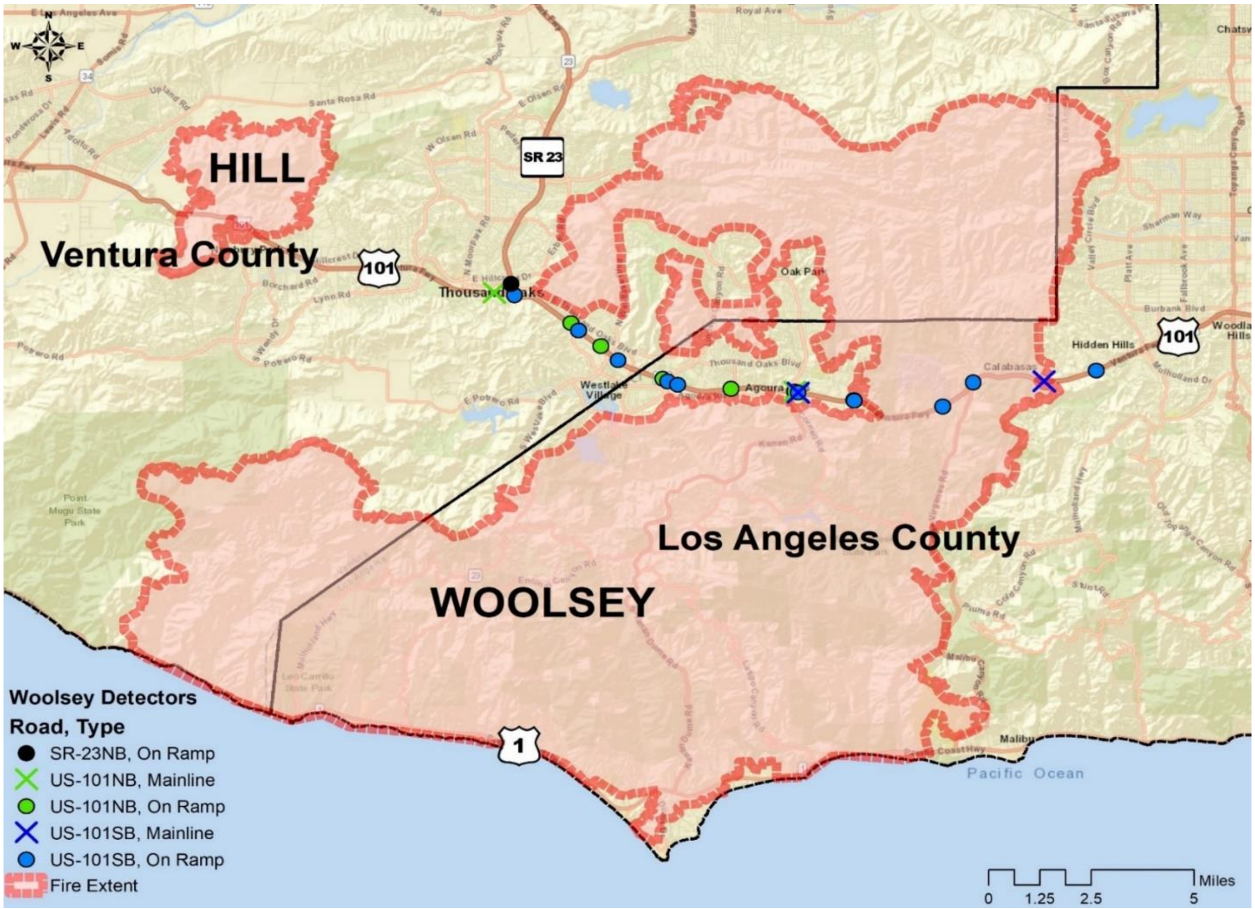


Figure 6 Woolsey Wildfire and the Roadway Detectors

All detector data used were extracted through PeMS, the California Department of Transportation's (Caltrans) web-based transportation data portal. As mentioned previously in Section 2, the evacuation process of the Woolsey fire led the research team to identify specific ON-ramps, and mainline detectors which would display the evacuee travel characteristics out of harm's way from the wildfire. It should be mentioned that only one detector was chosen for SR-23. This was at the judgment of the research team based on the wind direction of the fire, and the general path of destruction moving SW towards the coastline starting in Agoura Hills. The detectors chosen for the Woolsey Wildfire analysis are as shown in Table 3, the definitions of which are below.

- Detector Name – the PeMS detector identification used to locate individual detectors (see Figure 6).
- Mile Marker – Absolute mile marker, these are in the order of the travel direction

- Detector ID – this is used to identify each detector through PeMS.
- Location Type – Whether or not the detector was in an ON-Ramp or, Mainline, the average of all lanes of travel.

Table 3 Woolsey Wildfire Detectors (PeMS)

Detector Name	Mile Marker	Detector ID	Location Type
US-101NB			
PALO COMADO CYN**	35.1	765090	ON-Ramp
KANAN*	36.6	765093	ON-Ramp
REYES ADOBE*	37.6	759272	ON-Ramp
LINDERO 2*	39.0	718349	ON-Ramp
WESTLAKE 2*	40.5	765007	ON-Ramp
HAMPSHIRE*	41.3	765015	ON-Ramp
KANAN*	36.3	764963	Mainline
RTE 23 CN*	43.0	776465	Mainline
US-101SB			
RANCHO*	42.6	765019	ON-Ramp
HAMPSHIRE*	41.0	765011	ON-Ramp
WESTLAKE 1*	40.0	765151	ON-Ramp
LINDERO 2*	38.9	718347	ON-Ramp
LINDERO 1*	38.7	718346	ON-Ramp
KANAN*	36.2	716399	ON-Ramp
PALO COMADO CYN**	35.1	718345	ON-Ramp
LOST HILLS**	33.2	776441	ON-Ramp
LAS VIRGENES**	32.4	764752	ON-Ramp
PKWY CALABASAS 2***	29.8	718040	ON-Ramp
KANAN*	36.2	718149	Mainline
CALABASAS***	30.8	716390	Mainline
SR-23NB			
HILLCREST*	12.5	771253	ON-Ramp

* Indicates North of the Fires Path; **Indicates in the Fires Path; *** Indicates South of the Fires Path

3.3.Data Cleaning and Processing

All data was processed using R-Studio (an open source data analysis environment) to produce all quantitative outputs, and to prepare the data to be used in speed plots. The speed plots required the use of MATLAB. Data from RITIS which identified the trends that occurred during the evacuation required a script that could be repeatedly used for each roadway under observation. The research team setup a script inside of the R-Studio platform to compute the desired outputs, the sheer computational complexity of which would have deemed MS Excel and other platforms unfit for this task. Moreover, the replication of the script certainly reduced the computational time involved in obtaining the data readymade for subsequent analyses.

In a similar fashion, the 5-minute data for each matching detector which was used for the Hurricane Irma also required scripts that were again written in a manner that could be reproducible for each roadway under consideration. It should be mentioned that a critical component in evaluating each roadway in its respective district required the identification of mile markers. The hourly continuous data extracted from Florida Traffic Online also needed a script to produce the quantitative results, and the line plots. This data did not need requiring cleaning but was processed, again in an environment which allowed the research team to quickly receive outputs for each detector.

As for the Woolsey fire, the researchers had determined that because of the increase in volume, and or general traffic direction during the short-time evacuation window, it would only require traffic flow visualizations to be extracted from PeMS. The data cleaning exercise involved matching each detector to its geocoordinate in order to produce maps of the detectors.

4. Results and Discussion

4.1. Evacuation During Hurricane Irma

As mentioned in the earlier sections, (i) vehicle miles traveled, (ii) percent of vehicle miles traveled congested, and (iii) delay hours were the primary performance measures for the roadway. In addition to this, a measure for the validity of the detector itself, was used to demonstrate the portion of the day captured (percent day captured). Lastly, two other indicators of the traffic stream were calculated as reference, $\mathbf{V_f}$ (mean speed of the traffic that was not in the congested state), and $\bar{V}$ (the mean speed of the entire traffic stream). These values for each roadway in each district with probe data, and the corresponding days leading up to the arrival of

Hurricane Irma are shown in

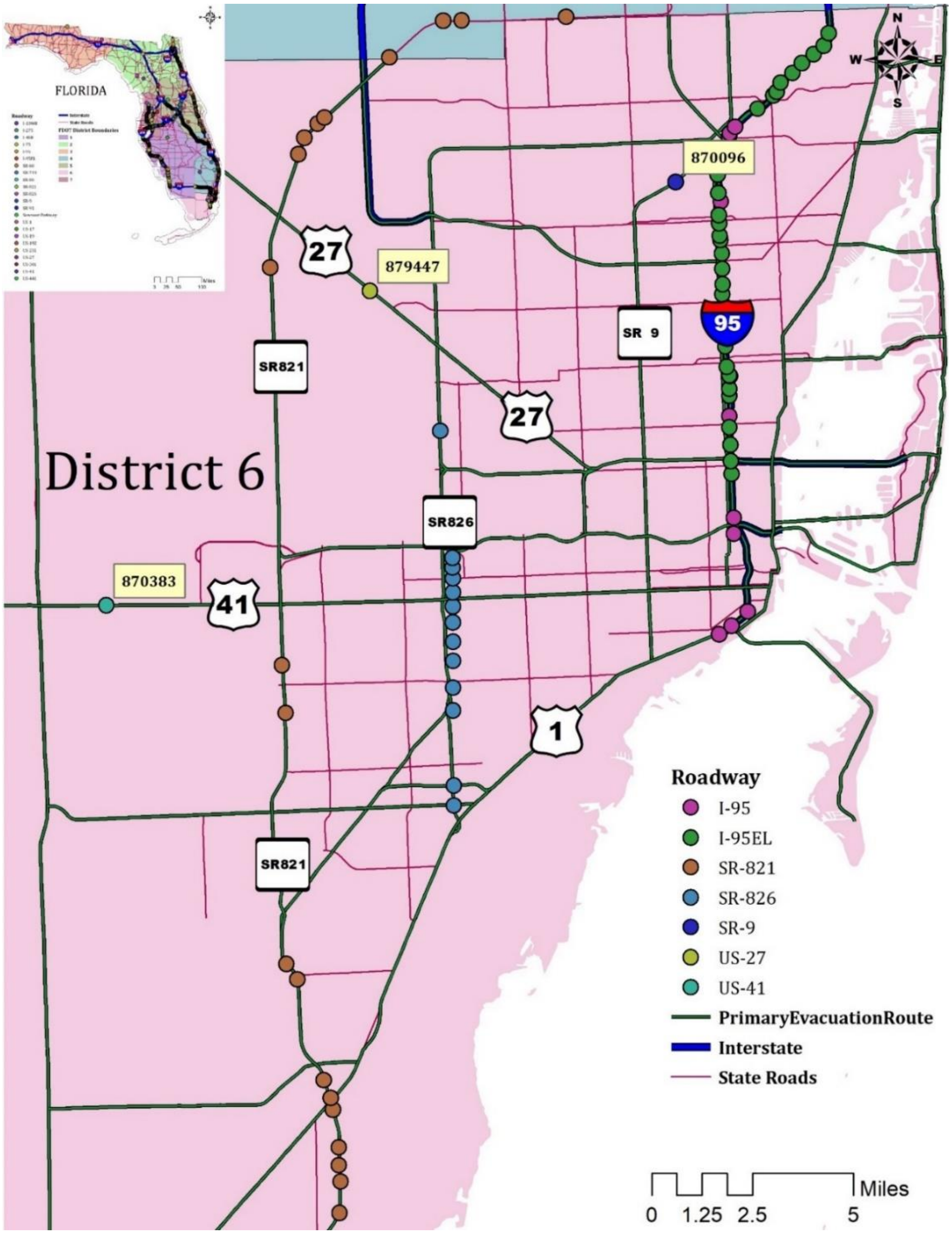


Figure 7 D6 Roadway Detectors – Hurricane Irma

Table 4 (District 6), Table 8 (District 4), Table 12 (District 1), Table 16 (District 7), Table 20 (District 5), and Table 24 (District 2).

The RITIS probe detector data collected for each roadway facility during the evacuation days were then compared to a 3-month 5-minute 85th percentile RITIS probe detector data collected for each roadway. The detectors used for the 5-minute comparisons were the same as those used in the analysis of the evacuation. That said, detectors which were not functional during the evacuation but available to be used for the 5-minute examination were excluded from the analysis. The research team faced significant computational challenges in using month-long streams of data, deeming the final decision to use a three-month period for the 5-minute data and not a years' worth of data as an appropriate strategy. Therefore, the comparison to 5-minute data used only three months that spanned from February 1, 2017 to April 30, 2017. The three-month performance averages using the 5-minute probe data were the average vehicle miles traveled, and average percent vehicles miles traveled congested, with the corresponding average speed of the congested vehicles, $\mathbf{V_f}$, and average speed of the traffic stream, $\overline{\boldsymbol{V}}$. These are as shown in Table 5 (District 6), Table 9 (District 4), Table 13 (District 1), Table 17 (District 7), Table 21 (District 5), and Table 25 (District 2).

It must be noted that the vehicle hours of delay calculated for the 5-minute data used the lower 15th percentile. The reasoning behind this was to depict the vehicle hours of delay shown through the speed plots (which compared the observed speeds of the roadway segment for that day) to be compared with the 5-minute 85th percentile speeds of that corresponding day, time, and location. The speed plots were used to demonstrate the speed observed on the roadway segment, when the observed percent vehicle miles congested breached ten percent, and compared it to the 85th percentile of speeds observed across the roadway segment from the 5-minute data. The 85th percentile was used as a comparison measure based on past literature (FHWA 2018).

The research team also compiled additional results including the total number of observations for each detector on the roadway segment on an evacuation day. It should be noted carefully that these can also be repeat observations. For instance, if a single vehicle traveled the entire length of the roadway facility (such as the I-95), that vehicle would count an equal number of times as there are detectors[2]. The second measure here, the average vehicles per detector per day, is simply the total number of vehicles observed divided by the number of detectors. The research team used this metric to determine the daily traffic for that day across the entire segment of the roadway instead of only choosing a single detector to depict this value. These are as shown in Table 6 (District 6), Table 10 (District 4), Table 14 (District 1), Table 18 (District 7), Table 22 (District 5), and Table 26 (District 2).

---

[2] An example of this would be if a vehicle traveled through the entire roadway section of I-95, which based Table 1 has 33 detectors that vehicle would be counted 33 times.

Lastly, the hourly continuous counts from Florida Traffic Online were compiled. The performance metrics from this dataset were (i) the observed volume for that day, and (ii) the percent difference of that day compared to the entire year of observations. Plots for each facility were chosen based on whether there was a day during the mass evacuation which resulted in a 100-percent increase in the average volume for the corresponding evacuation day. This also provided a tool for validating some of the findings from the RITIS probe detector data and gave a sense of the trends observed in evacuation in each FDOT district. Additionally, the last four digits of the detectors were used as the ID and were shown on the plots, and in parenthesis under Facility (refer to Table 2 for the full ID). These are as shown in Table 7 (District 6), Table 11 (District 4), Table 15 (District 1), Table 19 (District 7), Table 23 (District 5), Table 27 (District 2), and Table 28 (District 3).

4.1.1. District 6 Evacuation Performance

The figure below shows a list of the analyzed detectors in District 6 for Hurricane Irma. The main facilities that the research team investigated in this district were the I-95, the I-95 express lane, SR-821, and SR-826.

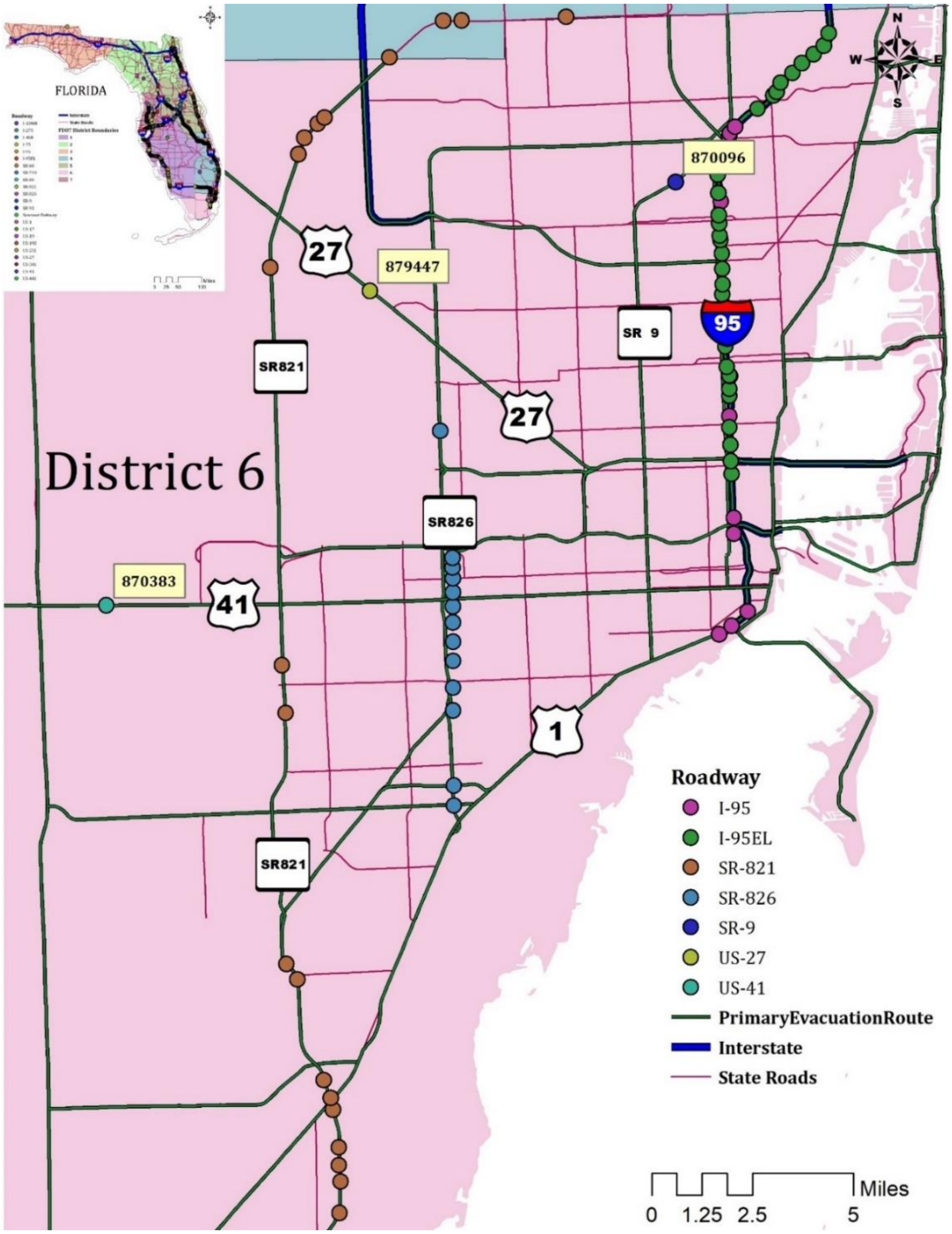


Figure 7 D6 Roadway Detectors – Hurricane Irma

Table 4 District 6: RITIS Probe Detector Data Performance Measures

Facility	%VMT Congested (VMT) (% Day Captured) (Veh-Hours of Delay) (V_f)($\overline{V}$)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-95	17.4% (1,481,835) (98.1%) (6,287) (61.5) (57.6)	12.7% (1,270,613) (94.4%) (4,670) (61.4) (58.5)	1.2% (1,086,492) (98.3%) (213) (62.3) (62.1)	0.1% (616,236) (90.7%) (9) (63.1) (63.1)	1.1% (135,568) (63.8%) (124) (61.3) (61.0)
I-95EL	14.7% (244,223) (69.5%) (1,201) (67.2) (63.5)	17.6% (289,172) (69.9%) (1,798) (66.0) (61.2)	1.8% (237,091) (83.1%) (182) (67.5) (67.1)	0.3% (107,762) (66.9%) (1) (68.3) (68.3)	1.8% (11,654) (17.8%) (24) (65.8) (65.5)
SR-821	8.5% (214,587) (27.9%) (433) (71.1) (68.8)	10.4% (1,089,156) (52.0%) (856) (66.3) (65.4)	0.8% (1,670,590) (99.8%) (79) (68.3) (68.1)	0.0% (1,080,246) (99.8%) (1) (69.6) (69.6)	0.2% (191,502) (69.9%) (7.8) (68.2) (68.2)
SR-826	17.6% (822,987) (95.6%) (3,491) (59.1) (55.2)	9.5% (762,462) (95.2%) (971) (59.0) (57.6)	2.1% (629,593) (90.6%) (275) (60.4) (60.2)	0.0% (405,344) (88.6%) (0) (62.3) (62.3)	0.1% (86,732) (63.3%) (17) (62.4) (62.3)

Table 5 District 6: RITIS Probe Detector Three Month Performance Averages

Facility	%VMT Congested (VMT) (Veh-Hours of Delay) (V_f) ($\overline{V}$)				
	Tuesday	**Wednesday**	**Thursday**	**Friday**	**Saturday**
I-95*	19.7% (1,217,415) (4,608) (62.3) (56.9)	21.0% (1,227,698) (5,152) (62.1) (56.5)	20.5% (1,263,223) (4,808) (62.0) (56.4)	21.9% (1,308,143) (5,733) (61.7) (55.7)	7.9% (1,278,076) (4,215) (62.3) (60.3)
I-95EL	-	-	-	-	-
SR-821	8.6% (773,642) (1,628) (70.1) (68.2)	6.9% (793,110) (1,081) (69.8) (67.6)	7.6% (797,598) (1,131) (69.8) (67.7)	6.5% (849,650) (991) (69.6) (68.4)	0.2% (705,554) (2) (72.2) (72.1)
SR-826	16.7% (366,104) (1,160) (55.7) (51.2)	17.0% (368,459) (1,252) (56.0) (51.5)	16.2% (378,254) (1,164) (55.7) (51.4)	19.3% (386,981) (1,589) (55.4) (50.6)	1.3% (345,790) (393) (58.7) (58.2)

* The 5-minute data did not include some detectors on I-95

Table 6 District 6: RITIS Probe Detector Total Observations

Facility	Number of vehicles observed (Average vehicles per detector per day)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
I-95	2,742,873 (83,117)	2,350,750 (71,235)	2,042,783 (61,903)	1,173,792 (35,569)	256,765 (7,781)
I-95EL	680,354 (21,261)	796,898 (24,903)	659,988 (20,625)	301,867 (9,433)	33,366 (1,043)
SR-821	127,564 (6,378)	631,285 (31,564)	954,065 (47,703)	629,265 (31,463)	116,929 (5,847)
SR-826	2,503,670 (89,417)	2,309,249 (82,473)	1,920,144 (68,577)	1,126,844 (45,316)	269,357 (9,620)

Table 7 District 6: Florida Traffic Online Hourly Continuous Count Stations

Facility (ID)	Evacuation Volume (% Difference from Yearly Average)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
US-41 (0383)	9,213 (2.1%)	9,070 (1.2%)	8,586 (-6.4%)	5,712 (-45.2%)	1,655 (-83.5%)
US-27 (9447)	23,888 (9.6%)	22,945 (5.3%)	20,150 (-9.6%)	11,910 (-47.9%)	1,842 (-86.6%)
SR-9 (0096)	17,151 (-5.1%)	15,439 (-18.4%)	12,616 (-33.9%)	8,334 (-57.7%)	2,073 (-86.2%)

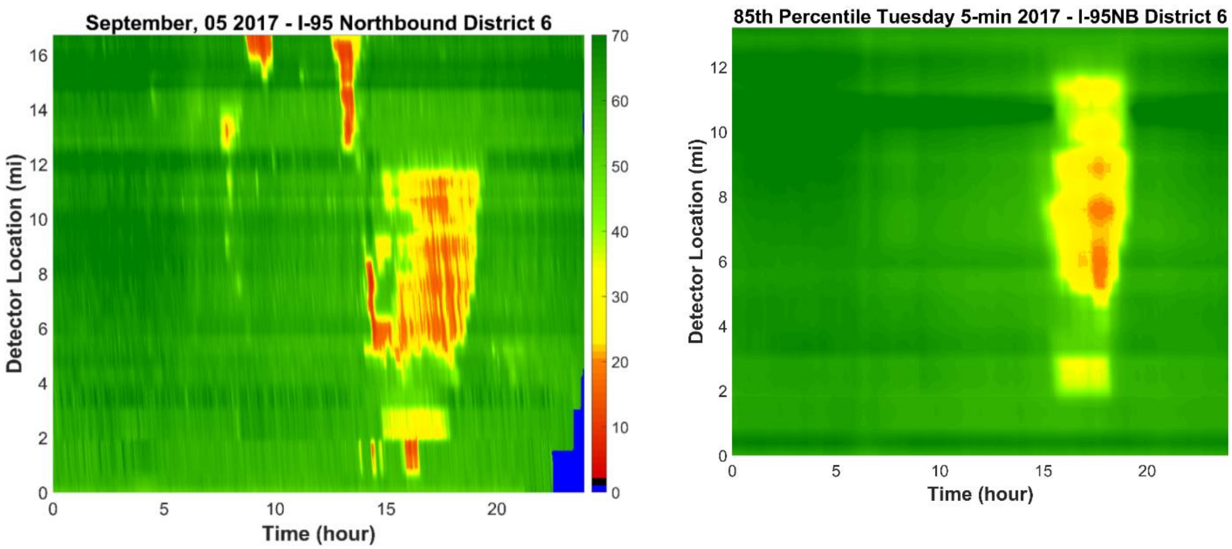


Figure 8 D6: I-95 NB Speed (Tue, Sep 5, 2017) vs Three-Month 85th Percentile Speeds

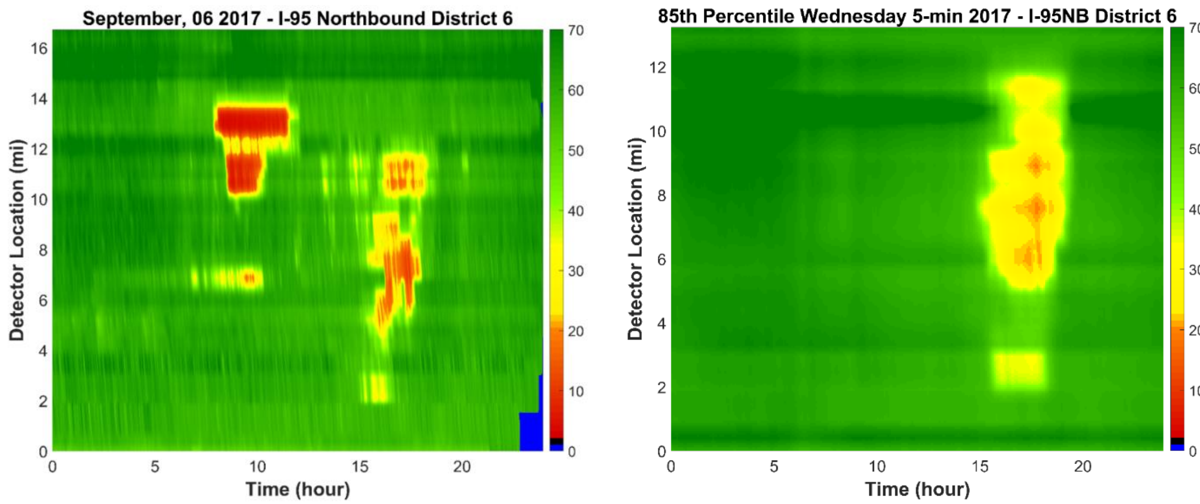


Figure 9 D6: I-95 NB Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

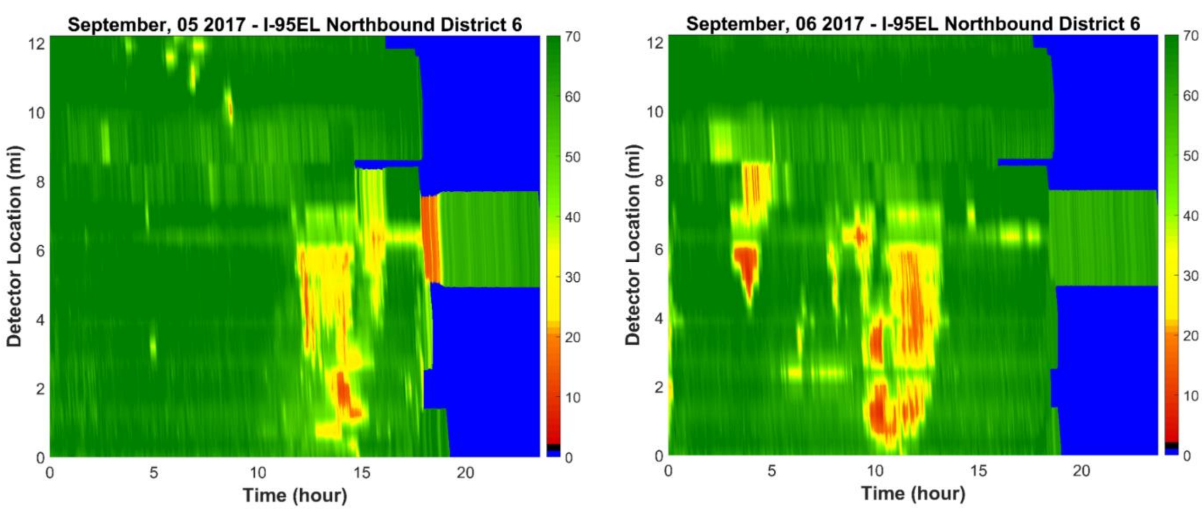


Figure 10 D6: I-95 NB EL Speeds – Tue, Sep 5, 2017 vs Wed, Sep 6, 2017

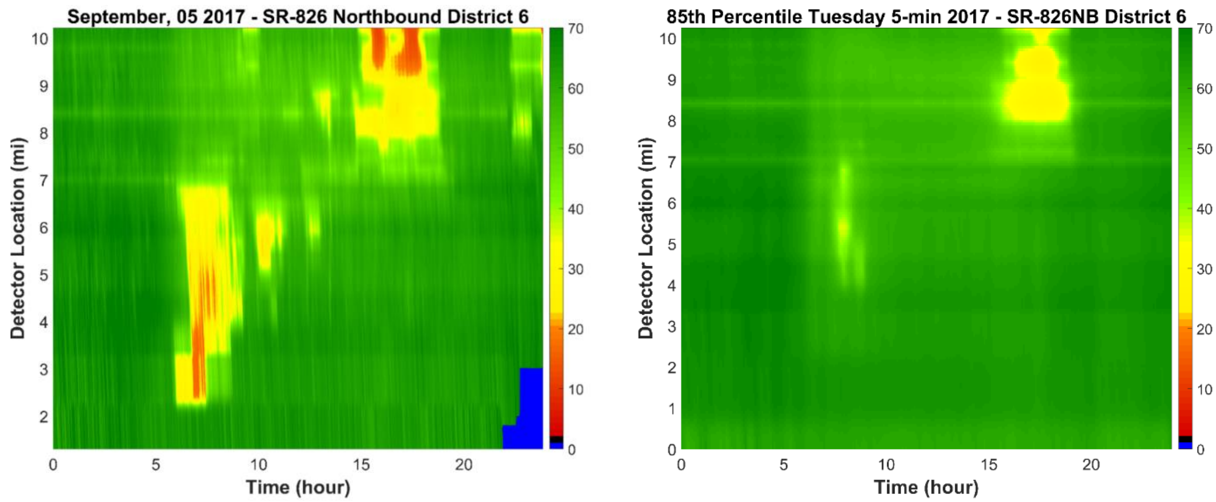


Figure 11 D6: SR 826 Speed (Tue, Sep 5, 2017) vs Three-Month 85th Percentile Speeds

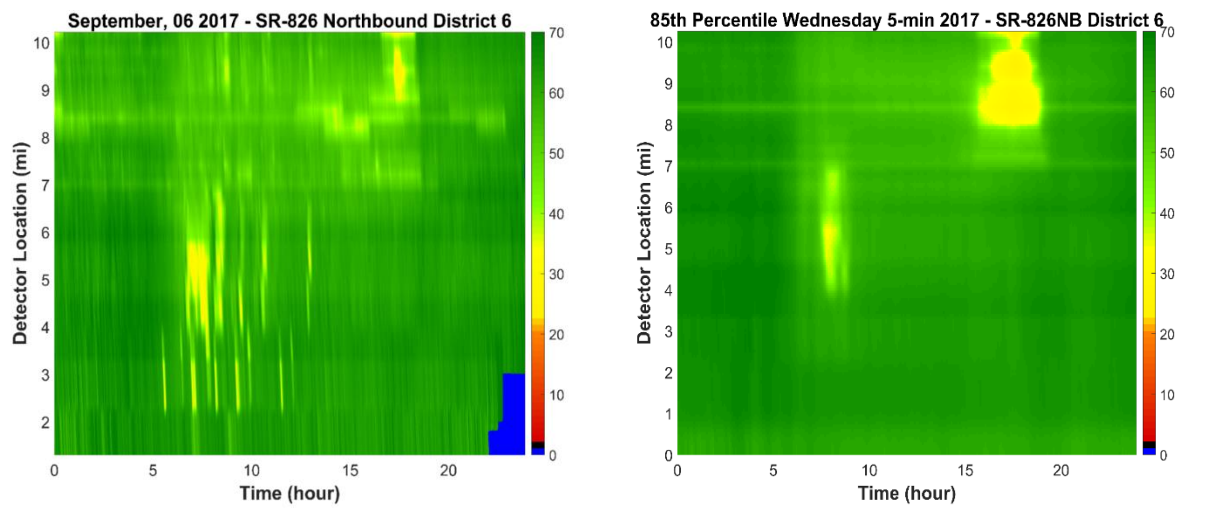


Figure 12 D6: SR 826 Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

Key Findings

As seen in Table 4, the percent VMT congested and the corresponding VMT on the day of the evacuation is compared to the 5-minute 85^{th} percentile 3-month averaged RITIS probe detector data. This means that Tuesday, Sep 5 for I-95 in

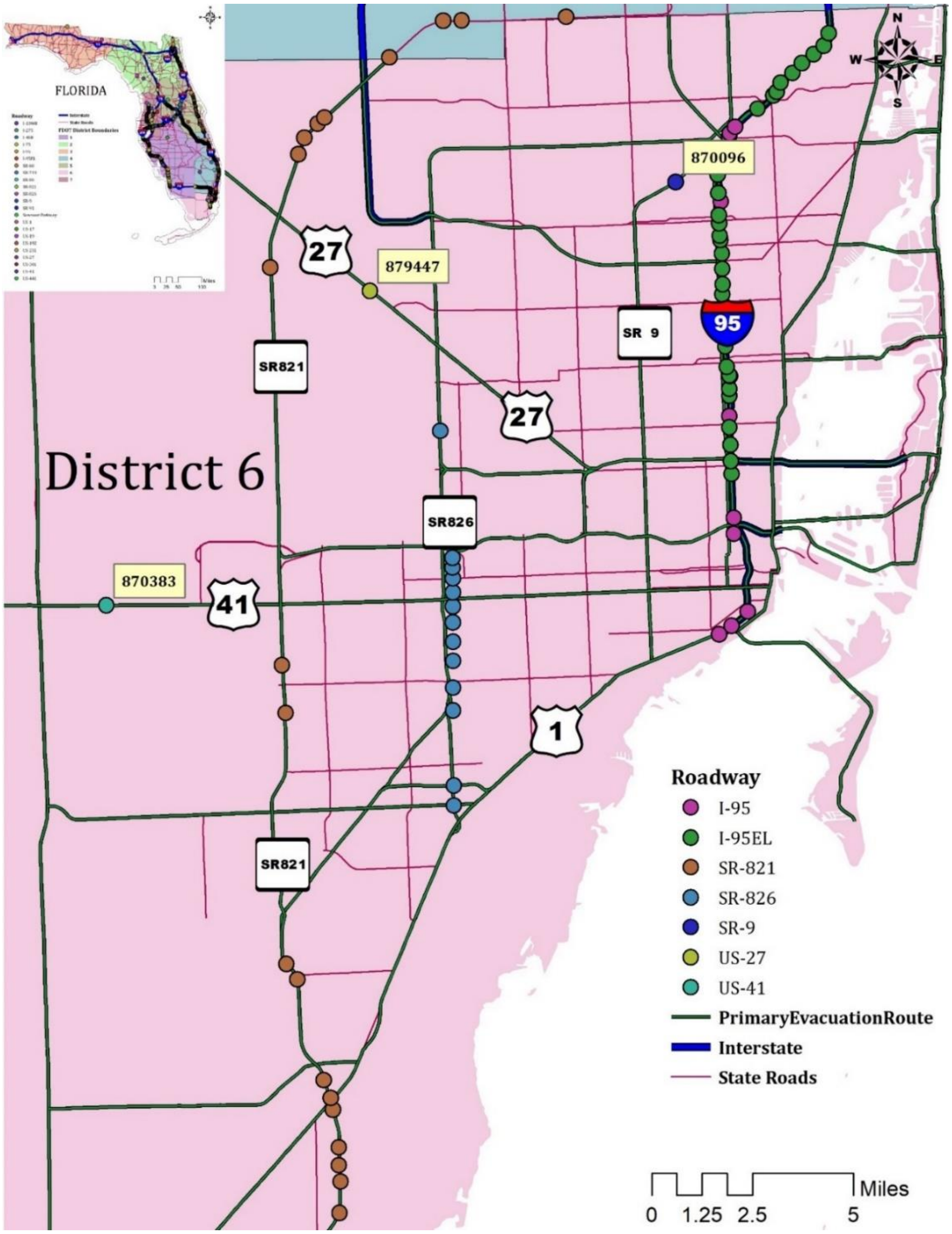


Figure 7 D6 Roadway Detectors – Hurricane Irma

Table 4 is compared to the 3-month average Tuesday during the three-month period in Table 5. The percent VMT congested on Tuesday Sep 5 is higher for the 3-month averages than during the evacuation day, however the VMT observed on Tuesday, Sep 5 (in Table 4) was greater than the 3-month average observed in Table 5. In addition to this, evacuation day $\mathbf{V_f}$ and $\overline{\boldsymbol{V}}$ (for Sep 5) are very similar to the 3-month averages. It can thus be concluded that I-95 in District 6 on Tuesday Sep 5 saw little deviation from normal operating conditions. IT can also be observed how the I-95 in District 6 experienced considerably lesser traffic volumes after the 7th of September indicating that most of the peak evacuation from these areas had taken place by then.

Moving to SR-826, on the same day, Tuesday, Sep 5, a comparison of Table 4 to Figure 11 shows that delays were prevalent on the stretch ranging from MM 2.5 to MM 7 on the morning between 5 AM and 10 AM. Later in the day, queues were observed downstream of MM 10, extending all the way upstream to MM 8 in the afternoon from 3 PM to 8 PM. The associated vehicle hours of delay observed for this day were 3,491 (see Table 4). Comparing the speed plots observed on Tuesday, Sep 5, to the 3-month 85th percentile Tuesday speeds, it is clear that the queuing which was present during the evacuation on Sep 5 from MM 8 to MM 10 is also typically present during normal operating hours (as seen through Table 5 with hours of delay equal to 1,160). Thus, it can be concluded that this location was not a bottleneck caused by the hurricane evacuation but is a preexisting bottleneck that became more severe during the evacuation.

The final set of observations are gleaned from the hourly continuous count stations from Florida Traffic Online. As shown in Table 7, three stations were identified in D6 as priority observation points for traffic moving NB and out of harm's way: US-41, US-27, and SR-9. Of these three stations, there was no day where the volume met a 100% increase from typical volumes, as such the flow visualizations were not of much significance. Nonetheless, for the reader's convenience, however, sample plots for US-27 are as shown in Figure 13 below. It can be observed that evacuation volumes fell drastically during the later hours of September 7 indicating that a large volume of evacuees had moved out of the district by that time. This is consistent with earlier findings based on the performance metrics used by the research team to characterize the performance of the transportation network (see Table 4, and Table 5).

A detailed visualization of the performance of the analyzed roadways for each evacuation day are as shown in Appendix A (see Figure 71 to Figure 75).

Key Detector Issues

The I-95 express lane had sparse data; Only 9 of the 33 detectors for the 5-minute aggregation were functioning during our investigations. Of these detectors, only normal operating speeds were observed, and therefore unused for comparison purposes.

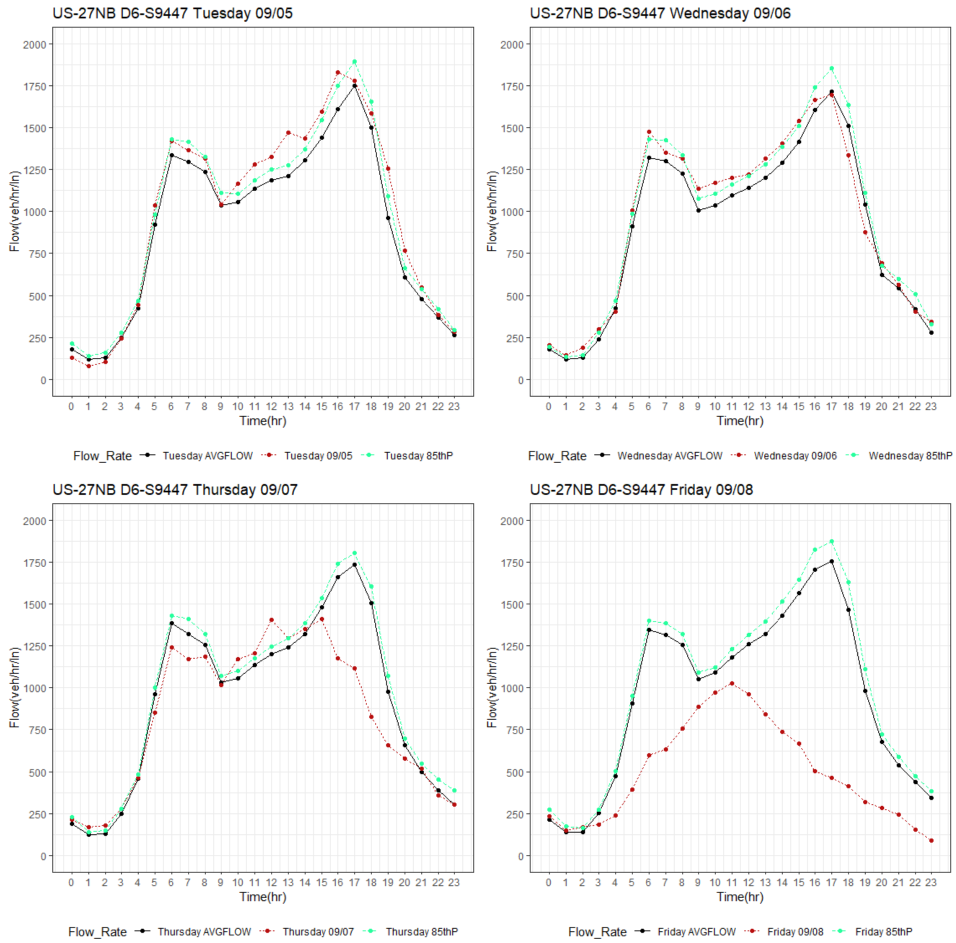


Figure 13 D6: US-27 (879447) – Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/05 to 09/08)

4.1.2. District 4 Evacuation Performance

The figure below shows a list of the analyzed detectors in District 4 for Hurricane Irma. The main facilities that the research team investigated in this district were the I-95, the I-95 express lane, SR-91, and the I-75. The analyzed detectors mostly were present along the eastern coastline in the populous South Florida counties of Miami Dade, Broward, Palm Beach, Martin, Indian River, and St. Lucie.

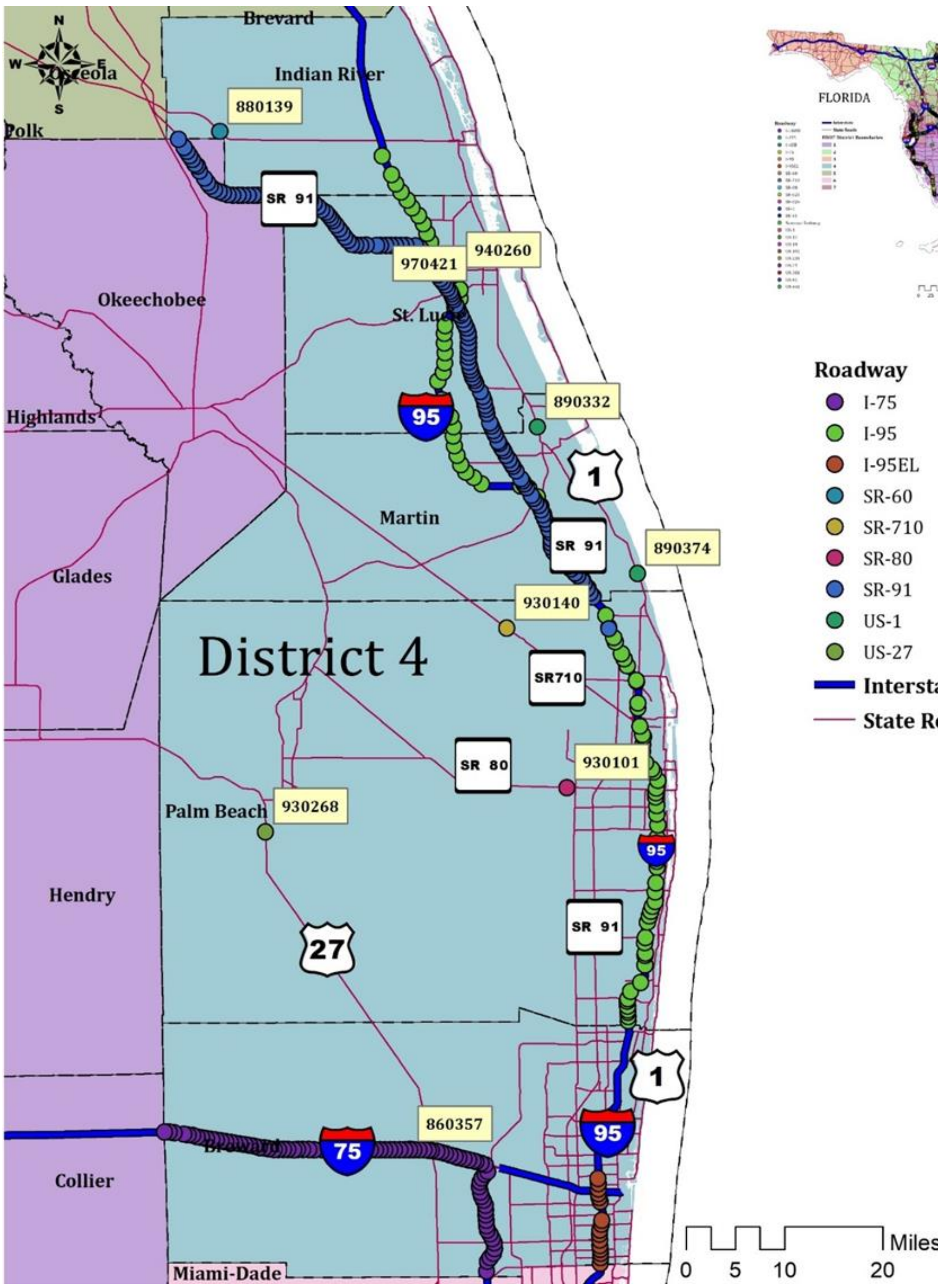


Figure 14 D4 Roadway Detectors – Hurricane Irma

Table 8 District 4: RITIS Probe Detector Data Performance Measures

Facility	%VMT Congested (VMT) (% Day Captured) (Veh-Hours of Delay) (V_f)($\overline{V}$)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
I-95	4.4% (5,036,740) (91.8%) (3,739) (73.0) (72.2)	11.1% (7,000,997) (99.0%) (18,536) (71.1) (67.4)	10.8% (7,711,449) (98.7%) (32,252) (70.6) (65.5)	1.0% (4,249,383) (97.2%) (1,968) (73.0) (72.8)	0.1% (531,728) (54.4%) (7) (71.7) (71.7)
I-95EL	7.4% (137,584) (71.2%) (588) (72.9) (70.7)	5.1% (164,814) (76.0%) (117) (72.4) (71.6)	2.2% (133,138) (78.6%) (10) (73.4) (73.4)	0.0% (50,755) (58.5%) (0) 74.7 74.2	0.0% (2,462) (5.9%) (0) 73.2 73.2
SR-91	0.2% (151,245) (27.2%) (10.7) (70.9) (70.8)	18.5% (2,017,201) (51.7%) (10,931) (65.0) (57.2)	28.0% (3,448,287) (99.1%) (34,456) (62.7) (49.9)	14.0% (2,389,155) (98.0%) (16,746) (70.2) (62.5)	0.0% (239,441) 69.5% (0) (73.6) (73.6)
I-75	4.2% (1,226,823) (80.8%) (555) (74.3) (74.0)	3.0% (1,344,794) (84.7%) (331) (73.8) (73.6)	1.9% (1,535,144) (88.2%) (370) (73.7) (73.5)	0.2% (868,821) (80.3%) (2) (73.7) (73.5)	0.9% (101,913) (24.3%) (34) (73.3) (73.3)

Table 9 District 4: RITIS Probe Detector Three Month Performance Averages

Facility	%VMT Congested (VMT) (Veh-Hours of Delay) (V_f)($\overline{V}$)				
	Tuesday	Wednesday	Thursday	Friday	Saturday
I-95	2.9% (5,330,976) (8,343) (72.3) (71.7)	2.8% (5,407,855) (8,241) (72.4) (71.8)	3.0% (5,591,401) (9,549) (72.4) (71.7)	2.9% (6,017,201) (11,521) (72.7) (71.8)	0.0% (5,085,301) (75) (74.0) (74.0)
I-95EL	-	-	-	-	-
SR-91	0.0% (1,040,002) (0) (70.7) (70.7)	0.0% (1,097,053) (0) (70.3) (70.3)	0.0% (1,309,733) (361) (71.3) (71.2)	0.0% (1,843,441) (116) (73.6) (73.5)	0.0% (1,333,314) (346) (75.0) (74.9)
I-75	4.6% (1,198,454) (5,725) (73.1) (72.8)	4.3% (1,212,540) (5,126) (73.0) (72.7)	4.0% (1,262,688) (5,690) (73.3) (73.0)	2.9% (1,418,767) (2,967) (73.9) (73.7)	4.7% (1,189,008) - (76.8) (76.8)

* The 5-minute data did not include some detectors on I-95

Table 10 District 4: RITIS Probe Detector Total Observations

Facility District	Number of vehicles observed (Average vehicles per detector per day)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
I-95	5,460,338 (55,718)	7,303,176 (74,522)	7.806,738 (79,661)	4,289,828 (43,774)	568,339 (5,799)
I-95EL	250,284 (15,643)	299,118 (18,694)	243,324 (15,208)	92,752 (5,797)	4,471 (279)
SR-91	284,743 (2,034)	3,826,788 (27,334)	6,517,516 (46,554)	4,509,269 (32,209)	452,377 (3,231)
I-75	2,442,335 (27,754)	2,675,638 (30,405)	3,055,003 (34,716)	1,730,619 (19,666)	204,005 (2,318)

Table 11 District 4: Florida Traffic Online Hourly Continuous Count Stations

Facility	Evacuation Volume (% Difference from Yearly Average)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
US-27 (0268)	4,463 (4.0%)	7,990 (82.1%)	15,771 (251.1%)	9,982 (91.0%)	344 (-91.5%)
SR-60 (0139)	3,353 (5.2%)	4,973 (50.7%)	8,668 (149.5%)	6,229 (43.8%)	473 (-86.7%)
SR-710 (0140)	2,630 (-10.3%)	7,390 (139.6%)	10,410 (228.2%)	3,046 (-13.6%)	265 (-90.1%)
SR-80 (0101)	43,625 (15.6%)	39,759 (3.7%)	34,348 (-10.4%)	23,452 (-41.3%)	5,717 (-83.9%)
US-1 (0374)	10,154 (-4.1%)	14,401 (32.9%)	12,718 (17.2%)	5,162 (-53.5%)	1,659 (-80.5%)
US-1 (0332)	31,434 (2.3%)	31,587 (1.6%)	28,495 (-7.4%)	15,764 (-51.4%)	5,840 (-78.4%)
I-75 (0357)	12,428 (11.4%)	17,161 (46.8%)	29,616 (140.5%)	16,531 (-1.2%)	900 (-94.5)
I-95 (0260)	32,239 (12.1%)	55,770 (87.2%)	80,915 (159.4%)	51,778 (40.7%)	5,133 (-83.0%)
SR-91 (0421)	16,537 (24.6%)	41,916 (196.0%)	50,542 (206.2%)	26,729 (4.1%)	2,819 (-85.7%)

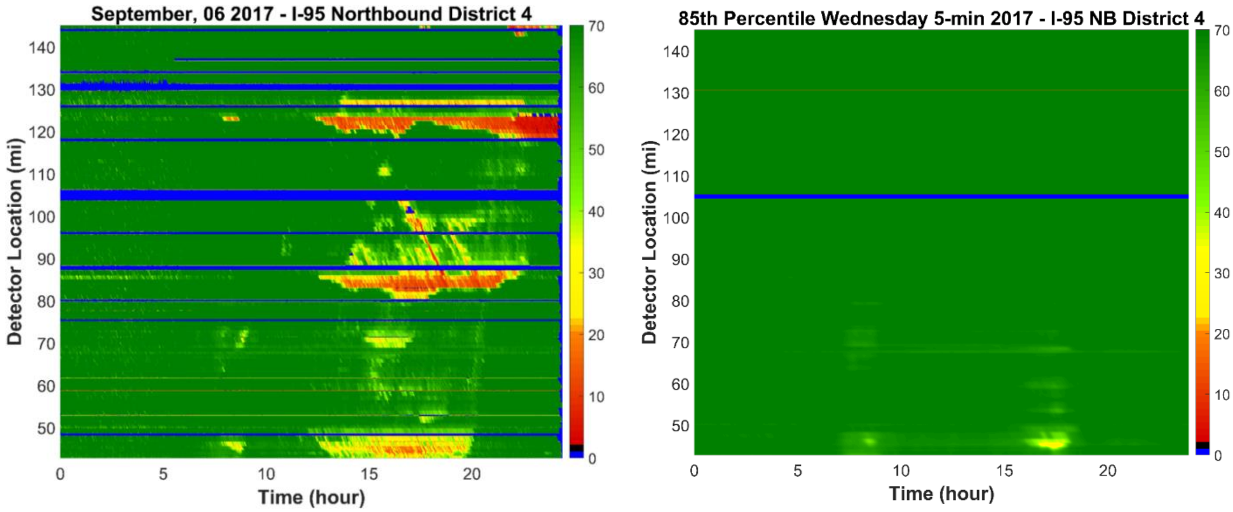


Figure 15 D4: I-95 NB Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

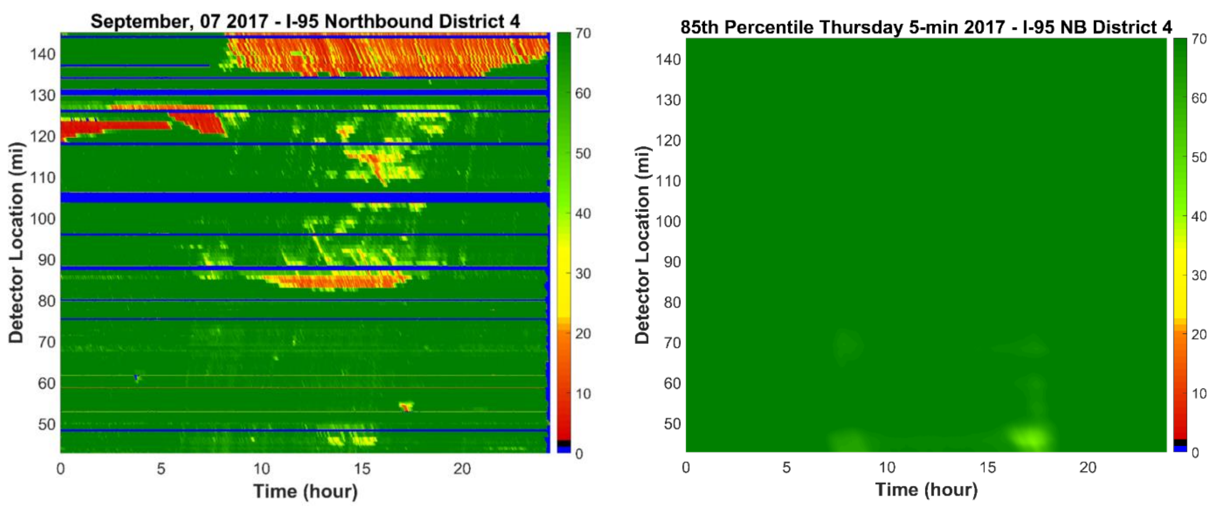


Figure 16 D4: I-95 NB Speed (Thu, Sep 7, 2017) vs Three-Month 85th Percentile Speeds

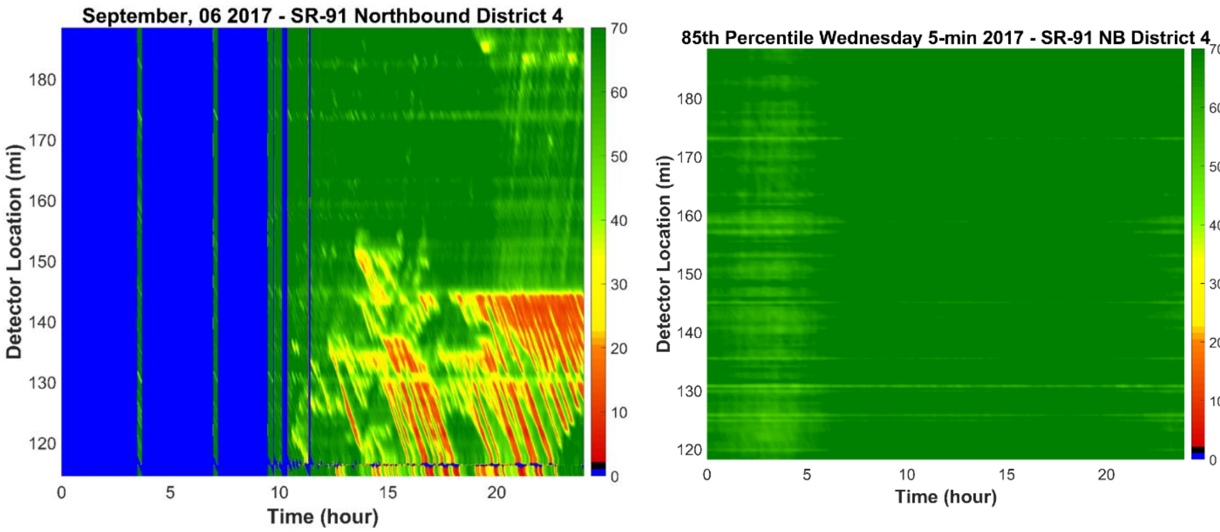


Figure 17 D4: SR-91 NB Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

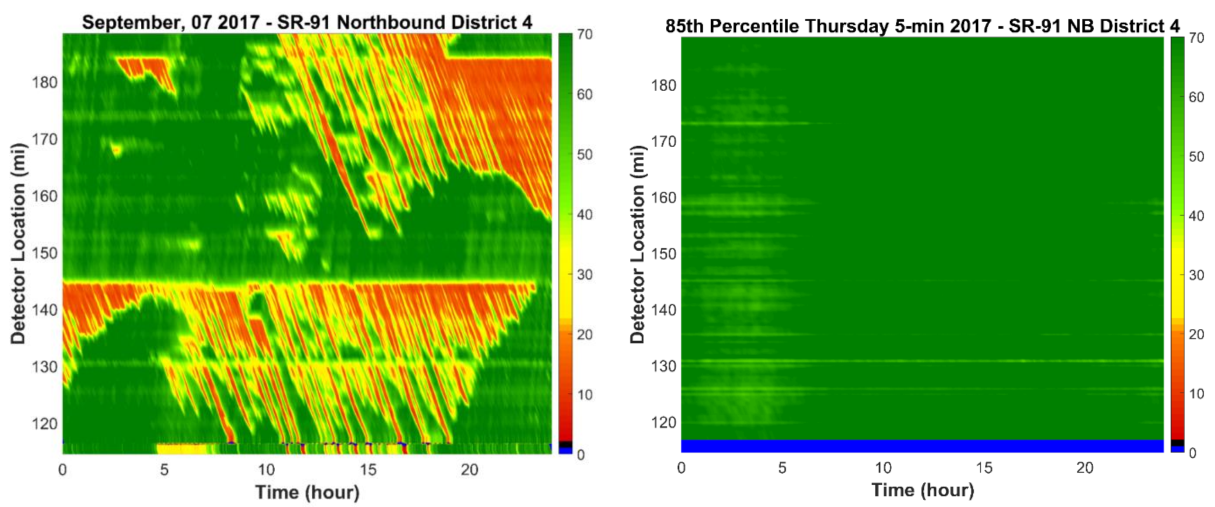


Figure 18 D4: SR-91 NB Speed (Thu, Sep 7, 2017) vs Three-Month 85th Percentile Speeds

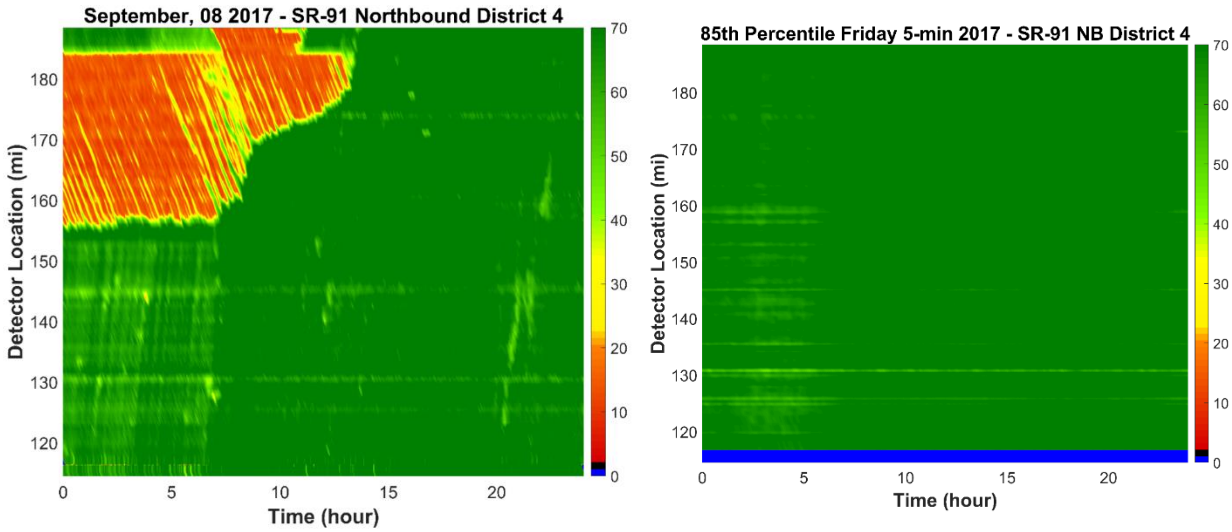


Figure 19 D4: SR-91 NB Speed (Fri, Sep 8, 2017) vs Three-Month 85th Percentile Speeds

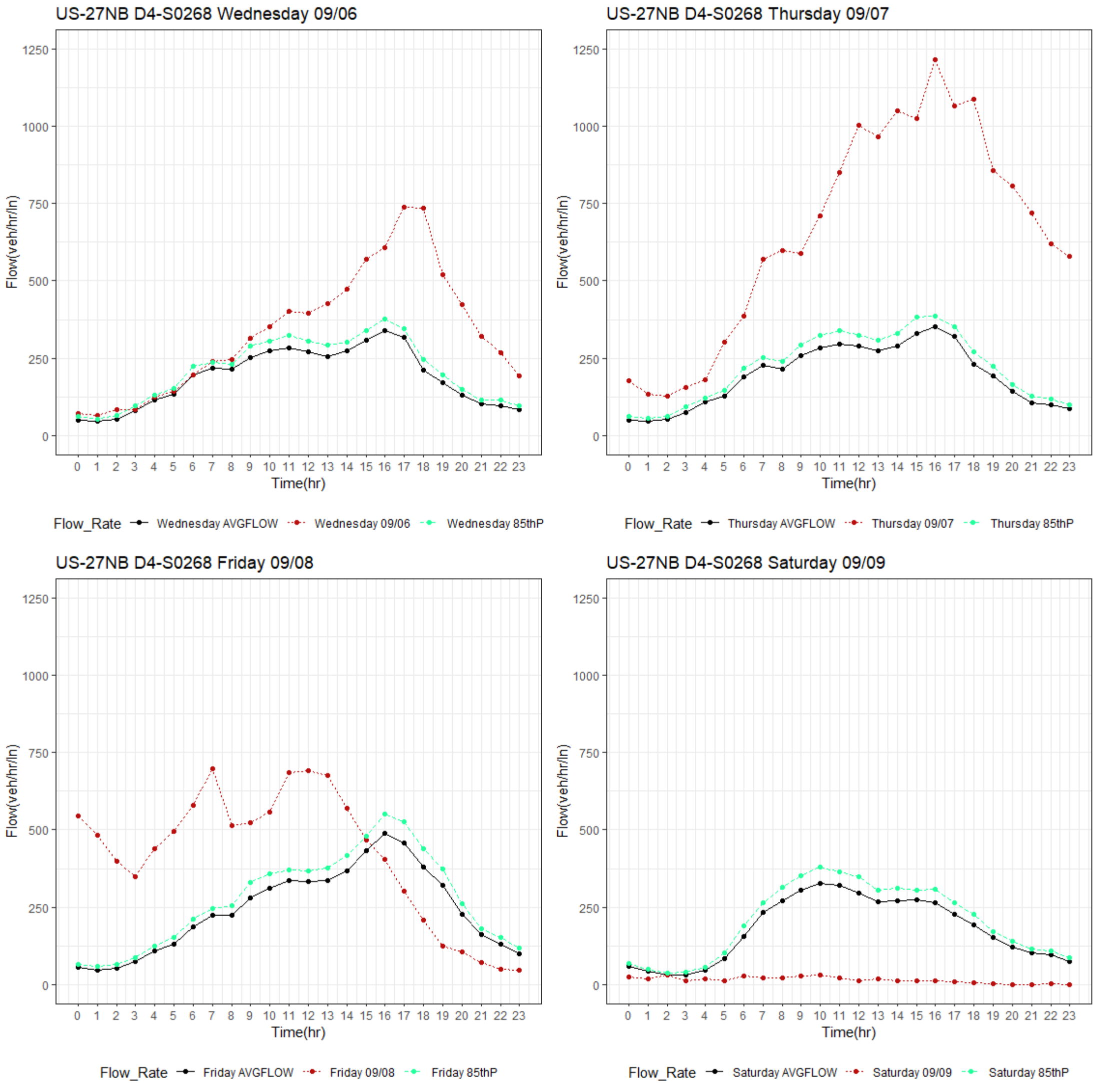


Figure 20 D4: US-27 (930268) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

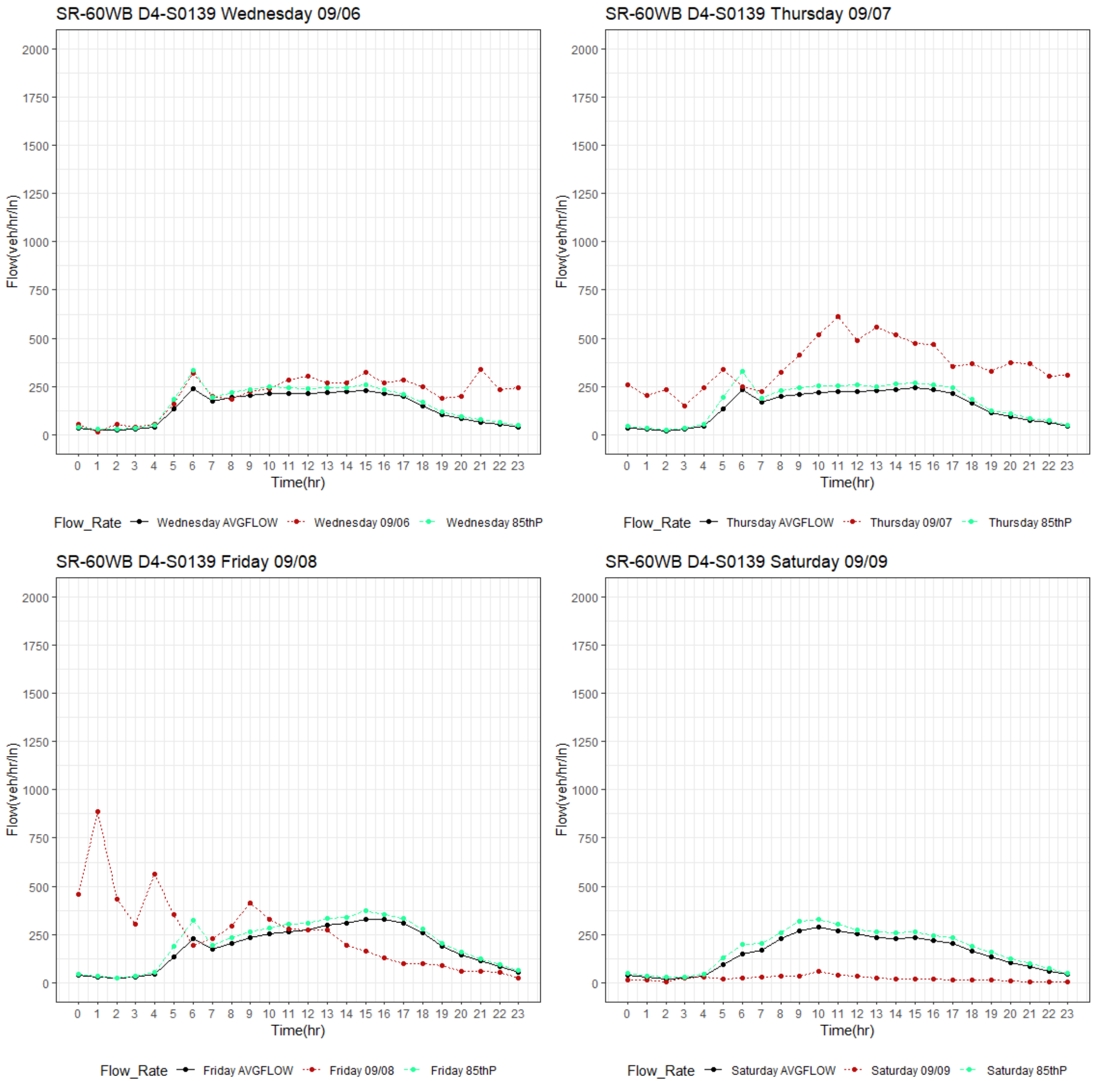


Figure 21 D4: SR-60 (880139) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

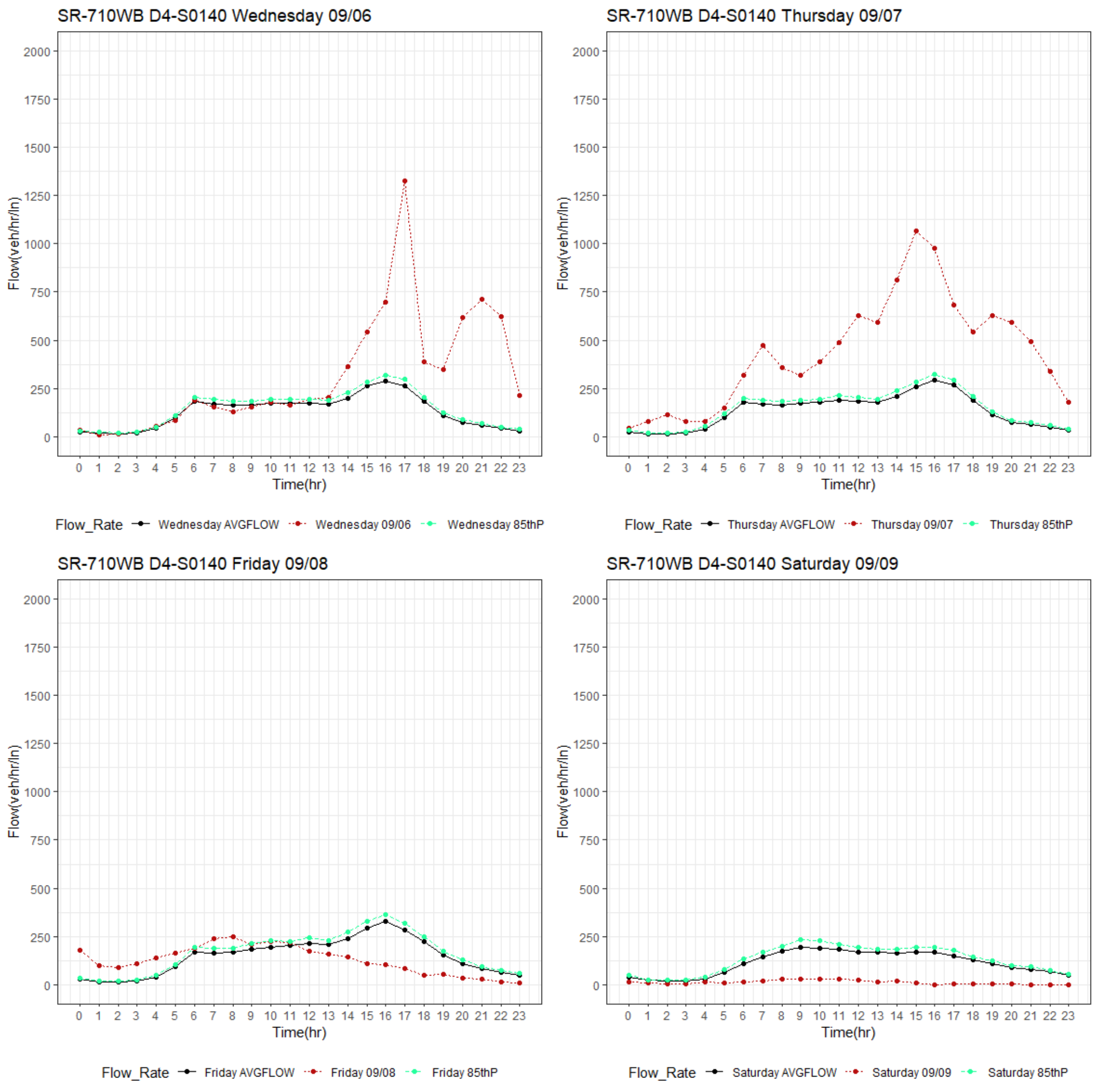


Figure 22 D4: SR-710 (930410) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

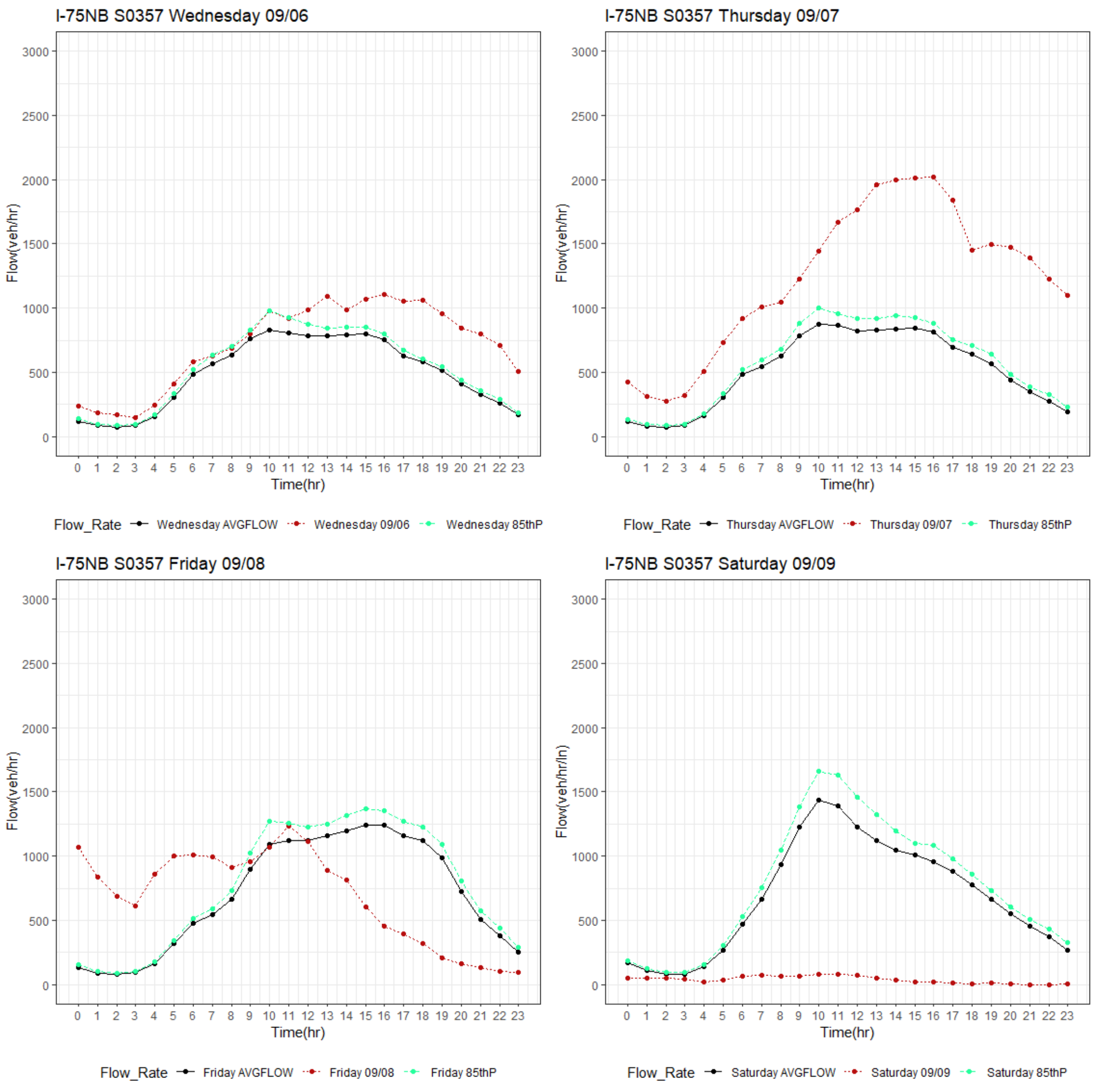


Figure 23 D4: I-75 (860357) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Figure 24 D4: I-95 (940260) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

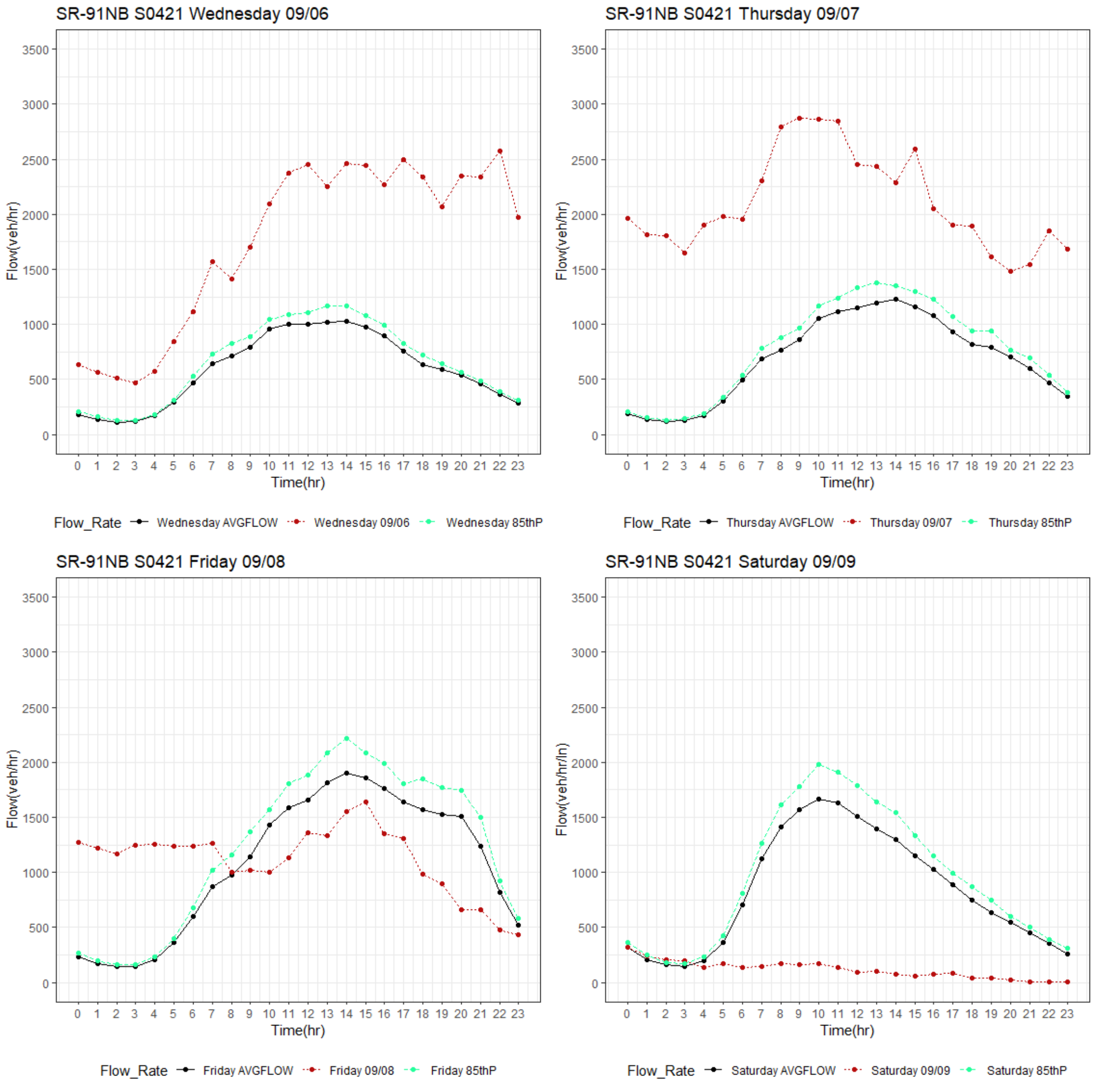


Figure 25 D4: SR-91 (Florida's Turnpike) (970421) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Key Findings

The I-95 NB in District 4 experienced significantly higher VMT on Sep 6 and Sep 7, in comparison to the 3-month averages for Wednesdays and Thursdays. This was also supplemented with higher percent VMT congested on these two days, in comparison to the 3-month data. Queueing was identified on Wednesday Sep 6 on the I-95 NB between mile markers 90 and 125. The queues started forming around noon and extended into the morning of Sep 7, 2017 (see Figure 15, and Figure 16). The end of the substantial queueing was observed nearby mile marker 135 on Sept 7. The research team believes that the queue may have propagated somewhere in District 5, however speed plots were not shown for district 5 due to the original constraint of needing at least 10% CVMT. It is the researchers understanding that most delay hours captured on Thursday, Sep 7 on I-95 were caused by this bottleneck.

SR-91, Florida's Turnpike, made for a very interesting case study along the entire span of the facility. Massive queuing was observed across the facility from Sep 6-8, as can be seen from the left hand-side of Figure 17, Figure 18, and Figure 19. This is also supplemented by observations from Table 8 and Table 9 with significantly higher values of percent VMT congested (+18.5%, +28%, and +14% for Sep 6, 7, and 8 in comparison to their 3-month avg), and substantially higher vehicle hours of delay. On closer inspection of the mile markers, extreme queueing was observed close to a service plaza located in the facility. Our analysis revealed that the service plaza was the only one of its nature located along the entire facility with the option to fill gas once on the Turnpike. Incredibly, the queues on this facility spanned well over 20 miles over the course of the three days. An investigation of the subsequent 3-month data revealed no such patterns at the same location. Therefore, this is a prime example of a case study where mass evacuation may have resulted in extreme congestion and formation of a bottleneck.

Our analysis of the Florida Traffic Online Hourly Continuous Counts revealed the possible trend in evacuation patterns surrounding District 4 – it seems from the plots that most evacuation flows were experienced on the 6^{th}, and the 7^{th} of September. These findings are corroborated by observations in Table 11 that show an extreme spike in evacuation-day flows in comparison to the yearly averages experienced at the same count station. Notable are the observations from SR 710 on Sep 6 and 7, US 27 (on Sep 7), SR 60 (on Sep 7) as well as the corresponding observations from SR-91 for the same days. Evacuation flows gradually dropped around the 8^{th} of September (see Figure 20 – Figure 25).

A detailed visualization of the performance of the analyzed roadways for each evacuation day are as shown in Appendix A (see Figure 71 to Figure 75).

Key Detector Issues

No major detector issues were observed in our analysis of District 4.

4.1.3. District 1 Evacuation Performance

The figure below shows a list of the analyzed detectors in District 1 analyzed during the mass evacuation for Hurricane Irma. The main facility that the research team investigated in this district was the I-75. The analyzed detectors mostly were present along the western coastline counties of Collier, Lee, Charlotte, Sarasota, and Manatee.

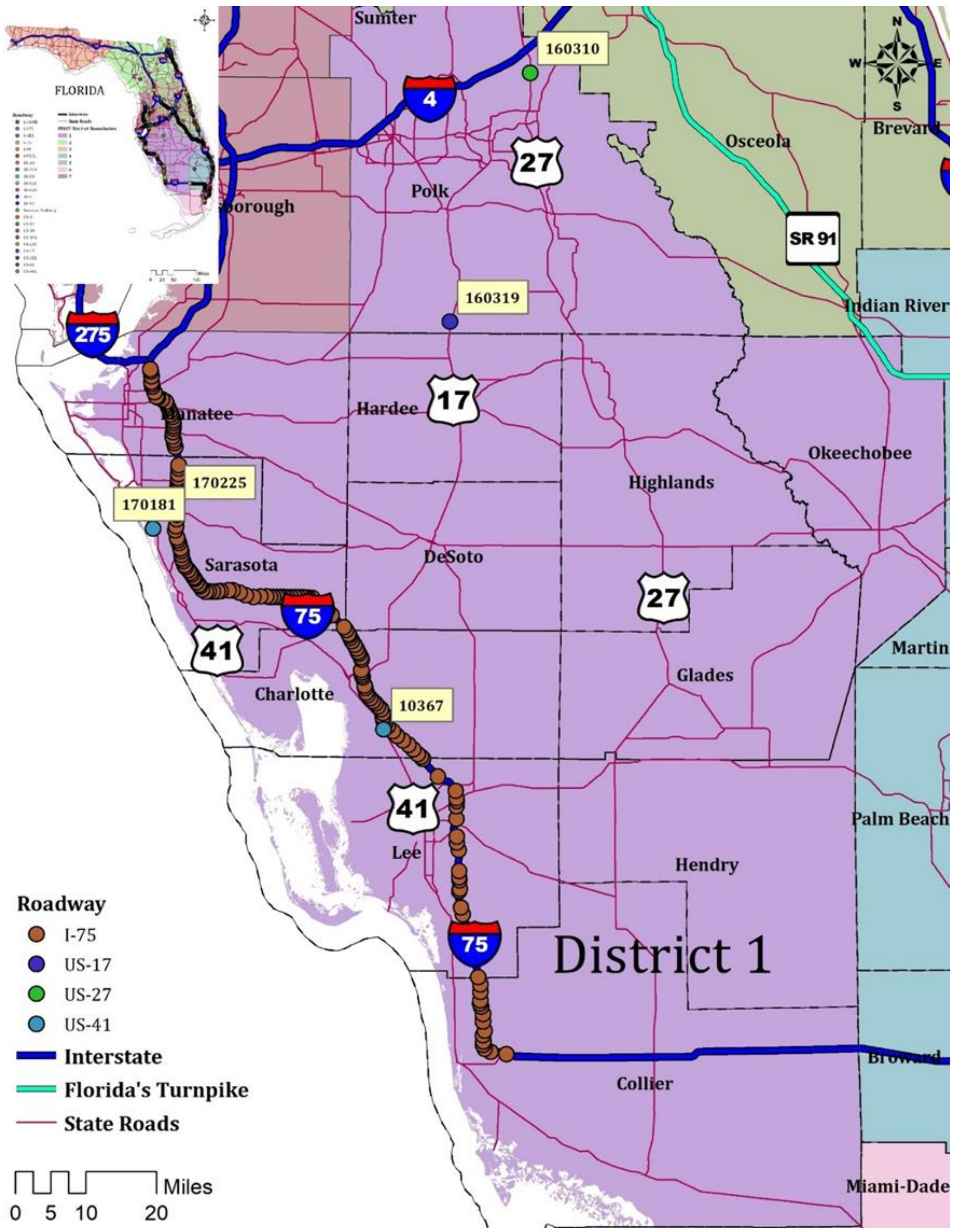


Figure 26 D1 Roadway Detectors – Hurricane Irma

Table 12 District 1: RITIS Probe Detector Data Performance Measures

Facility	%VMT Congested (VMT) (% Day Captured) (Veh-Hours of Delay) (V_f)($\overline{V}$)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-75	1.8% (6,579,854) (95.0%) (1,588) (71.0) (70.8)	11.2% (8,412,014) (88.4%) (30,516) (70.4) (66.1)	2.8% (10,419,719) (99.1%) (6,462) (69.6) (68.5)	2.3% (9,050,487) (98.9%) (5,862) (70.4) (69.6)	0.2% (2,917,645) (78.1%) (185) (72.4) (72.4)

Table 13 District 1: RITIS Probe Detector Three Month Performance Averages

Facility	%VMT Congested (VMT) (Veh-Hours of Delay) (V_f)($\overline{V}$)				
	Tuesday	**Wednesday**	**Thursday**	**Friday**	**Saturday**
I-75	3.2% (6,628,972) (28,447) (70.5) (70.0)	2.9% (6,748,714) (24,312) (70.5) (70.0)	4.2% (6,848,920) (25,002) (70.6) (69.9)	6.7% (7,488,342) (54,355) (71.1) (69.7)	2.1.% (6,487,875) (26,345) (73.4) (72.9)

Table 14 District 1: RITIS Probe Detector Total Observations

Facility District	Number of vehicles observed (Average vehicles per detector per day)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-75	9,383,533 (56,870)	11,392,698 (71,204)	14,130,273 (88,314)	12,676,375 (79,227)	4,466,773 (27,917)

Table 15 District 1: Florida Traffic Online Hourly Continuous Count Stations

Facility	Evacuation Volume (% Difference from Yearly Average)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
US-17 (0319)	5,633 (3.9%)	11,450 (102.0%)	10,604 (86.4%)	11,345 (65.3%)	7,866 (45.9%)
US-27 (0310)	30,907 (1.8%)	34,230 (11.0%)	42,332 (35.6%)	38,900 (16.2%)	17,886 (-38.5%)
US-41 (0367)	9,233 (0.7%)	13,374 (39.9%)	10,353 (7.2%)	10,272 (1.5%)	6,562 (-17.8%)
US-41 (0181)	16,917 (-4.6%)	18,943 (5.8%)	16,311 (-9.4%)	13,715 (-27.0%)	6,267 (-61.3%)
I-75 (0225)	58,682 (6.5%)	68.942 (21.6%)	76,580 (31.7%)	70,858 (14.8%)	37,385 (-26.6%)

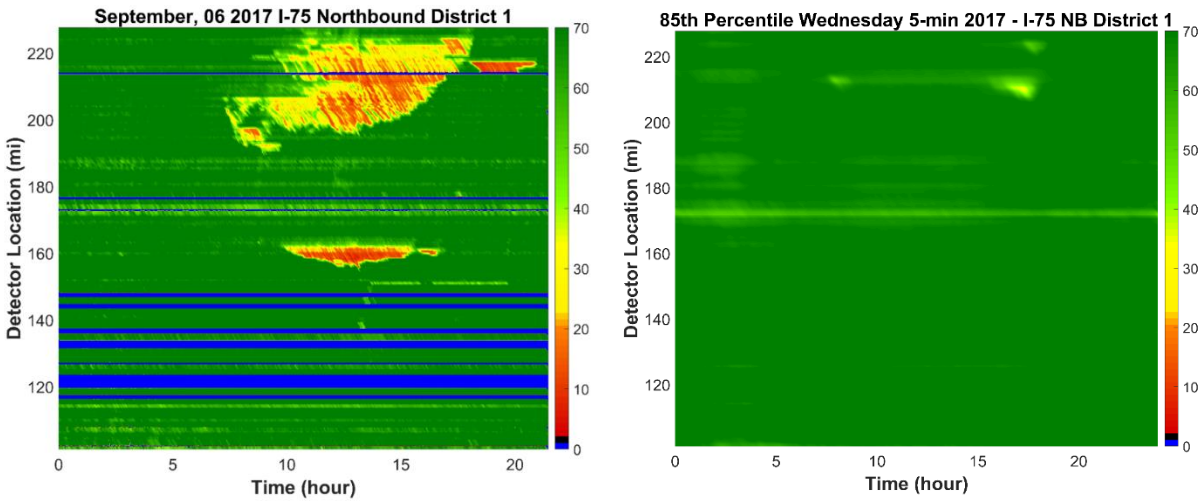


Figure 27 D1: I-75 NB Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

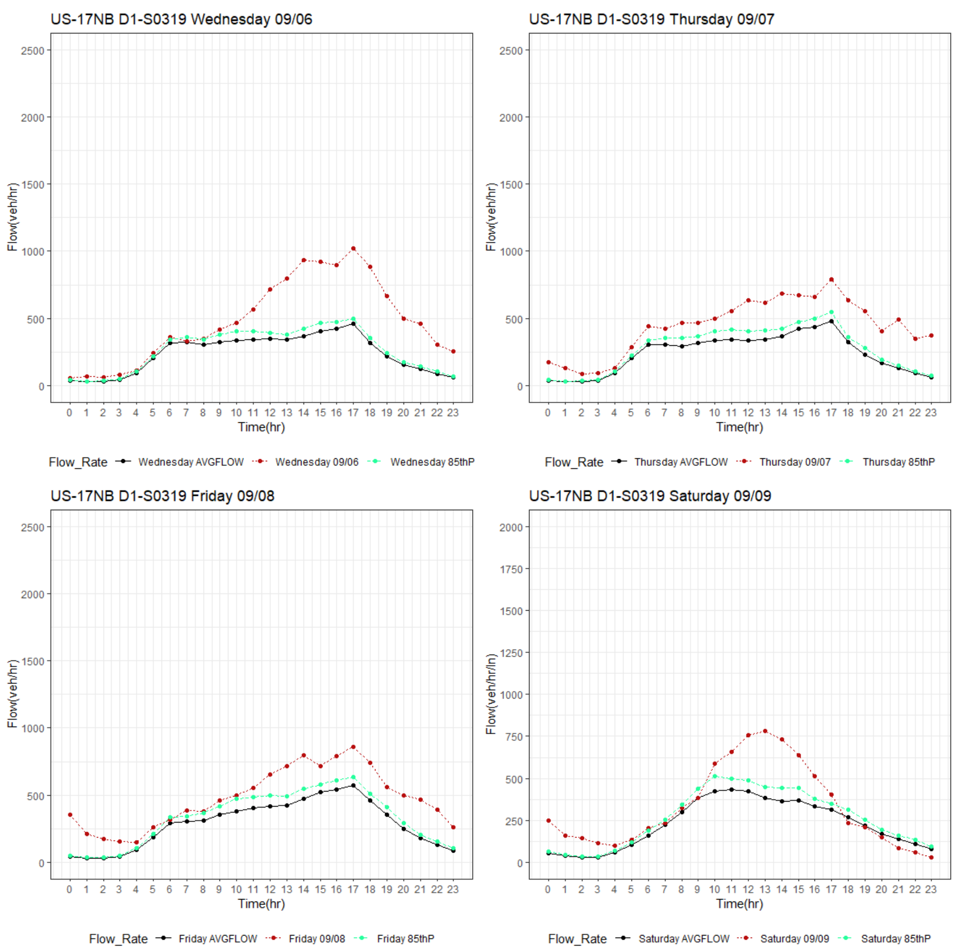


Figure 28 District 1: US-17 (160319) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Key Findings

As we move northward, we see the potential shift in evacuation patterns. As seen in Table 12 and Table 13, the I-75 NB in District 1 experienced significant evacuation movements on the 6th, 7th, and 8th of September, in comparison to the 3-month averages. Queueing was identified on Wednesday Sep 6 on the I-75 NB between MM 190 and MM 220. Even though a comparison with the 3-month data reveals a minor hotspot along the same mile markers, there is reason to believe that the region may have experienced some enhanced congestion due to the evacuations along the western coastal cities.

Our analysis of the Florida Traffic Online Hourly Continuous Counts revealed the possible trend in evacuation patterns in District 1 – most evacuation flows were experienced on the 6th, and the 7th of September. Evacuation flows continued to be well over the general trends observed for Friday and Saturday, eventually dropping around the 9th of September (see Figure 28). These findings are also corroborated by observations in Table 15 that show a spike in flows experienced on US-17 during Sep 6, Sep 7, and Sep 8. Interestingly, the US-41, a major North-South highway running parallel to the congested I-75, was not used as much during the evacuation process. Concerns over fuel availability may have led to its non-use but this is a scenario that warrants further investigation. This is also in line with some initial observations made by the research team which threw light into the fact that some of the congestion experienced along major roadways could have been mitigated if the alternative paths were utilized to a good extent.

A detailed visualization of the performance of the analyzed roadways for each evacuation day are as shown in Appendix A (see Figure 71 to Figure 75).

Key Detector Issues

No detector issues were found in our analysis of District 1

4.1.4. District 7 Evacuation Performance

The figure below shows a list of the analyzed detectors in District 7 analyzed during the mass evacuation for Hurricane Irma. The main facilities that the research team investigated in this district were the I-75, the I-4, the I-275, and the Suncoast Parkway. The analyzed detectors mostly were present along the western coastline counties of Pinellas, Hillsborough, Pasco and Hernando. The biggest MSA in the region, Tampa Bay has a population of over 2 million.

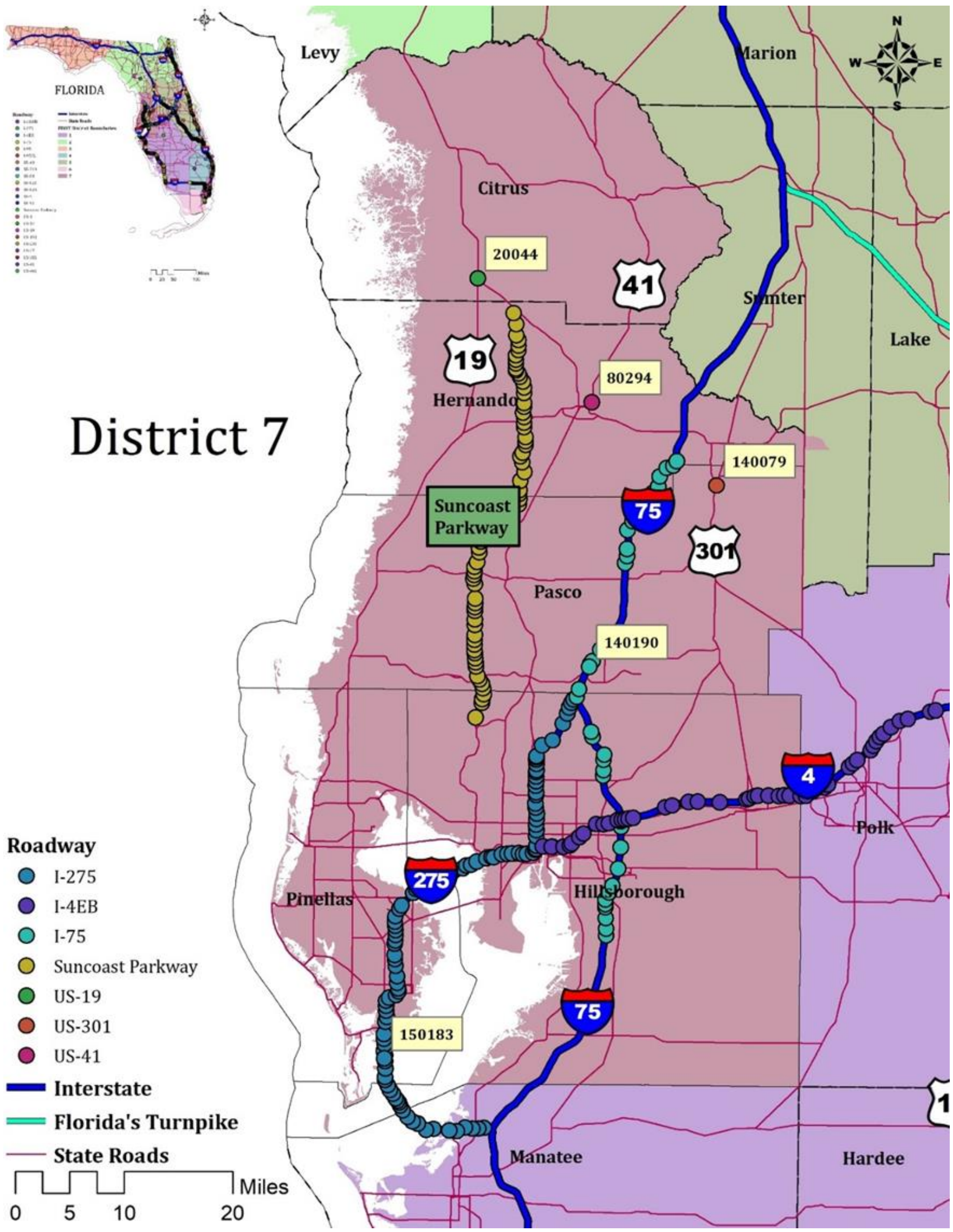


Figure 29 D7 Roadway Detectors – Hurricane Irma

Table 16 District 7: RITIS Probe Detector Data Performance Measures

Facility	%VMT Congested (VMT) (% Day Captured) (Veh-Hours of Delay) $(V_f)(\overline{V})$				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-275	8.8% (2,768,855) (96.9%) (4,526) (66.6) (65.3)	9.6% (2,932,991) (94.4%) (6,297) (66.6) (65.4)	2.9% (2,864,313) (99.3%) (901) (66.5) (66.2)	3.7% (2,334,861) (98.5%) (309) (66.5) (66.2)	4.6% (1,496,212) (92.7%) (291) (66.9) (66.7)
I-75	4.6% (2,169,459) (97.8%) (3,758) (71.4) (70.6)	18.6% (3,059,148) (99.7%) (20,516) (68.3) (62.2)	2.4% (3,252,633) (99.4%) (3,713) (69.9) (67.8)	5.7% (3,451,660) (99.0%) (7,842) (68.5) (65.0)	14.9% (2,626,729) (98.2%) (17,214) (70.4) (63.9)
I-4EB	3.6% (2,740,960) (99.5%) (1,576) (67.6) (66.7)	3.3% (2,839,764) (99.7%) (1,761) (67.2) (66.3)	1.6% (2,617,104) (99.7%) (539) (67.1) (66.7)	0.3% (2,315,992) (98.9%) (18) (67.3) (67.2)	11.1% (2,582,756) (98.0%) (6,711) (66.6) (64.3)
Suncoast Parkway	2.5% (29,770) (12.3%) (78.2) (78.2)	0.1% (424,062) (48.9%) (79.6) (79.6)	0.1% (664,891) (87.3%) (79.7) (79.7)	0.1% (806,300) (94.9%) (79.3) (79.2)	0.1% (581,488) (86.7%) (78.7) (78.7)

Table 17 District 7: RITIS Probe Detector Three Month Performance Averages

Facility	%VMT Congested (VMT) (Veh-Hours of Delay) $(V_f)(\overline{V})$				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-275	12.4% (2,497,590) (24,893) (66.1) (64.0)	12.6% (2,498,115) (24,896) (66.1) (63.9)	13.9% (2,551,485) (29,632) (65.8) (63.3)	13.5% (2,637,649) (34,574) (65.9) (63.4)	6.4% (2,460,229) (17,011) (67.0) (66.1)
I-75	2.2% (2,166,138) (5,937) (71.2) (70.8)	2.8% (2,184,469) (11,207) (71.1) (70.7)	2.9% (2,281,674) (6,139) (71.4) (70.9)	5.4% (2,519,266) (11,761) (72.0) (70.9)	2.2% (2,283,004) (945) (73.7) (73.3)
I-4EB	4.7% (3,047,445) (9,632) (68.3) (67.0)	5.5% (3,067,516) (9,693) (68.1) (66.5)	6.3% (3,174,597) (10,523) (68.1) (66.2)	12.7% (3,422,499) (13,273) (67.9) (64.1)	9.4% (3,377,597) (12,940) (68.9) (66.3)
Suncoast Parkway	-	-	-	-	-

Table 18 District 7: RITIS Probe Detector Total Observations

Facility	Number of vehicles observed (Average vehicles per detector per day)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
I-275	5,306,658 (52,026)	5,623,213 (56,230)	5,461,977 (53,550)	4,462,080 (43,750)	2,896,185 (28,390)
I-75	1,664,858 (46,246)	2,323,202 (64,533)	2,451,592 (68,100)	2,582,070 (71,724)	1,945,953 (54,054)
I-4EB	2,975,379 (53,132)	3,064,988 (54,731)	2,824,309 (50,434)	2,484,810 (44,372)	2,699,832 (48,211)
Suncoast Parkway	51,257 (712)	753,720 (10,468)	1,183,348 (16,435)	1,441,632 (20,0023)	1,034,338 (14,366)

Table 19 District 7: Florida Traffic Online Hourly Continuous Count Stations

Facility	Evacuation Volume (% Difference from Yearly Average)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
US-19 (0044)	12,337 (13.1%)	17,953 (59.8%)	26,320 (128.7%)	30,772 (131.2%)	23,850 (108.0%)
US-41 (0294)	5,873 (7.5%)	8,255 (47.2%)	9,117 (61.6%)	12,258 (109.5%)	9,379 (93.5%)
US-301 (0079)	8,412 (7.6%)	12,224 (52.5%)	13,120 (60.3%)	14,816 (62.8%)	13,993 (87.1%)
I-75 (0190)	50,455 (10.8%)	68,234 (45.1%)	76,121 (55.6%)	82,516 (51.6%)	67,093 (40.7%)
I-275 (0183)	28,968 (-2.8%)	32,807 (7.4%)	30,362 (-3.2%)	23,551 (-28.1%)	7,586 (-73.9%)

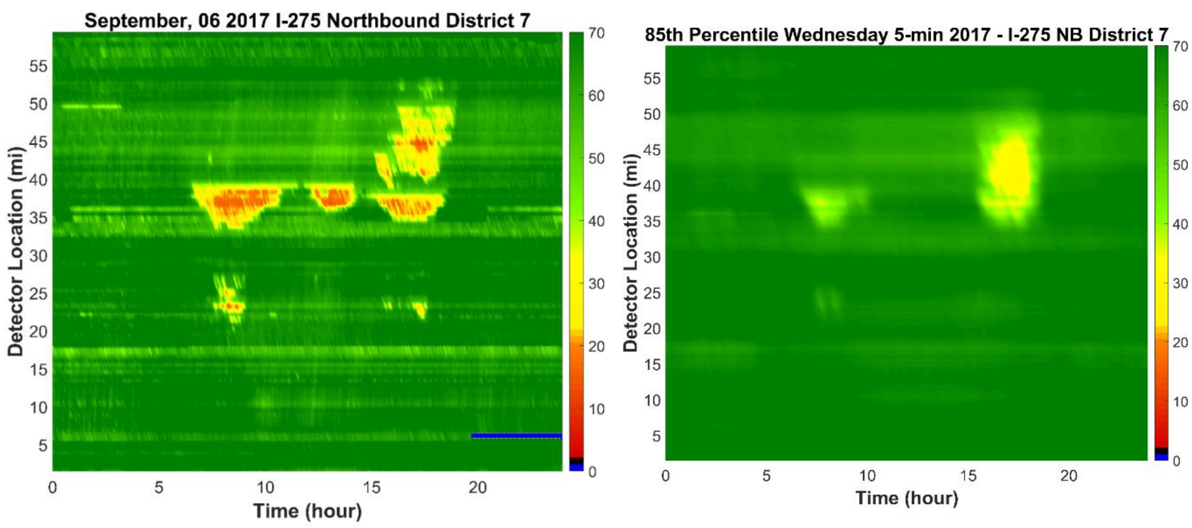


Figure 30 D7: I-275 NB Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

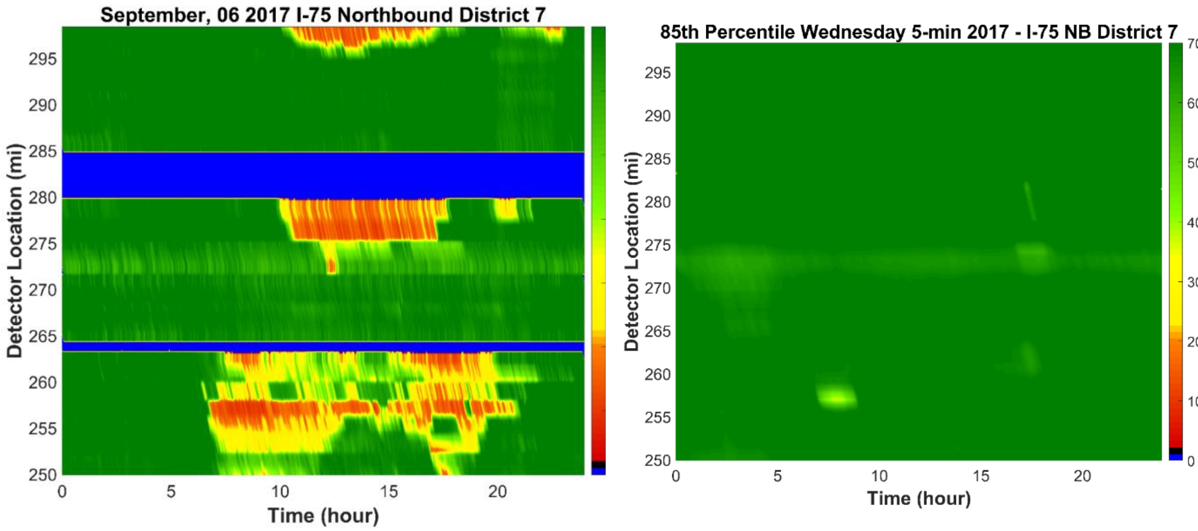


Figure 31 D7: I-75 NB Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

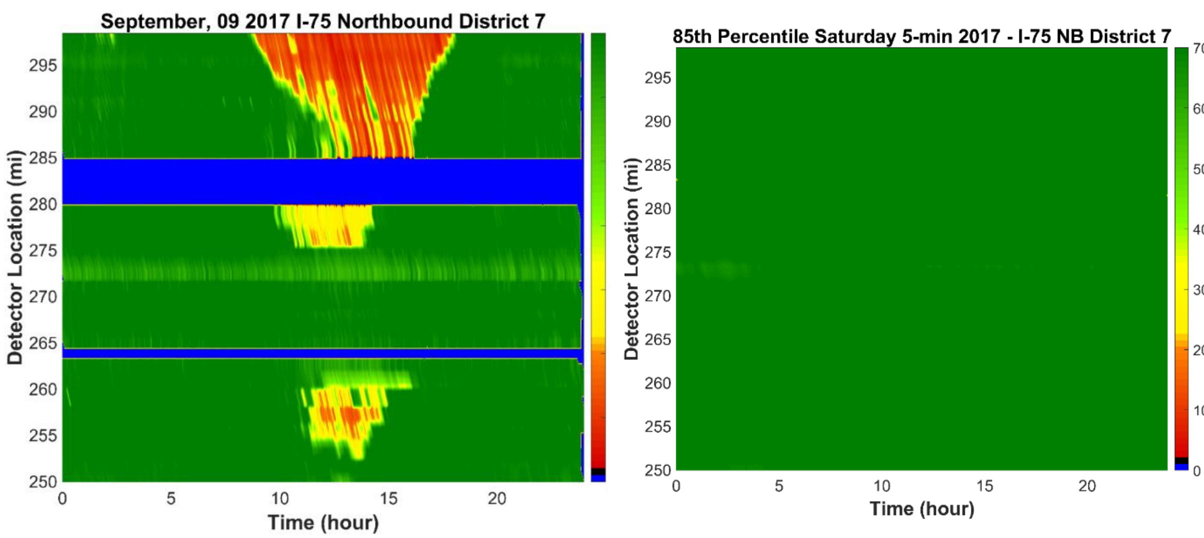


Figure 32 D7: I-75 NB Speed (Sat, Sep 9, 2017) vs Three-Month 85th Percentile Speeds

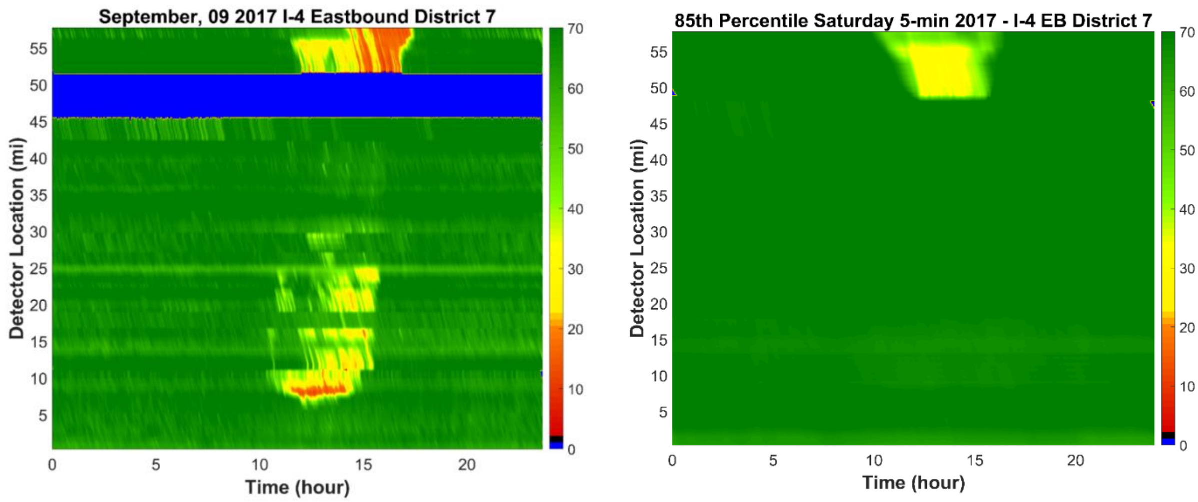


Figure 33 D7: I-4 EB Speed (Sat, Sep 9, 2017) vs Three-Month 85th Percentile Speeds

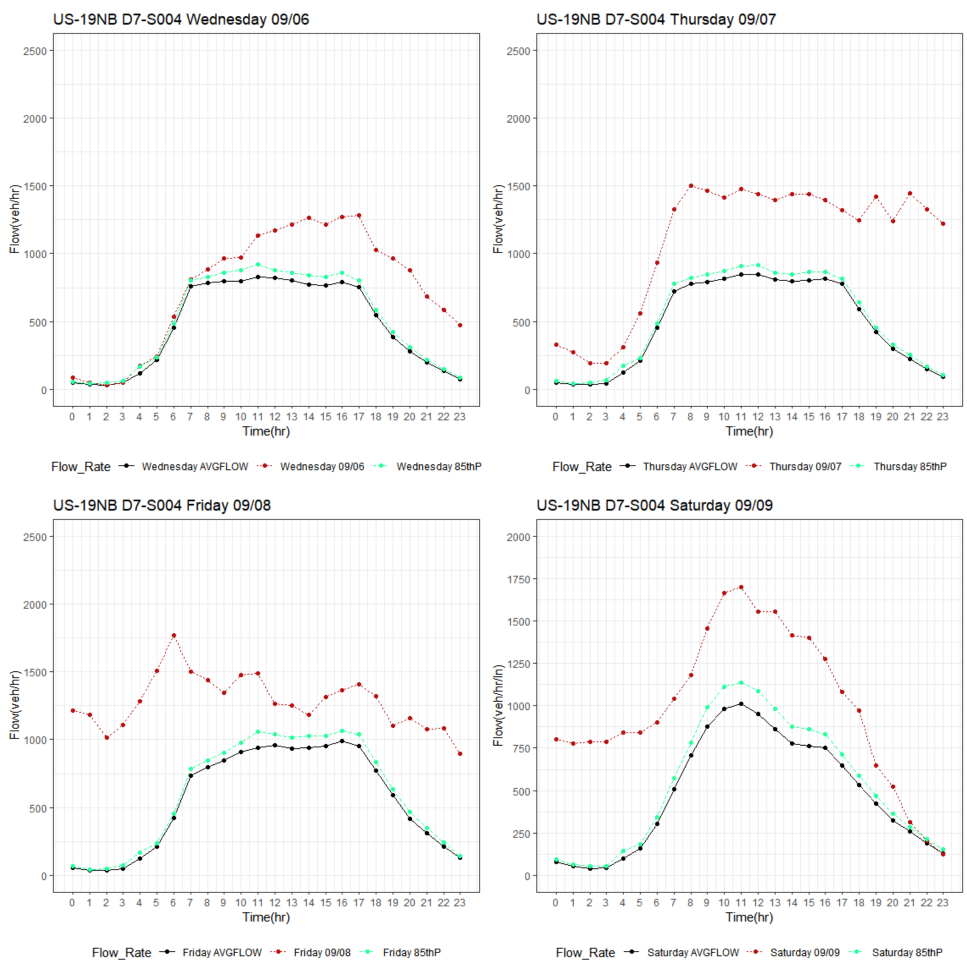


Figure 34 D7: US-19 (020044) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

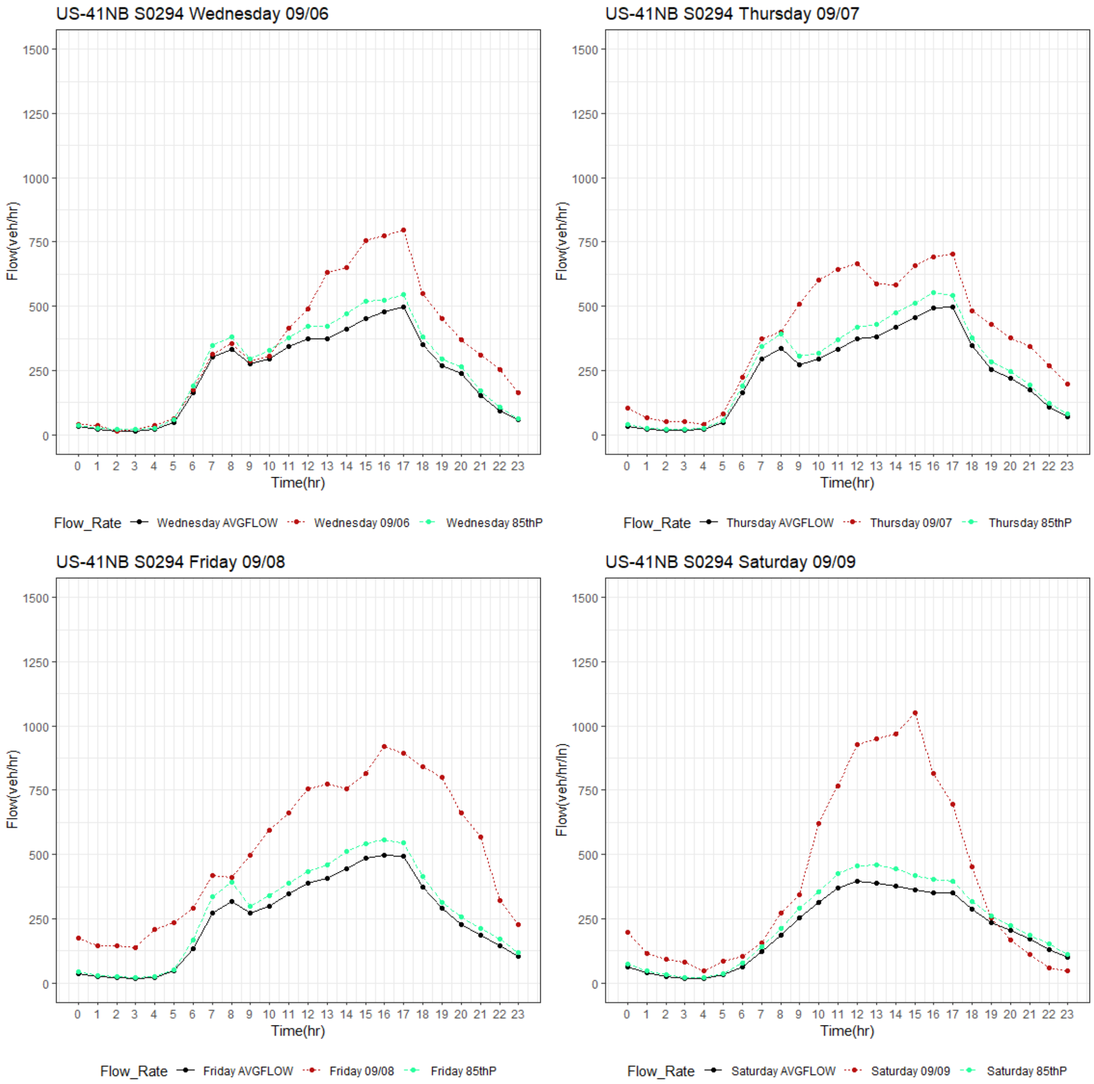


Figure 35 D7: US-41 (080294) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

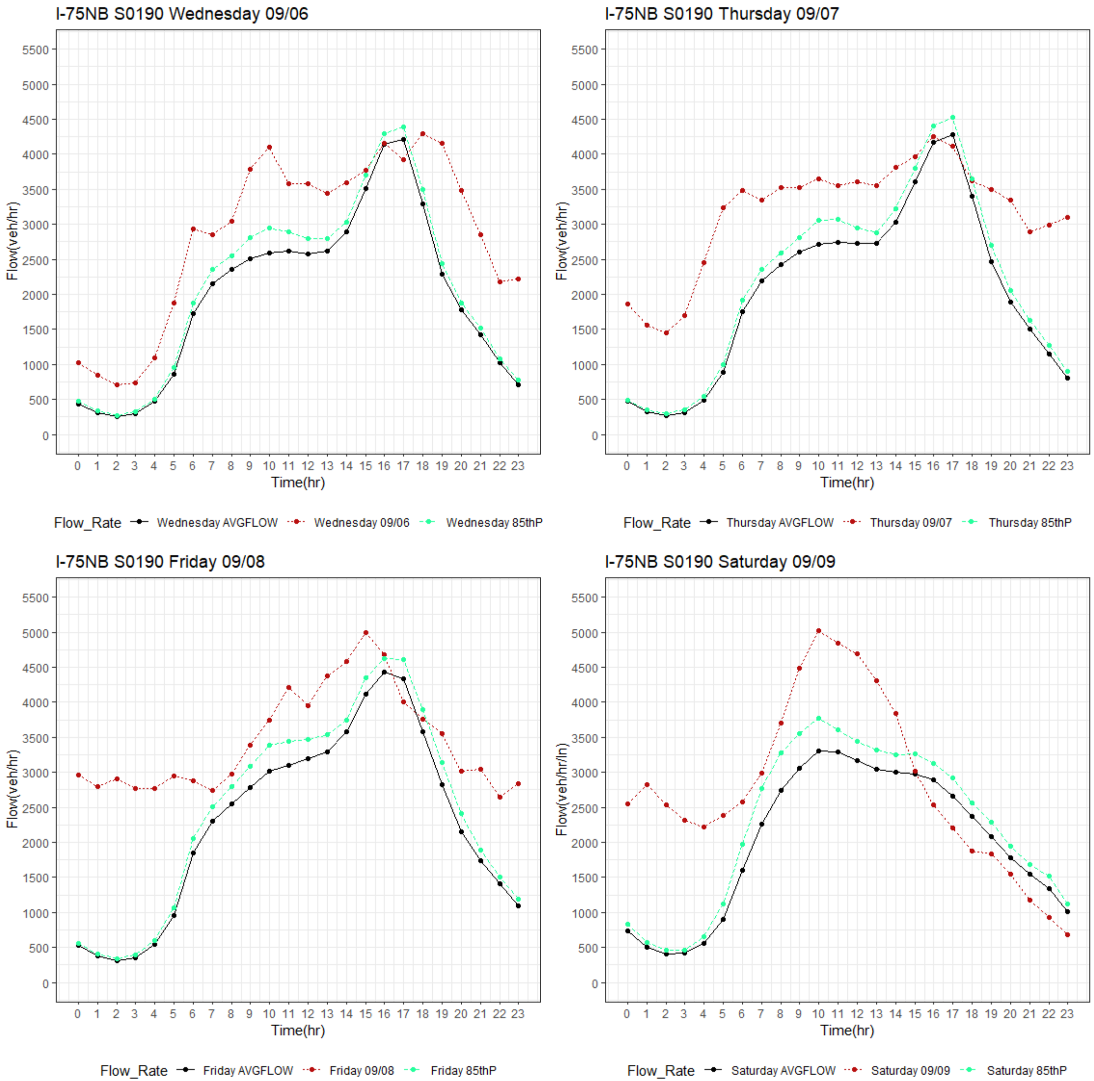


Figure 36 District 7: I-75 (140190) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Key Findings

Queueing was identified on Wednesday Sep 6 on the I-275 NB between mile markers 33 and 50 (Figure 30). Even though a comparison with the 3-month data revealed a minor hotspot along the same region, there is reason to believe that the region may have experienced some enhanced congestion due to the evacuations for Hurricane Irma. Expectedly, the I-75, one of the major roadways in the state and a major evacuation route for Hurricane Irma, experienced heavy congestion starting about 8 AM Sep 6 and continued in spurts even as far as Sep 9, 2017. This finding is supplemented further when comparing results from Table 16 and Table 17 that show a significantly higher percent VMT congested for the I-75 in this district (+16%), in comparison to the 3-month averages.

The I-4 EB, perhaps unsurprisingly, was relatively congestion free even during the evacuation period as most of the movement in this district was focused on moving northwards using the I-75, and associated roadway facilities. Our analysis of the Florida Traffic Online Hourly Continuous Counts revealed the possible trend in evacuation patterns surrounding District 7 – it is plausible that D7, being located in the Central Florida region, experienced evacuations much later than their southernmost counterparts – from the plots, it is evident that evacuation flows peaked on the 8^{th} and the 9^{th} of September even though the preceding days may have experienced above average flows. This may partly be contributed by the evacuation from the Southern districts, not necessarily from communities situated in District 7 (see Figure 34 – Figure 36).

This was further evidenced by observations from Table 19 that show how facilities such as US-19, and US-41 experienced more than 100% increase in flows, compared to the yearly averages. US-41 in District 7 was better utilized, in comparison to District 1, potentially pointing to specific traffic management activities undertaken by the regional agencies in providing information evacuees to use these facilities. The US 301, another North-South highway running parallel to the I-75 also experienced higher volumes, in comparison to their yearly averages pointing to the potential utility experienced by travelers in using these facilities to evacuate out of harm’s way. Lastly, the I-275, an auxiliary highway serving the Tampa Bay area was largely unutilized during the evacuation process with lesser than yearly average volumes experienced during the evacuation days.

A detailed visualization of the performance of the analyzed roadways for each evacuation day are as shown in Appendix A (see Figure 71 to Figure 75).

Key Detector Issues

No detector along the Veterans Expressway were functional for the evacuation period and were therefore, not considered during our analysis of District 7.

4.1.5. District 5 Evacuation Performance

The figure below shows a list of the analyzed detectors in District 5 analyzed during the mass evacuation for Hurricane Irma. The main facilities that the research team investigated in this district were the SR-91, the I-4, and the I-95. The analyzed detectors mostly were present along the counties of Sumter, Lake, Osceola, Orange, Seminole, Brevard, and Volusia. The Orlando MSA has a population of over 2 million.

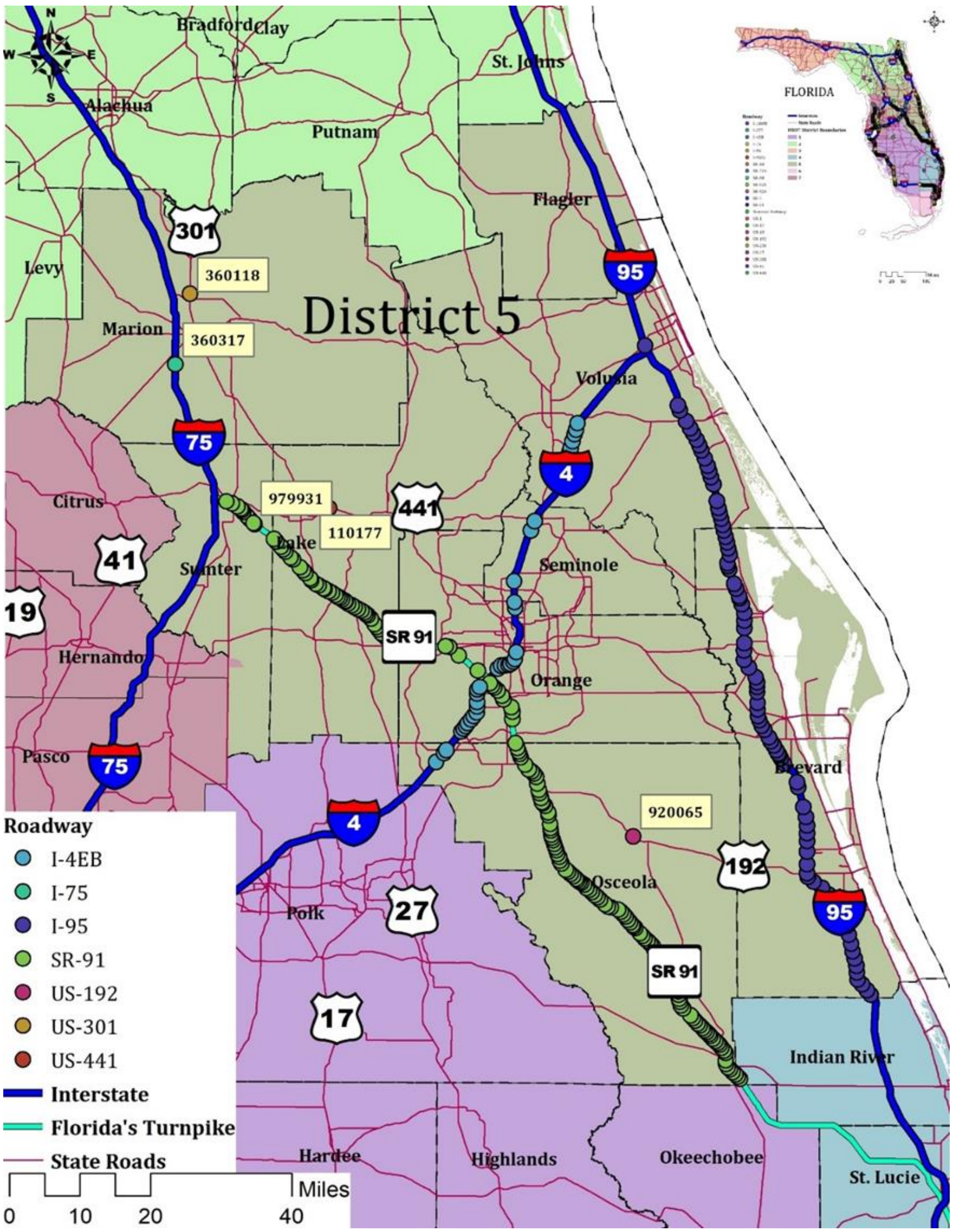


Figure 37 D5 Roadway Detectors – Hurricane Irma

Table 20 District 5: RITIS Probe Detector Data Performance Measures

Facility	%VMT Congested (VMT) (% Day Captured) (Veh-Hours of Delay) (V_f)($\bar{V}$)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
SR-91	0.0% (259,965) (24.2%) (1) (73.7) (73.6)	15.5% (3,110,216) (52.1%) (14,679) (69.9) (63.4)	26.2% (5,251,020) (99.7%) (51,912) (66.4) (53.6)	14.9% (4,219,300) (99.2%) (24,159) (69.6) (62.9)	0.0% (917,444) (81.2%) (0) (75.6) (75.6)
I-4EB	5.2% (3,213,445) (98.3%) (3,570) (67.2) (66.2)	6.3% (3,213,253) (96.7%) (4,129) (66.1) (64.8)	3.8% (3,266,289) (97.8%) (1,846) (66.5) (65.9)	1.1% (3,038,785) (98.9%) (1,694) (66.1) (65.6)	0.2% (2,141,930) (98.4%) (3,923) (66.8) (66.7)
I-95	0.2% (2,655,522) (87.3%) (17) (74.8) (74.8)	1.9% (4,870,388) (92.7%) (486) (74.2) (74.0)	6.3% (6,877,232) (93.1%) (8,078) (71.7) (69.8)	2.1% (5,806,654) (93.3%) (2,179) (71.5) (70.9)	0.1% (662,585) (69.9%) (3) (72.5) (72.5)

Table 21 District 5: RITIS Probe Detector Three Month Performance Averages

Facility	%VMT Congested (VMT) (Veh-Hours of Delay) (V_f)($\bar{V}$)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
SR-91	0.0% (2,098,543) (0) (71.8) (71.7)	0.0% (2,149,425) (0) (71.7) (71.5)	0.0% (2,466,186) (0) (72.6) (72.4)	0.0% (3,102,061) (0) (75.0) (74.8)	0.0% (2,473,264) (0) (77.3) (76.3)
I-4EB	8.9% (3,195,841) (11,635) (65.6) (63.8)	9.5% (3,265,959) (13,233) (65.4) (63.5)	10.9% (3,298,655) (14,578) (65.3) (62.9)	12.1% (3,518,154) (16,183) (65.1) (62.3)	5.5% (3,407,463) (15,492) (66.0) (64.3)
I-95	0.1% (1,169,316) (0) (73.9) (73.9)	0.1% (1,200,687) (0) (74.0) (74.0)	0.2% (1,258,327) (0) (74.4) (74.3)	0.1% (1,455,426) (0) (75.2) (75.2)	0.0% (1,265,697) (0) (76.2) (76.2)

Table 22 District 5: RITIS Probe Detector Total Observations

Facility District	Number of vehicles observed (Average vehicles per detector per day)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
SR-91	347,565 (1,998)	4,697,273 (26,996)	7,893,515 (45,365)	6,229,370 (35,801)	1,210,794 (6,959)
I-4EB	2,387,810 (62,837)	2,203,877 (57,997)	2,305,919 (60,682)	2,181,439 (57,406)	1,499,478 (39,460)
I-95	2,490,843 (27,372)	4,597,830 (50,526)	6,485,321 (71,267)	7,216,087 (79,298)	626,631 (6,886)

Table 23 District 5: Florida Traffic Online Hourly Continuous Count Stations

Facility	Evacuation Volume (% Difference from Yearly Average)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
US-301 (0118)	15,740 (9.1%)	21,770 (46.3%)	30,332 (97.1%)	30,608 (73.8%)	23,765 (62.2%)
US-441 (0177)	19,962 (2.8%)	19,334 (-2.4%)	21,832 (10.7%)	18,702 (-9.0%)	8,128 (-48.4%)
US-192 (0065)	4,887 (-2.3%)	8,151 (59.7%)	16,240 (215.2%)	12,785 (116.8%)	2,196 (-62.7%)
I-75 (0317)	48,219 (15.5%)	76,897 (78.9%)	92,340 (97.2%)	99,924 (75.0%)	80,522 (63.2%)
SR-91 (9931)	22,022 (9.9%)	39,072 (87.9%)	44,686 (95.2%)	43,631 (53.1%)	12,739 (-49.9%)

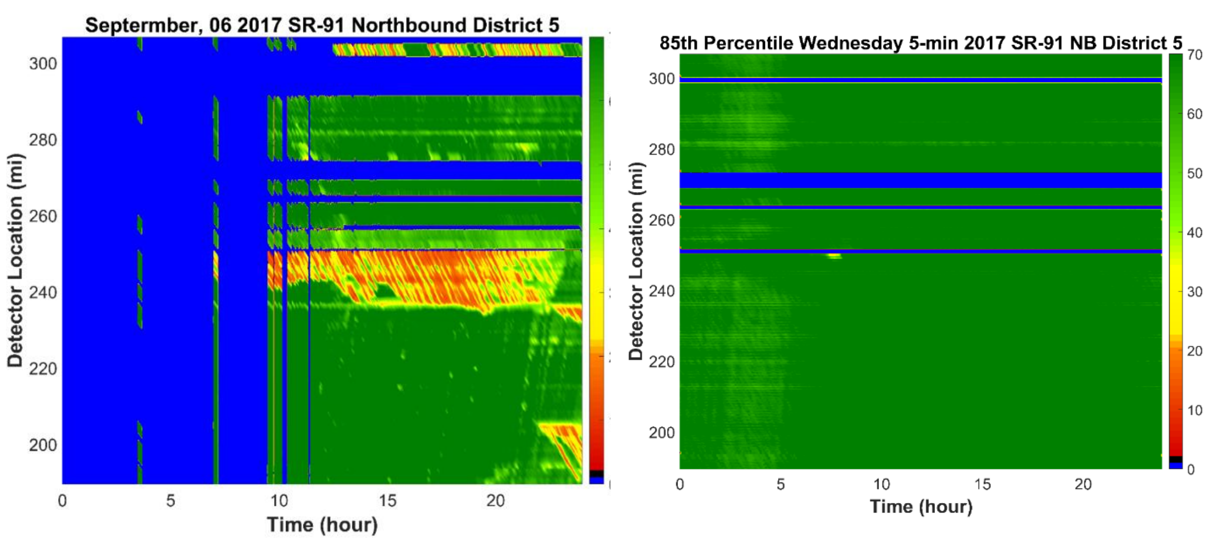


Figure 38 D5: SR-91 NB Speed (Wed, Sep 6, 2017) vs Three-Month 85th Percentile Speeds

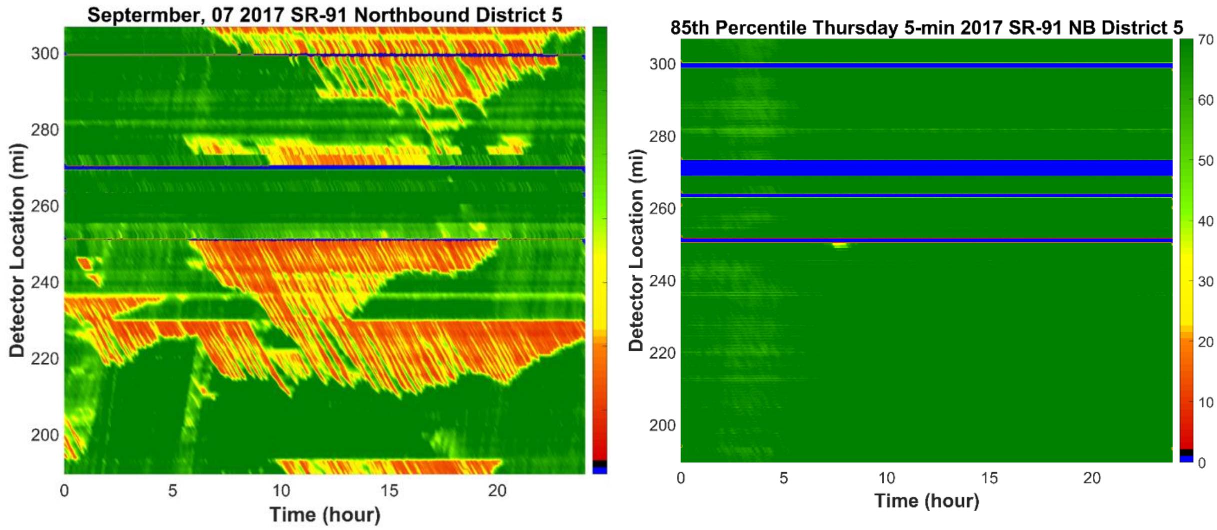


Figure 39 D5: SR-91 NB Speed (Thu, Sep 7, 2017) vs Three-Month 85th Percentile Speeds

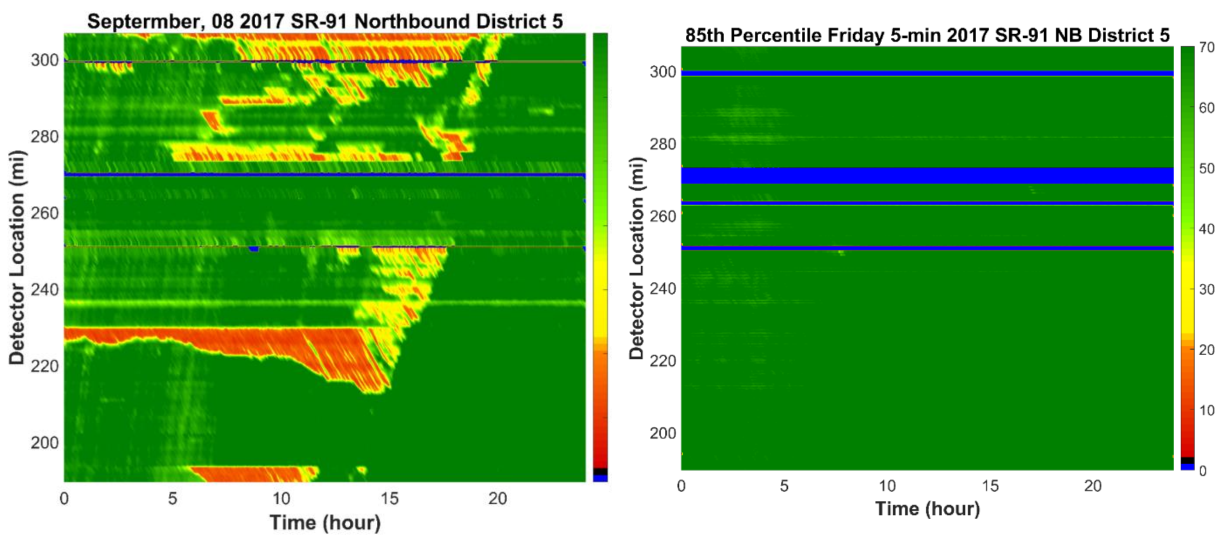


Figure 40 D5: SR-91 NB Speed (Fri, Sep 8, 2017) vs Three-Month 85th Percentile Speeds

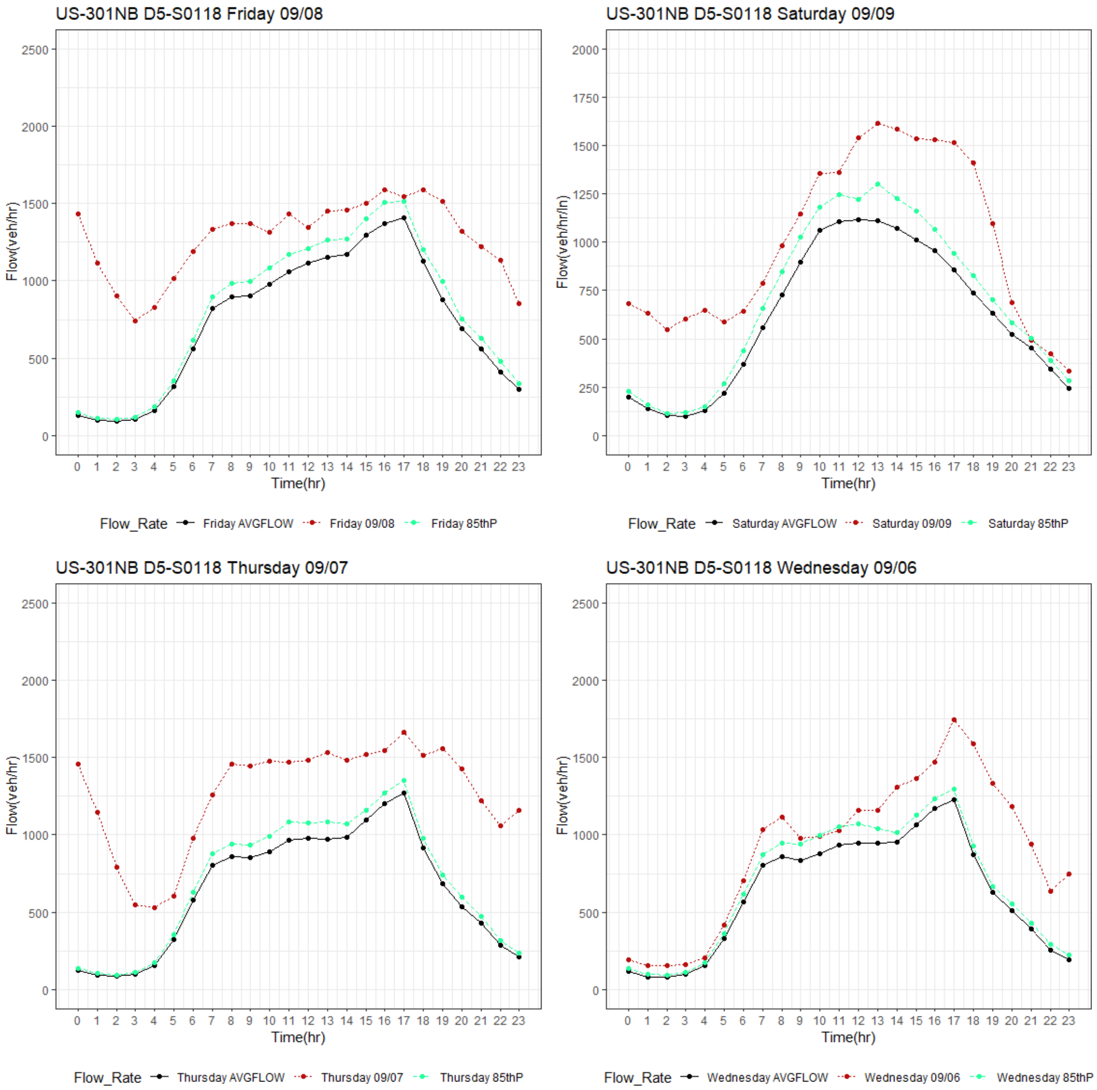


Figure 41 D5: US-301 (140079) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

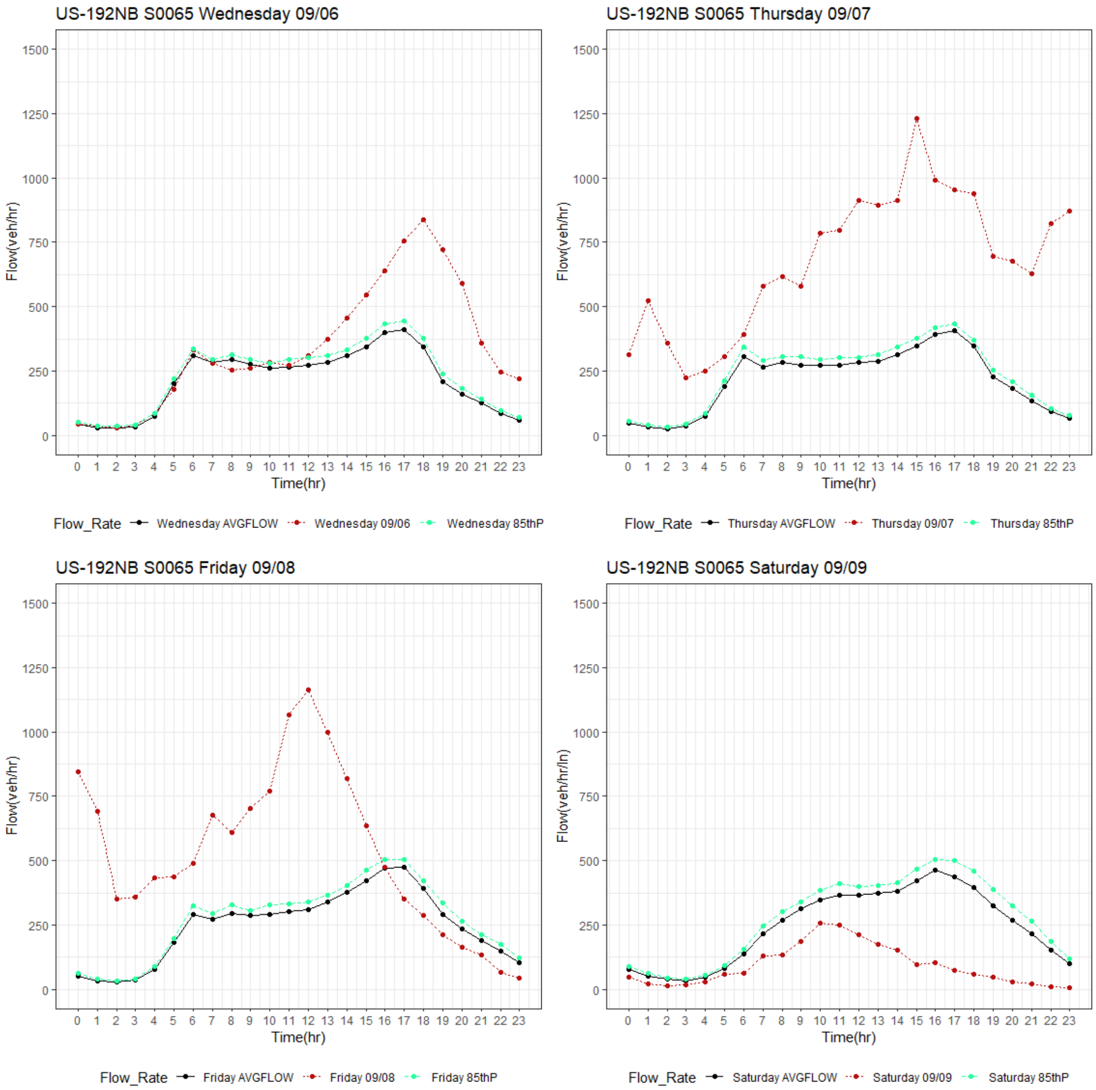


Figure 42 D5: US-192 (920065) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

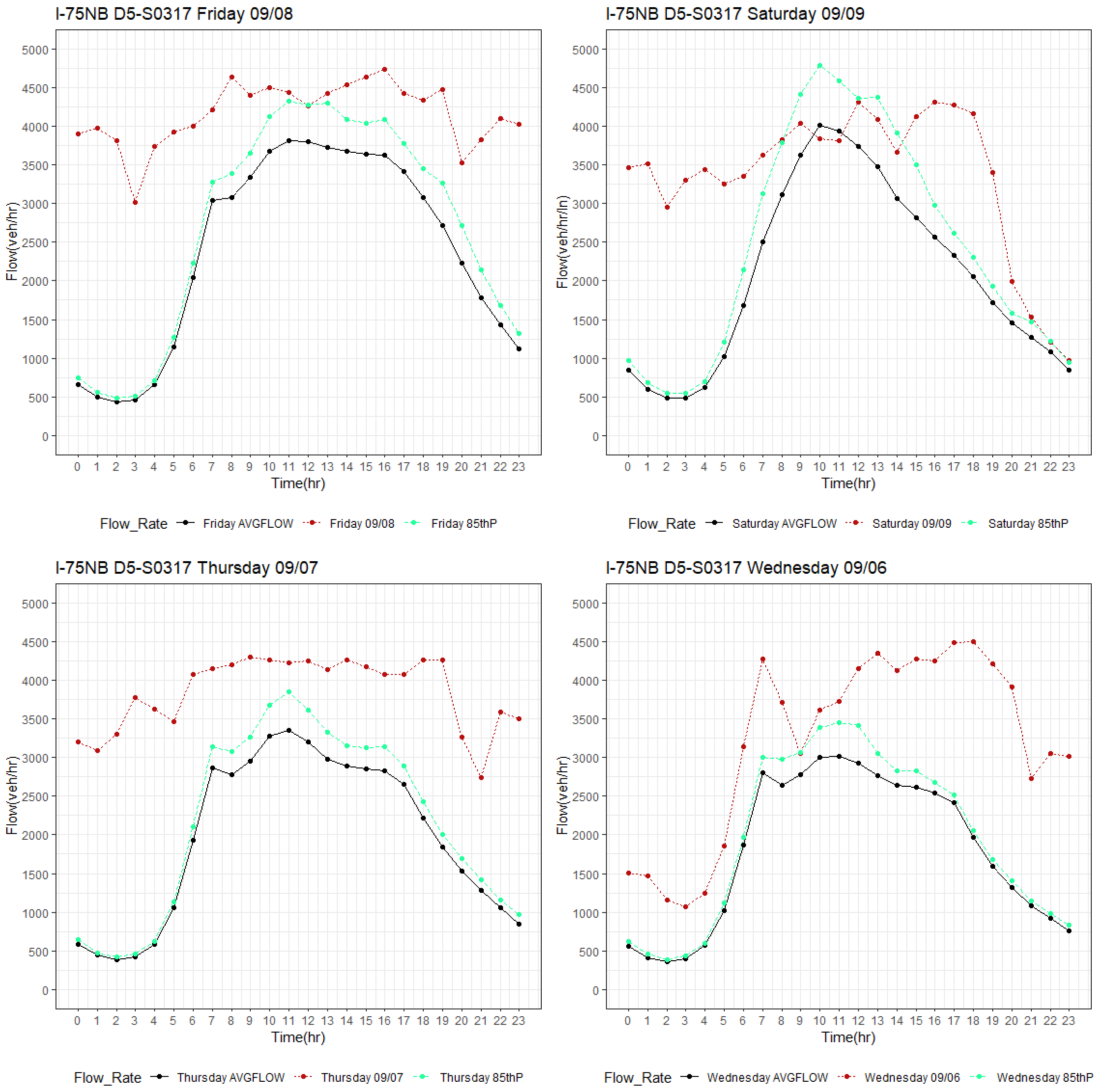


Figure 43 D5: I-75 (360317) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

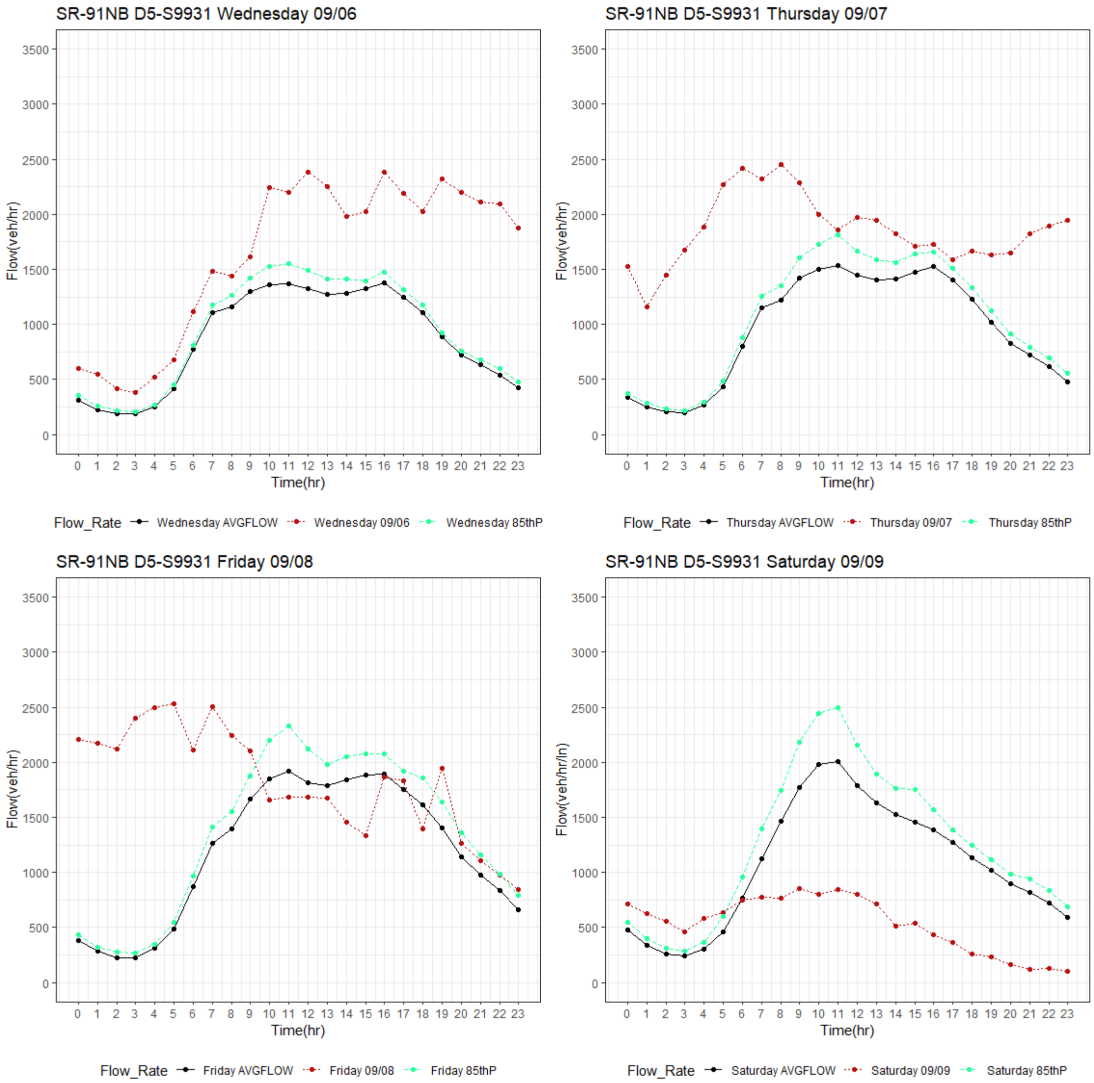


Figure 44 D5: SR-91 (Florida's Turnpike) (97331) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Key Findings

Similar to what was observed in District 4 on SR-91, massive queueing was once again observed stretching from the District 4/District 5 line to the SR-91/I-75 interchange, (see Figure 38, Figure 39, and Figure 40). Evidence from Table 20 and Table 21 also points in this direction, with significantly higher percent VMT congested as well as VMT experienced on the evacuation days, in comparison to the 3-month averages. Based on further analysis, the bottleneck frontiers were found to be located at the service plazas, exactly like that observed in District 4.

Our analysis of the Florida Traffic Online Hourly Continuous Counts revealed some interesting trends for District 5– while major roadways such as the I-75 and US-301 (Figure 41 and Figure 43) continued to experience significantly higher levels of evacuation flows well into the 9th of September, it was interesting how traffic along US-192 and SR-91 plateaued around the 8th of September (see Figure 42 and Figure 44) but not before the former experienced exponentially higher levels of traffic volume on September 8, 2017. The Turnpike was also utilized by some late evacuees during the night of the 8th and the early hours of the 9th, but it seems like they were largely utilized to gain access into nearby locations for onward journeys through the interstates.

A detailed visualization of the performance of the analyzed roadways for each evacuation day are as shown in Appendix A (see Figure 71 to Figure 75).

Key Detector Issues

There was approximately 30 miles of I-75 with missing detector data. The last responsive detector occurs at MM 298.2 in District 7, and the first preceding detector northbound occurs at MM 329.3 in District 5. For this reason, probe detector data from I-75 was not used for our analysis of District 5.

4.1.6. District 2 Evacuation Performance

The figure below shows a list of the analyzed detectors in District 2 analyzed during the mass evacuation for Hurricane Irma. The main facility that the research team investigated in this district was the I-95. The analyzed detectors mostly were present along the counties of St. Johns, Duval, and Nassau. The Jacksonville MSA is in this district.

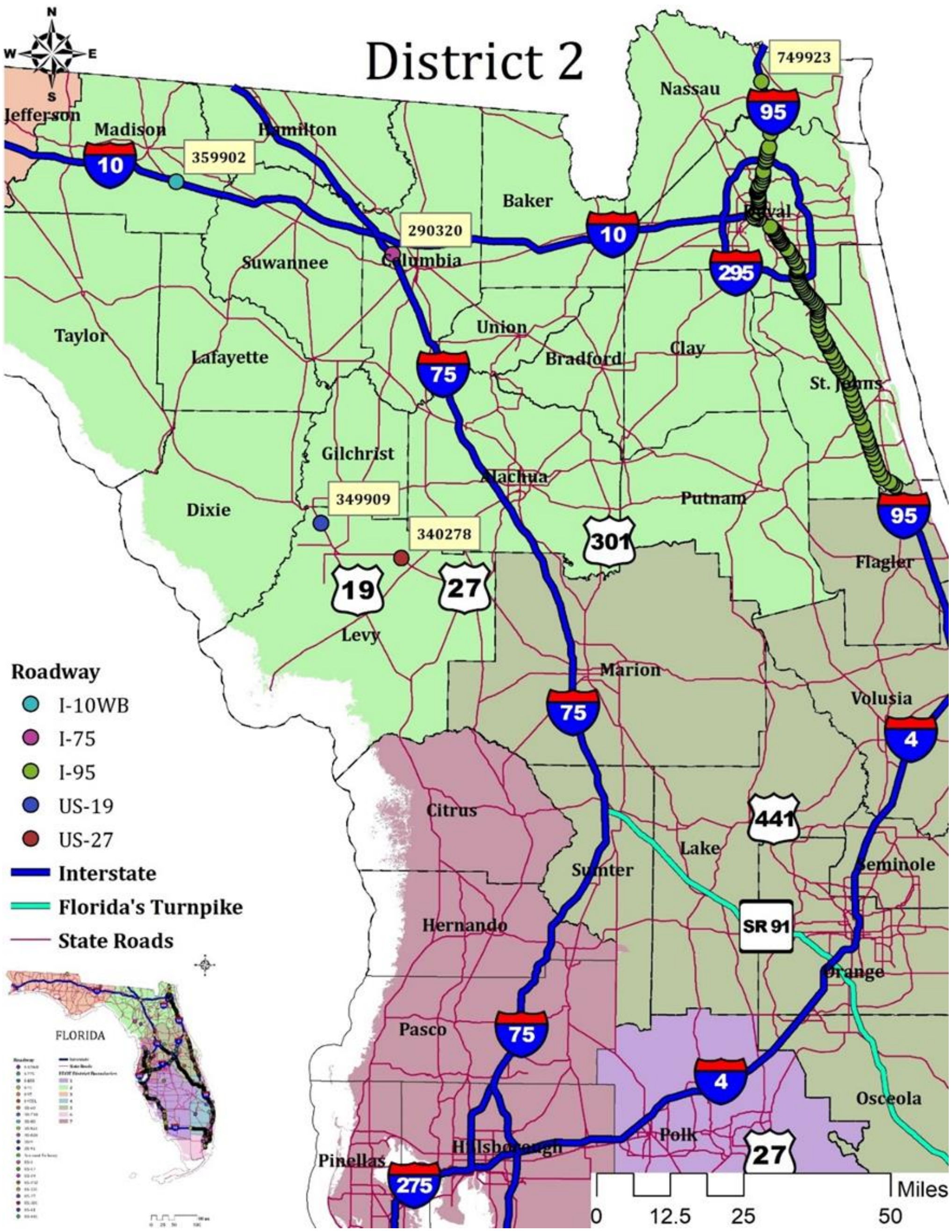


Figure 45 D2 Roadway Detectors – Hurricane Irma

Table 24 District 2: RITIS Probe Detector Data Performance Measures

Facility	%VMT Congested (VMT) (% Day Captured) (Veh-Hours of Delay) (V_f)($\overline{V}$)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-95	3.6% (3,780,240) (85.9%) (1,695) (70.5) (70.0)	8.7% (6,715,501) (98.1%) (12,781) (69.2) (66.3)	21.1% (8,304,746) (98.2%) (35,257) (65.9) (60.2)	9.7% (7,368,316) (97.4%) (14,326) (67.2) (65.1)	0.1% (3,197,715) (95.9%) (70) (71.1) (71.0)

Table 25 District 2: RITIS Probe Detector Three Month Performance Averages

Facility	%VMT Congested (VMT) (Veh-Hours of Delay) (V_f)($\overline{V}$)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-95	2.0% (4,006,255) (9,618) (69.1) (68.4)	2.0% (4,067,677) (10,928) (69.1) (68.4)	2.3% (4,315,291) (11,948) (69.6) (68.7)	1.8% (4,859,891) (11,787) (70.7) (69.8)	0.3% (4,505,986) (3) (72.4) (72.3)

Table 26 District 2: RITIS Probe Detector Total Observations

Facility	Number of vehicles observed (Average vehicles per detector per day)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
I-95	6,460,653 (58,204)	10,928,631 (98,456)	13,295,915 (119,783)	11,710,202 (105,497)	5,142,752 (46,331)

Table 27 District 2: Florida Traffic Online Hourly Continuous Count Stations

Facility	Evacuation Volume (% Difference from Yearly Average)				
	Tuesday 09/05	**Wednesday 09/06**	**Thursday 09/07**	**Friday 09/08**	**Saturday 09/09**
US-19 (9909)	6,952 (13.5%)	13,205 (108.7%)	26,149 (214.9%)	27,359 (309.7%)	23,696 (253.5%)
US-27 (0278)	3,987 (7.9%)	5,072 (33.2%)	10,506 (169.5%)	12,147 (165.8%)	3,037 (-13.2%)
I-75 (0320)	24,005 (14.4%)	58,541 (154.6%)	87,982 (252.9%)	74,235 (133.6%)	76,746 (178.9%)
I-10WB (9902)	12,213 (3.6%)	17,074 (41.5%)	34,951 (162.1%)	53,735 (209.1%)	29,667 (107.2%)
I-95 (9923)	28,389 (4.2%)	51,391 (82.8%)	78,950 (157.2%)	76,736 (112.2%)	50,522 (49.1%)

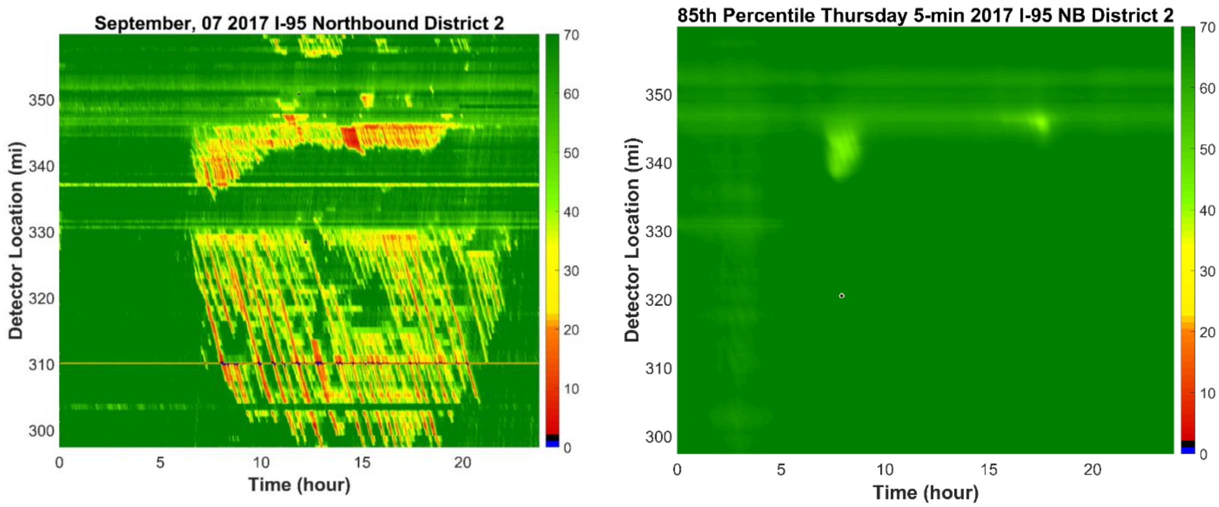


Figure 46 D2: I-95 NB Speed (Thu, Sep 7, 2017) vs Three-Month 85th Percentile Speeds

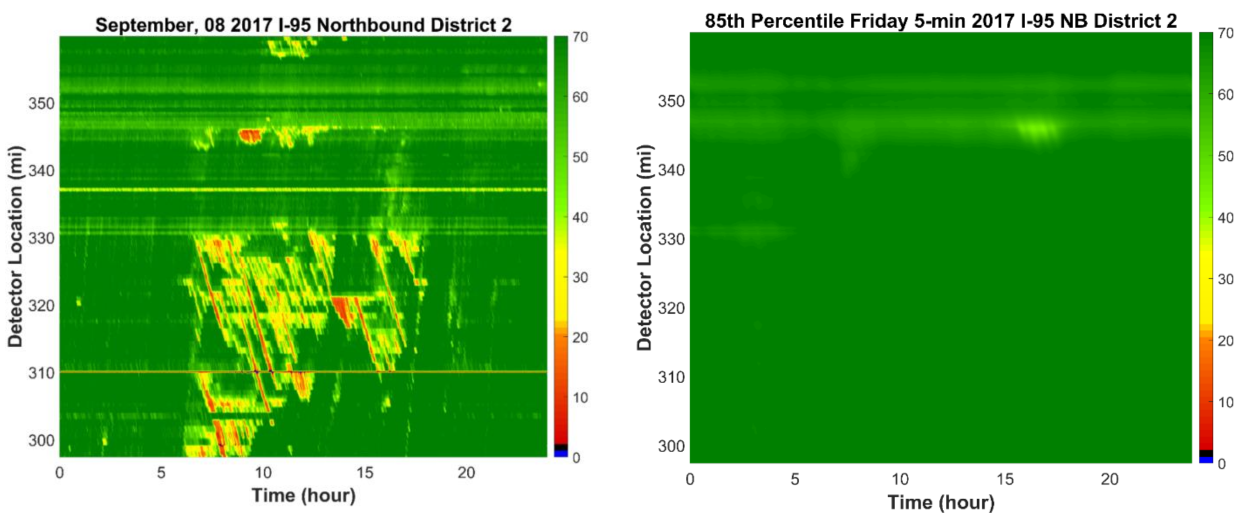


Figure 47 D2: I-95 NB Speed (Fri, Sep 8, 2017) vs Three-Month 85th Percentile Speeds

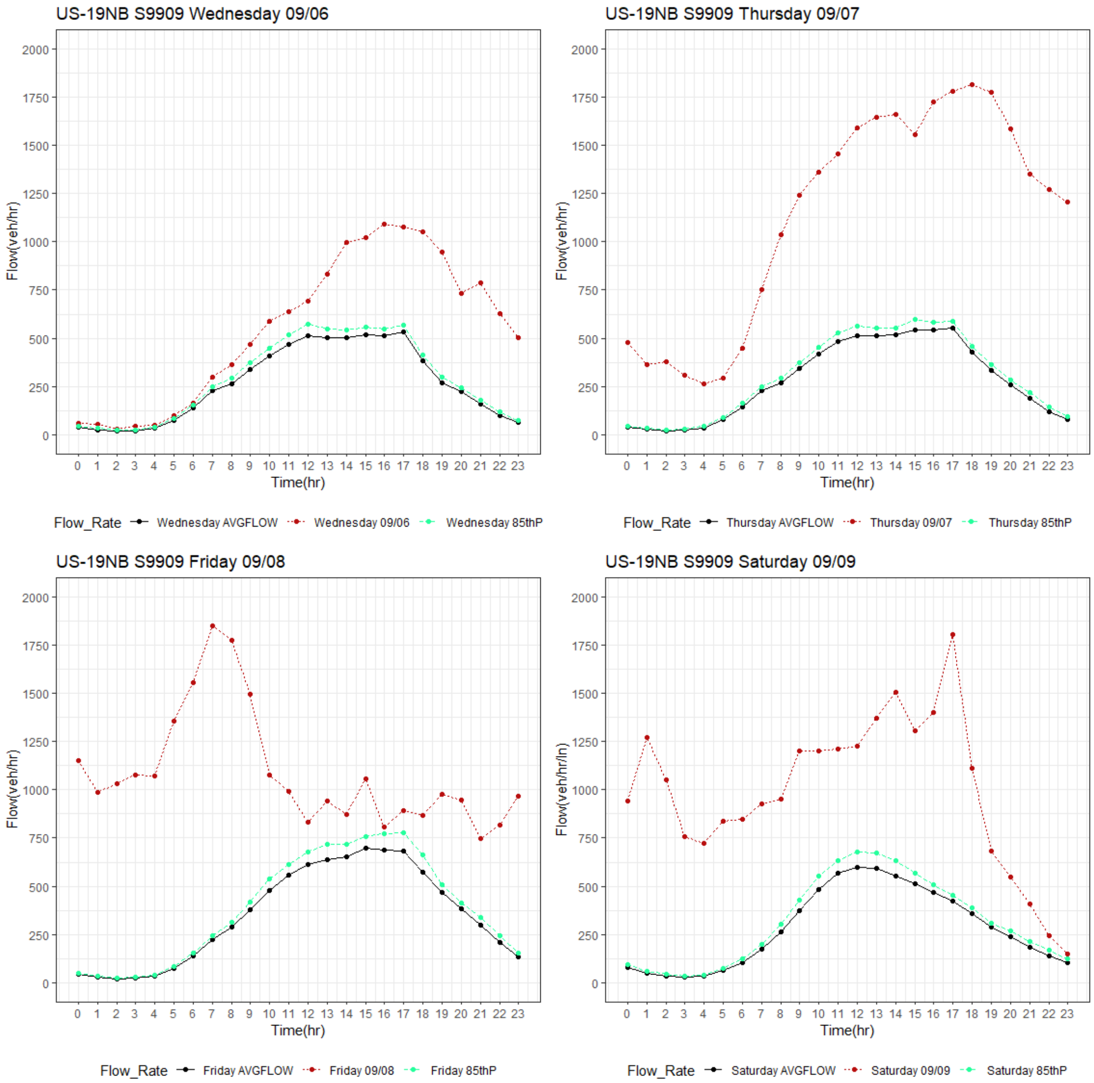


Figure 48 D2: US-19 (349909) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

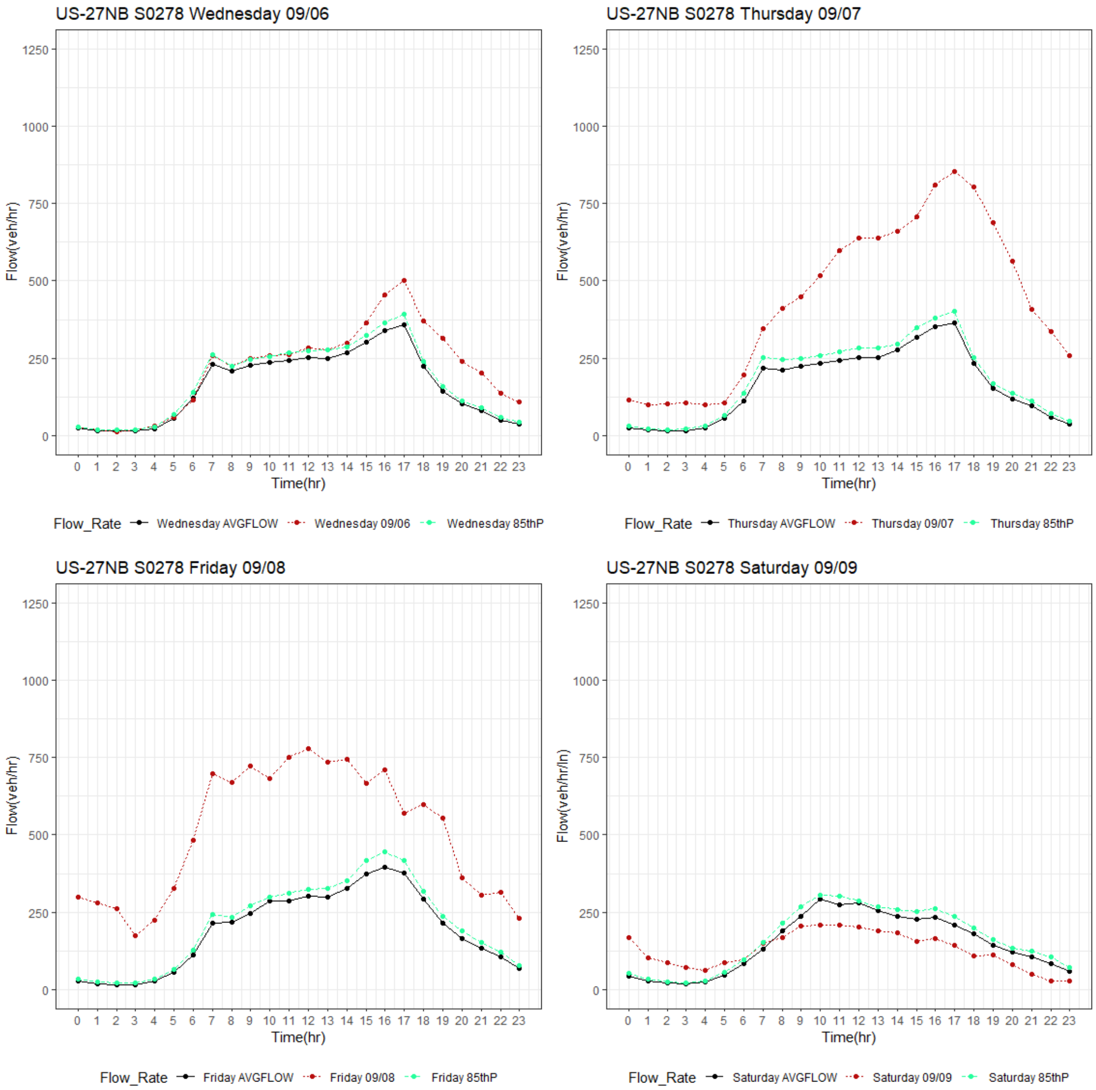


Figure 49 D2: US-27 (240278) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Figure 50 D2: I-75 (290320) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

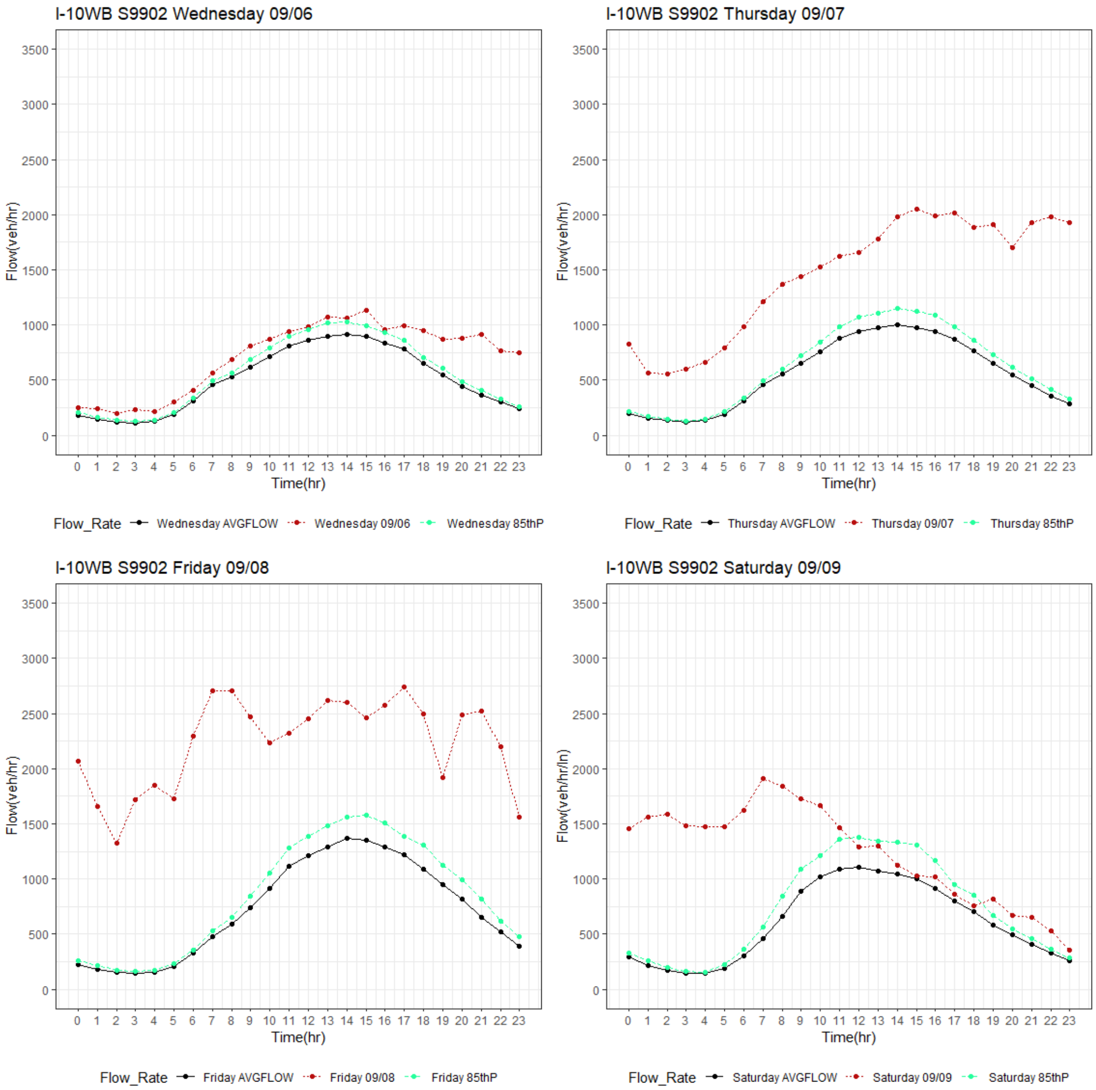


Figure 51 D2: I-10WB (359902) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

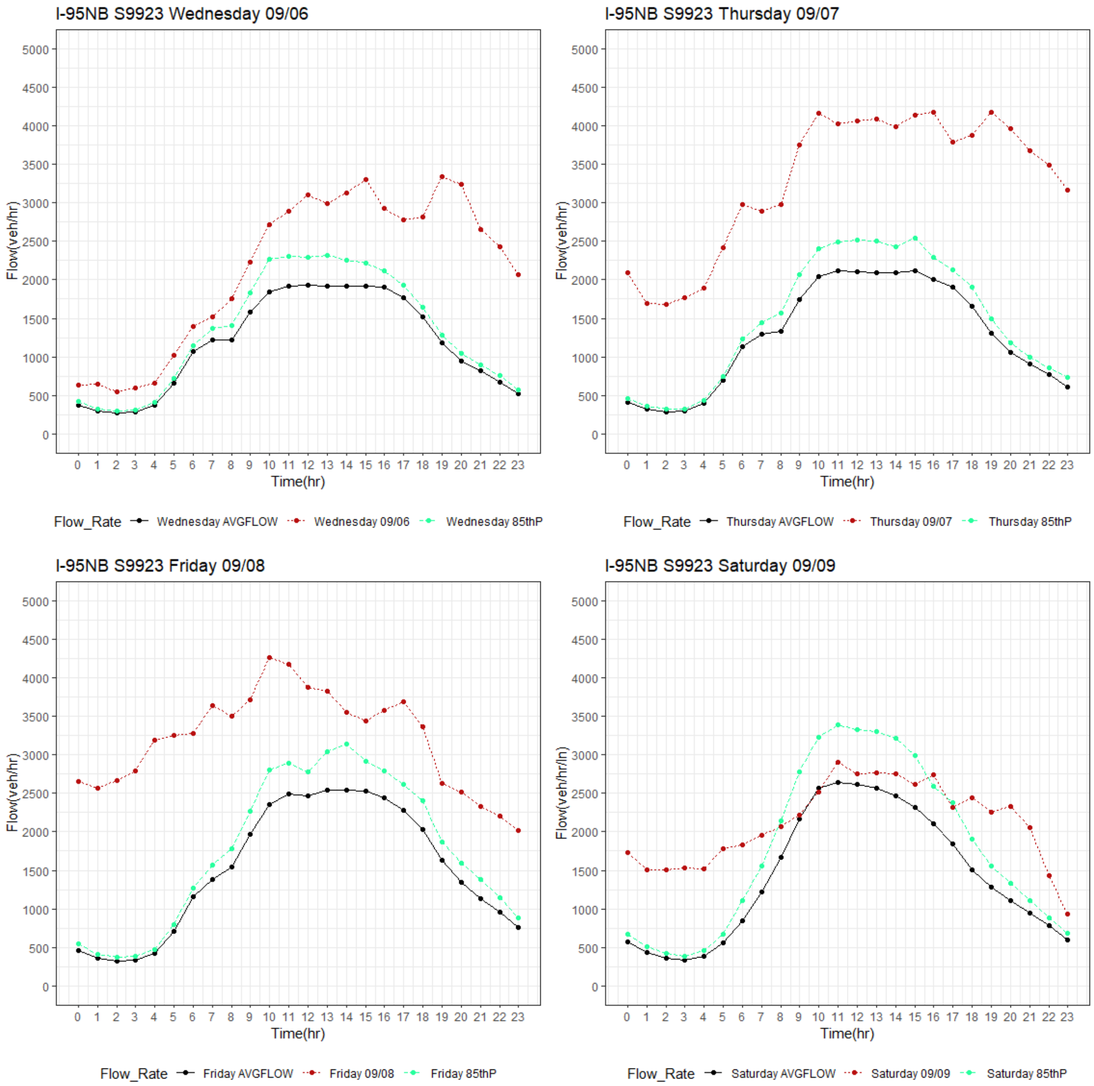


Figure 52 D2: I-95 (749923) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Key Findings

The I-95 NB experienced significant congestion and bottlenecking on Sep 7 and 8, much more than what the region typically experiences based on the 3-month data analyzed by the research team (see Figure 46, and Figure 47). This was particularly true for the region between MM 305 and MM 330. This is also backed up by the observations on the speed of the traffic stream during the evacuation days, in comparison to the 3-month averages (see Table 24 and Table 25).

Analyzing the Florida Traffic Online Hourly Continuous Counts, some interesting insights on evacuation trends for District 2 were gleaned – while major roadways such as the I-75 (Figure 50), and US-19 (Figure 48) continued to be experience significantly higher levels of evacuation flows well into the last hours of the 9th of September (with volumes sometimes more than 300% the yearly average), other routes such as the US-27 plateaued by the early hours of the 9th of September (see Figure 49). The westbound movement, a significant theme of evacuations in this district continued well into the 9th of September with more than 100% increase in observed evacuation volumes, in comparison to the yearly average.

A detailed visualization of the performance of the analyzed roadways for each evacuation day are as shown in Appendix A (see Figure 71 to Figure 75).

Key Detector Issues

Only 4 valid detectors were available on I-75 both NB and SB from MM 379.1 to MM 383. There were many missing detectors from MM 383 to 470.8/Florida-Georgia State Line, and therefore, probe detector data was not used for I-75 in District 2. The I-10 WB, which would have been a prominent evacuation route in the region had too many detectors offline during the evacuation period and therefore, was not considered for the purpose of this analysis.

4.1.7. District 3 Evacuation Performance

The figure below shows a list of the analyzed detectors in District 3 analyzed during the mass evacuation for Hurricane Irma. No major facility was available for analysis in this district as many of the I-10 WB detectors were offline during the analysis period.

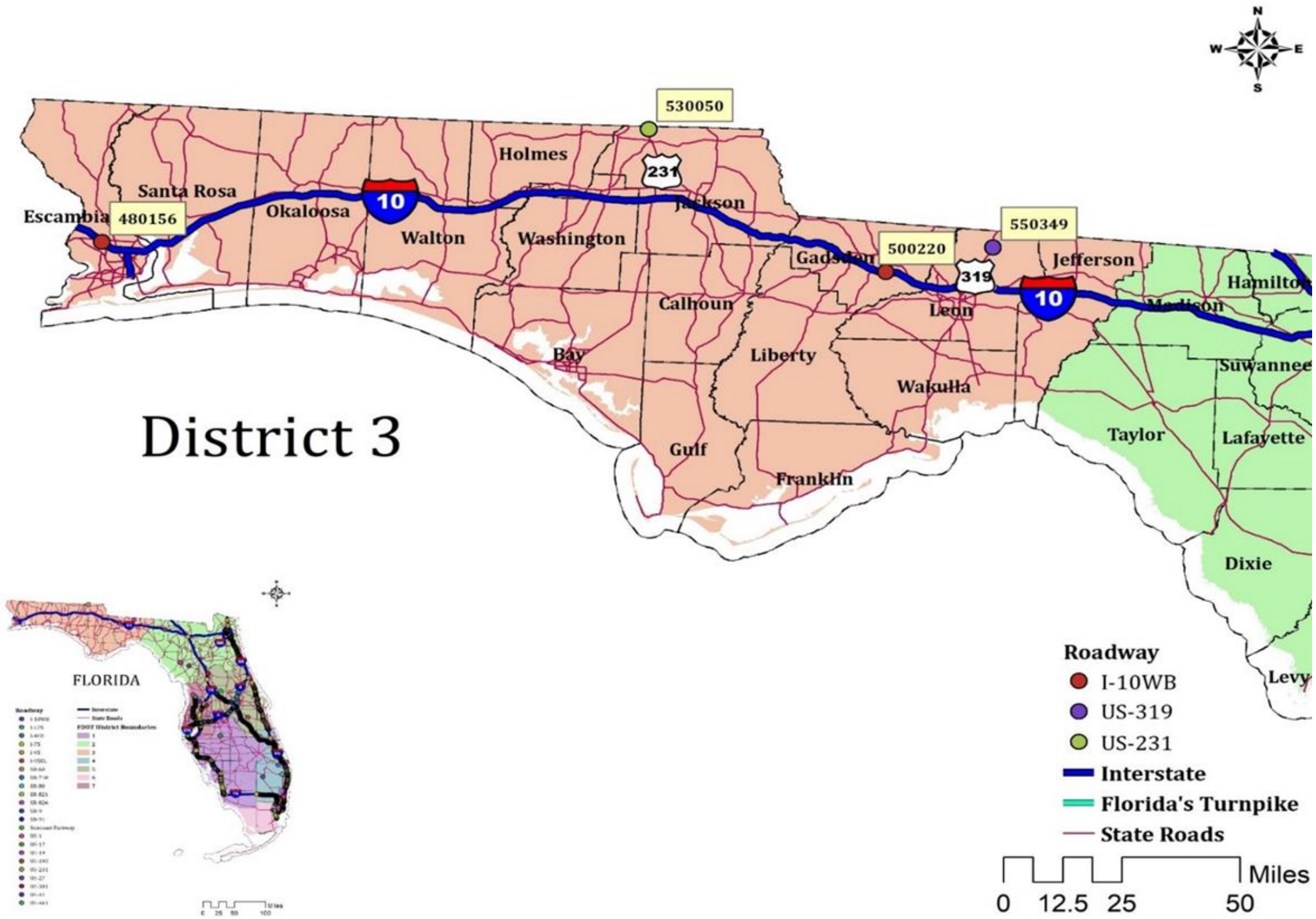


Figure 53 D3 Roadway Detectors – Hurricane Irma

Table 28 District 3: Florida Traffic Online Hourly Continuous Count Stations

Facility	Evacuation Volume (% Difference from Yearly Average)				
	Tuesday 09/05	Wednesday 09/06	Thursday 09/07	Friday 09/08	Saturday 09/09
US-231 (0050)	8,035 (31.2%)	8,191 (31.4%)	14,143 (113.0%)	14,480 (80.3%)	13,991 (59.9%)
I-10WB (0220)	14,657 (0.4%)	20,467 (35.8%)	42,096 (158.0%)	54,688 (179.1%)	46,056 (184.0%)
I-10WB (0156)	23,560 (7.4%)	24,008 (7.1%)	30,681 (33.2%)	43,857 (69.7%)	42,032 (94.2%)

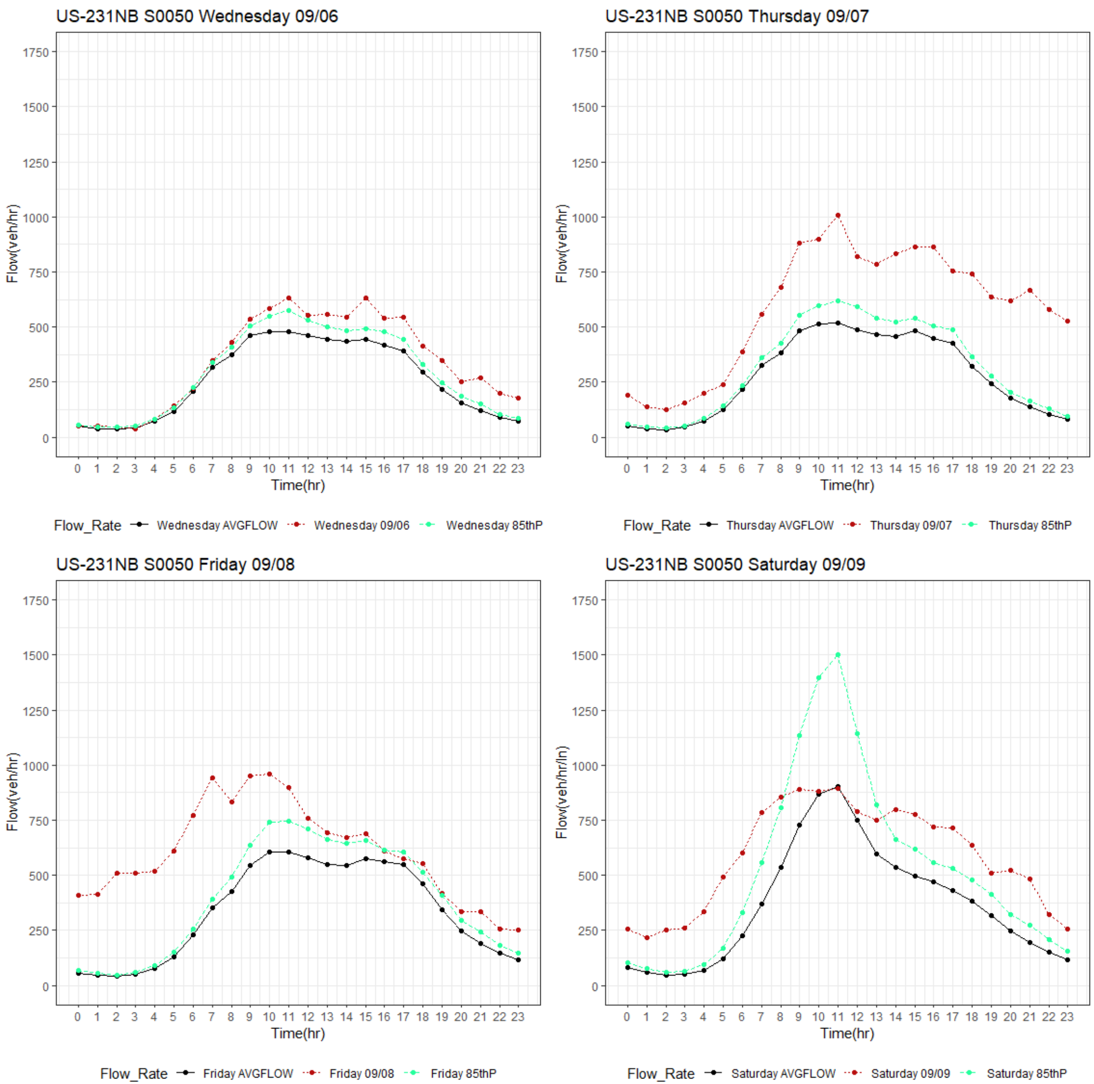


Figure 54 D3: US-231 (530050) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

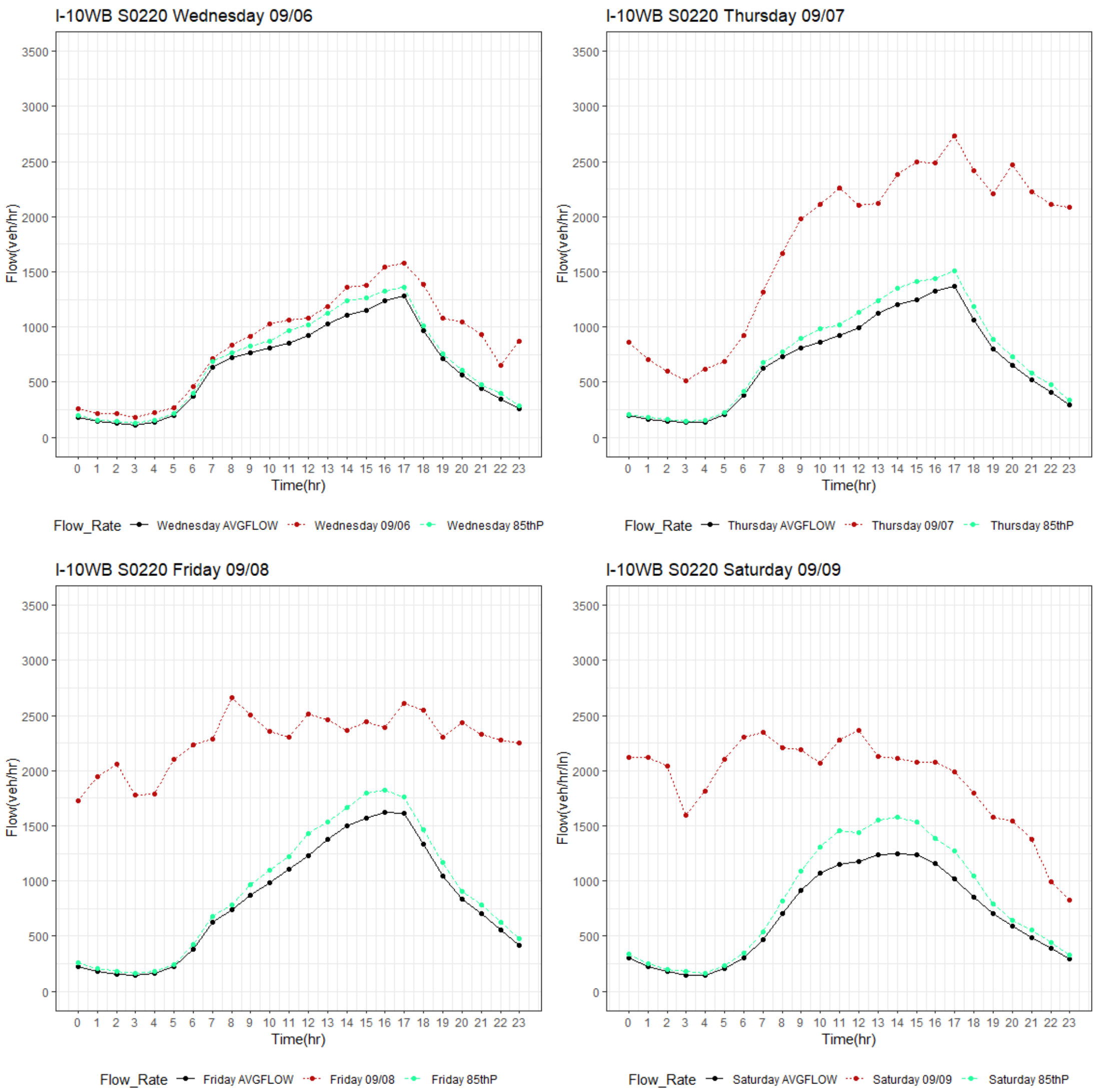


Figure 55 D3: I-10 WB (500220) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

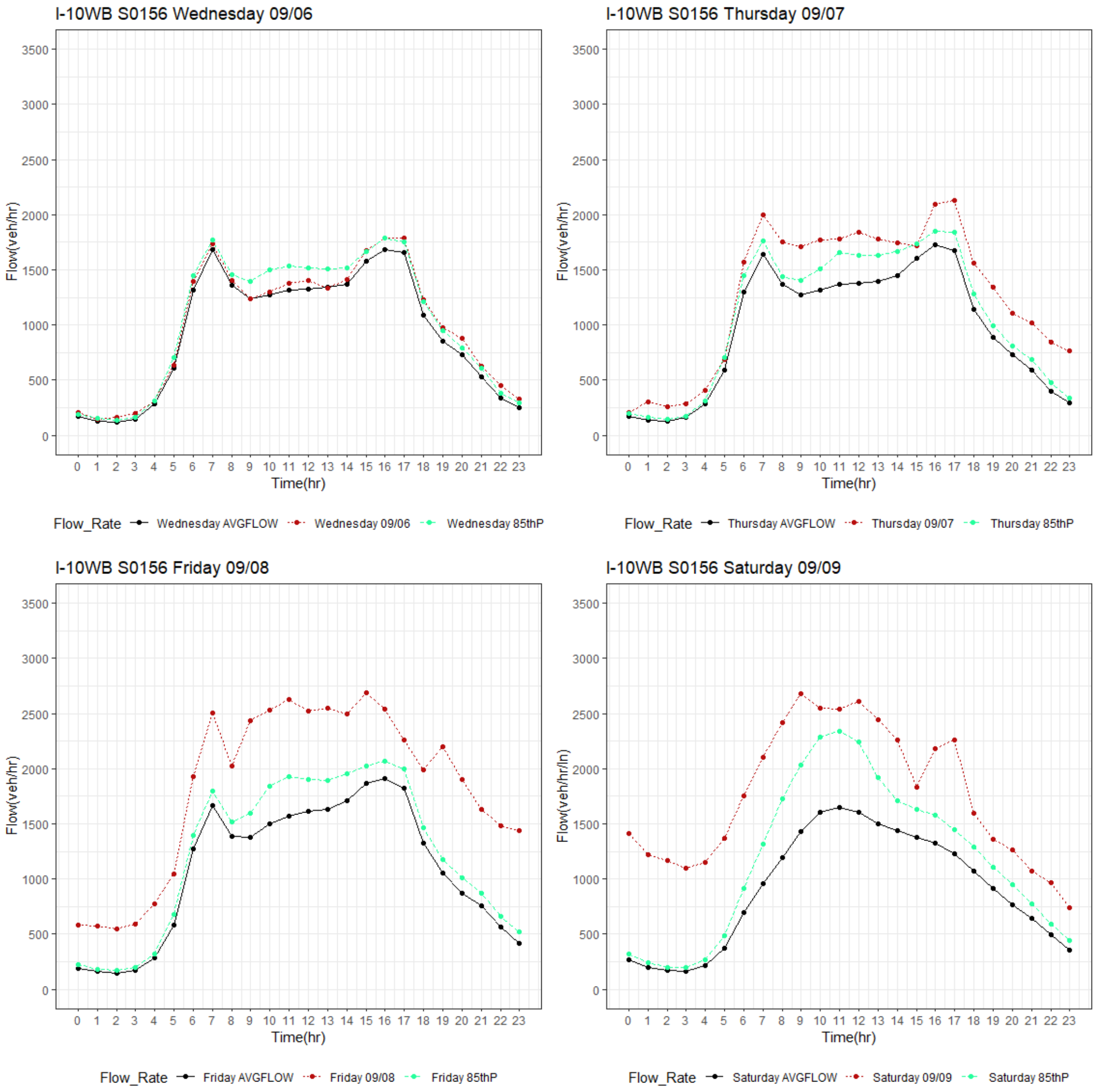


Figure 56 D3: I-10 WB (480156) Flow Rate Comparisons from Florida Traffic Online Hourly Continuous Count Station (09/06 to 09/09)

Key Findings

A majority of the RITIS probe detectors for the I-10 WB were offline during the analysis period. Therefore, the research team could only use the Florida Traffic Online Hourly Continuous Counts to observe for evacuation trends in the district. Results reveal that the I-10 WB continued to experience significant evacuation flows well into the late hours of the 9th of September. This is somewhat unsurprising considering the fact that the WB evacuation flows were predominant in this district and the last-minute course change experienced by Irma to move towards through Central Florida, just west of Ocala, may have only exacerbated this phenomenon (as seen from the results in Table 28, Figure 55, and Figure 56).

A detailed visualization of the performance of the analyzed roadways for each evacuation day are as shown in Appendix A (see Figure 71 to Figure 75).

Key Detector Issues

The I-10 WB, which would have been a prominent evacuation route in the region had too many detectors offline during the evacuation period and therefore, was not considered for the purpose of this analysis.

4.2.Evacuation During Woolsey Wildfire

As mentioned in the methodology section, visualizations at key detector locations were extracted from PeMS for the analysis and subsequent discussions. The main aim was to locate mainline detectors on the edges of the wildfire in addition to ON-ramp detectors within the breadth of the wildfire to observe any sudden fluctuations in volume. The complete list of detectors chosen based on this methodology are shown in Table 3 and is as shown in figure below.

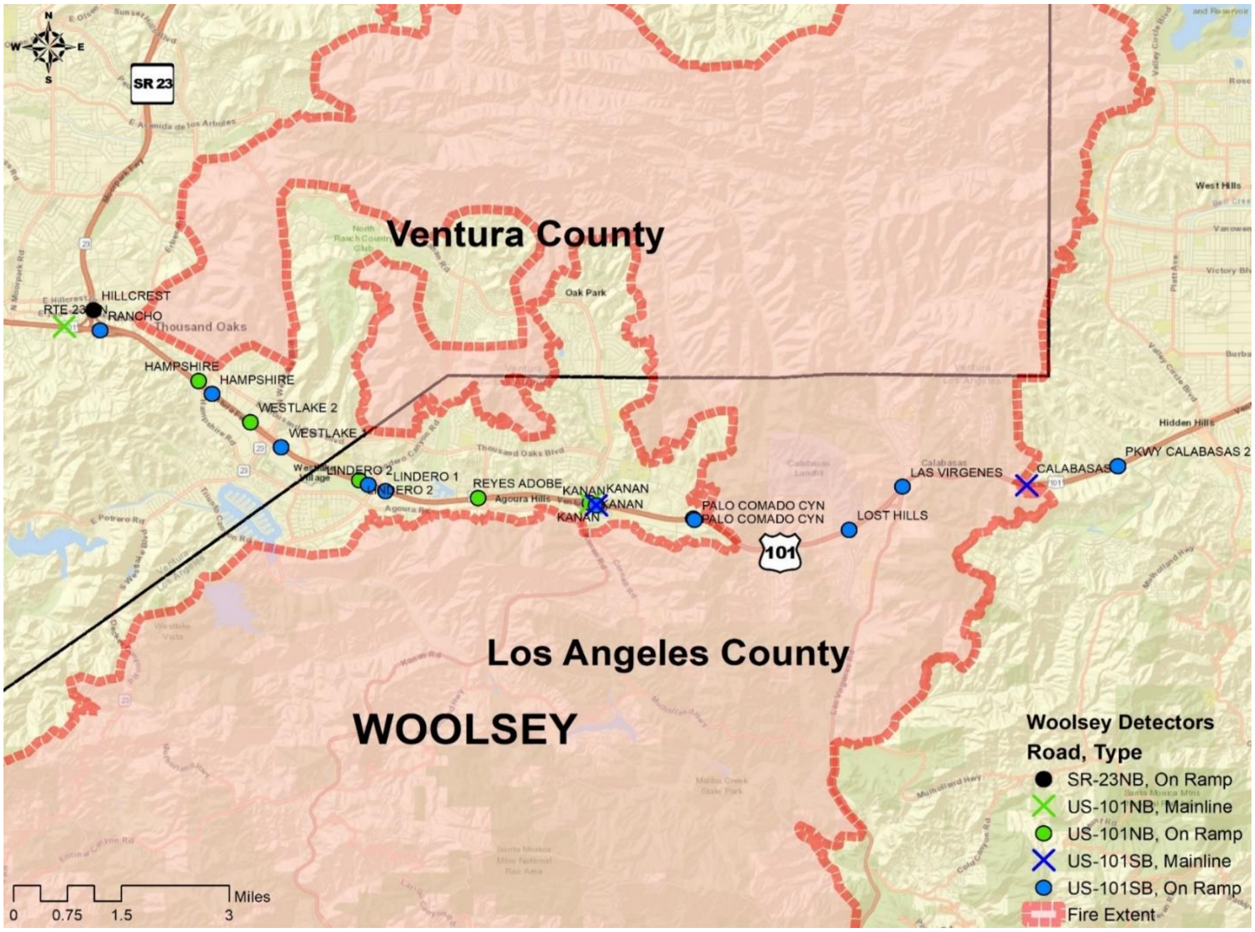


Figure 57 Analyzed Detectors for Woolsey Wildfire

The order in which the detectors are shown in Table 3 follow the order of which vehicles would travel to evacuate from the fire. Starting with the PALO COMADO CYN, northbound ON-ramp, which was in the path of the fire and ending with the last ON-ramp prior to SR-23 (RTE 23 CN). As mentioned previously, 5 miles to the north of the US-101/SR-23 interchange, the Hill Wildfire was raging and eventually crossed over US-101 cutting off all northbound traffic. Therefore, the only routes out of harm's way was through SR-23 NB or southbound on US-101. In addition to this, mainline detectors going northbound were chosen – one just to the north of the fire path, and another located north of the SR-23/US-101 interchange. The detectors demonstrating the flow of vehicles to the south were chosen in a similar manner. However, the mainline detectors for the southbound direction were chosen just north of the fires path and another just to the south. In addition to US-101NB, north of SR-23, preliminary investigations based on ramp data made it evident that either individuals did not evacuate, or the fire had engulfed the ramp detectors going southbound starting at KANAN at roughly 4 AM Nov 9. This is verified through Figure 58and Figure 59which display the detectors as being online (functional) on November 8th, and offline (non-functional) on November 9th.

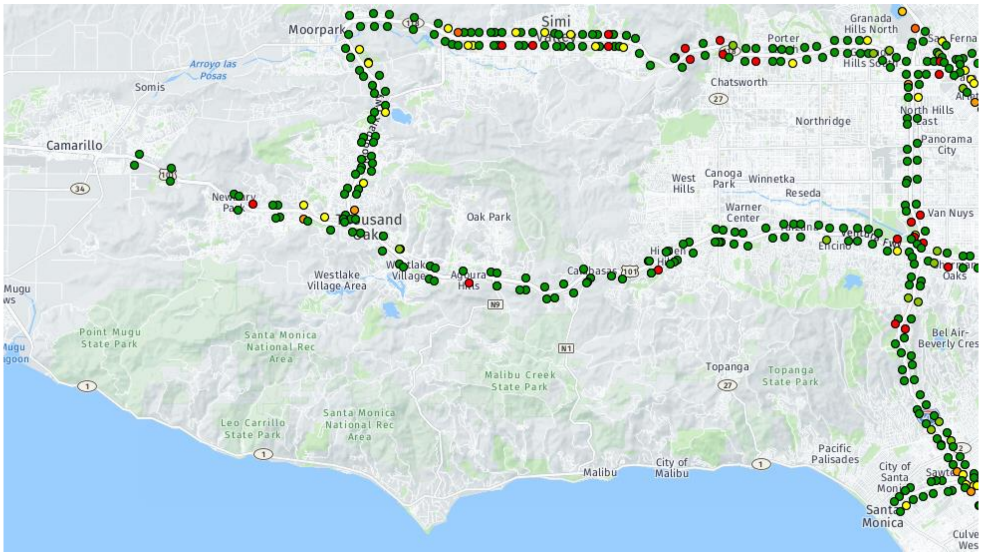


Figure 58 Woolsey Wildfire Detectors with US-101 Detectors Online – Nov 8, 2018 (Source: PeMS)

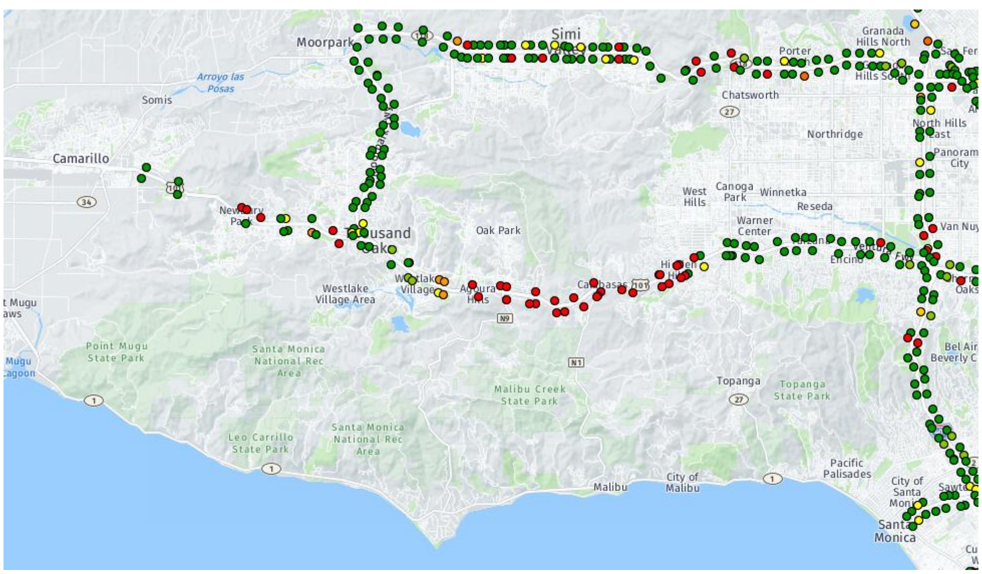


Figure 59 Woolsey Wildfire Detectors with US-101 Detectors Offline – Nov 9, 2018 (Source: PeMS)

This finding further cements the fact that the wildfire indeed breached US-101 in the morning of Nov 9 at this location.

4.2.1. US-101 NB

Based on the plots shown below (Figure 60), the mainline detector at KANAN experienced a steady decline in vehicular flow around mid-afternoon on the 8th November 2018 and drastically declined to zero vehicles by the morning of Nov 9. Moreover, RTE 23 C, located north of SR-23 (Figure 61), also experienced zero flow around 5 PM on November 8th and traffic picked up at around the early hours of November 9th. From our investigations, this timeline, and the associated trend in flow coincided with the Hill wildfire which was occurring simultaneously to the north of Woolsey.

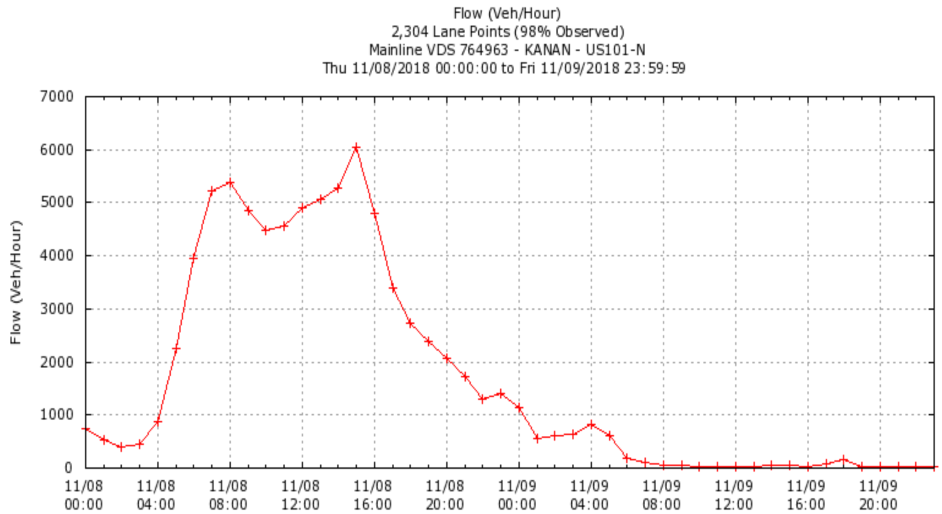


Figure 60 Flows on US-101 NB KANAN Mainline MM 36.3 (Source: PeMS)

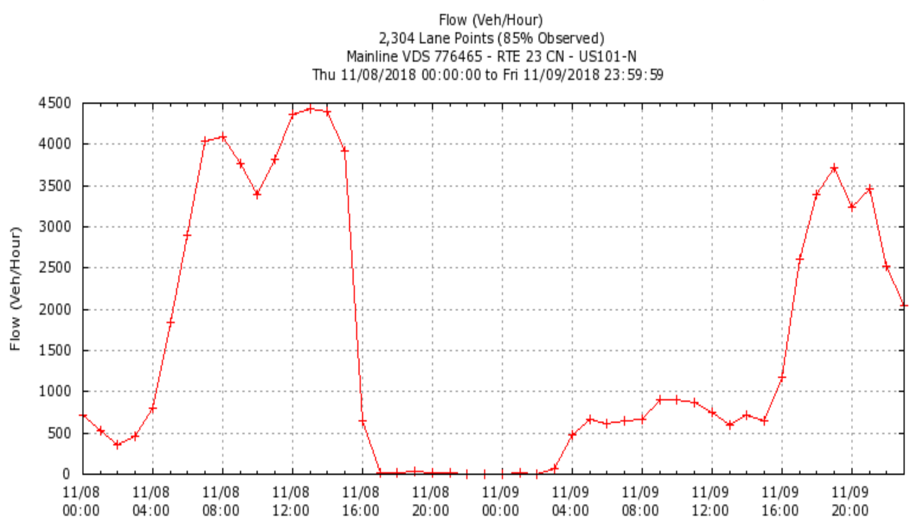


Figure 61 Flows on US-101 NB RTE 23 CN Mainline MM 43.0 (Source: PeMS)

Looking at the US-101 NB ON-ramps and starting with the southernmost detector (PALO COMADO CYN) located within the fire's eventual path, vehicular flow reduced to zero in the early hours of 9th November – this is most likely indicator that the fire burned over US-101 NB and consequentially destroyed the detector (see Figure 62).

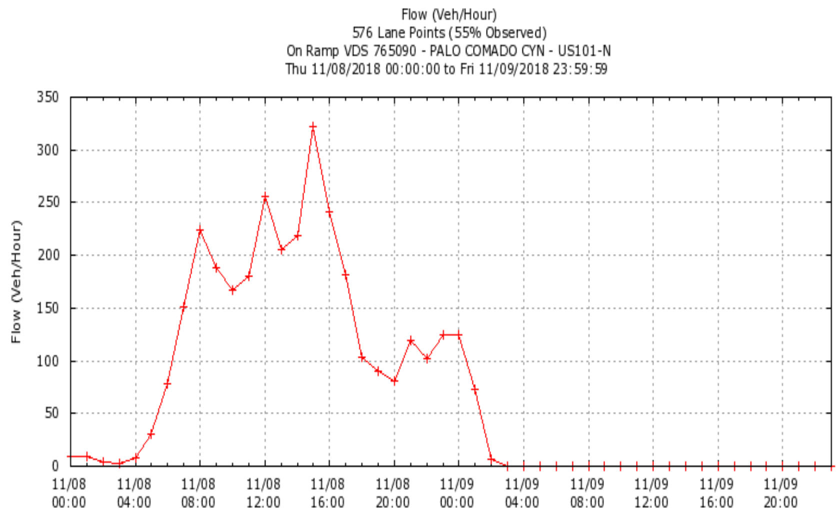


Figure 62 Flows on US-101 NB PALO COMADO CYN ON-ramp MM 35.1 (Source: PeMS)

Moving further north, the KANAN ON-ramp (located north of the fire's eventual path) witnessed a slight increase in traffic after 4:00 AM on the 9th of November (see Figure 63), and similarly, REYES ADOBE saw a massive increase in vehicles after 4:00 AM on Nov 9 (see Figure 64) which indicates a sudden increase in evacuees, which likely resulted from developments south of US-101.

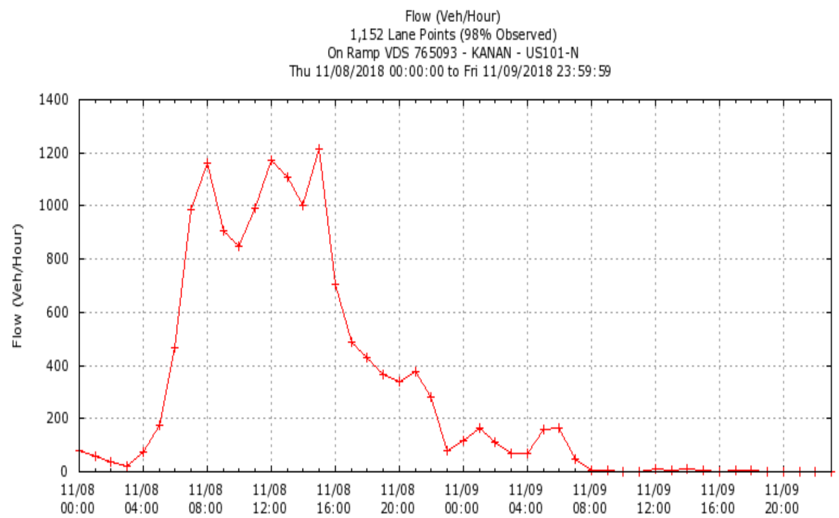


Figure 63 Flows on US-101 NB KANAN ON-ramp MM 36.6 (Source: PeMS)

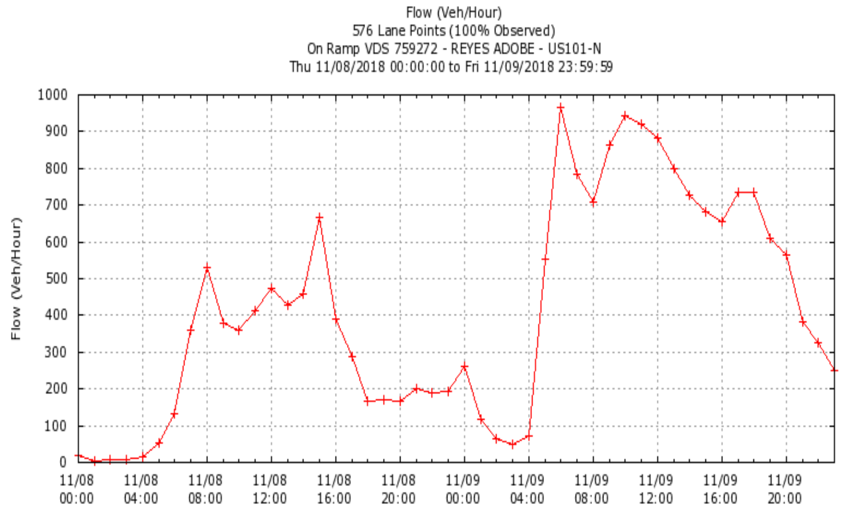


Figure 64 Flows on US-101 NB REYES ADOBE ON-ramp MM 37.6 (Source: PeMS)

Similar interpretations can be made for the remaining ON-ramps on US 101 NB (see Figure 65).

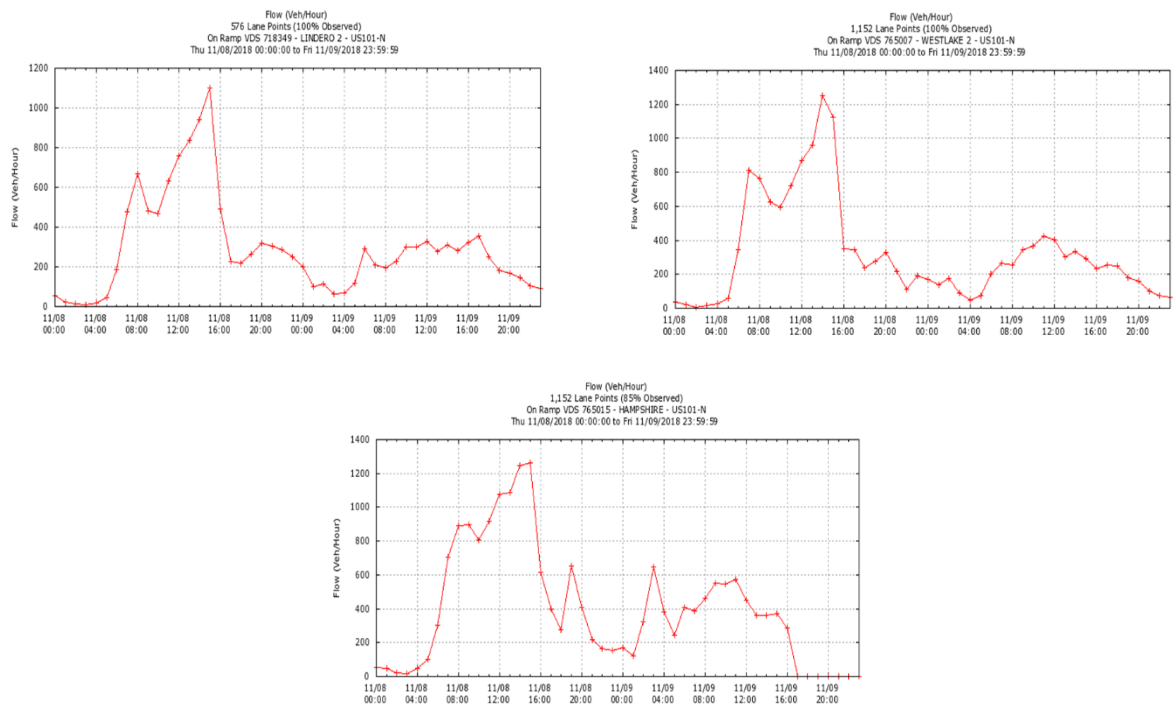


Figure 65 Flows on US -101 NB ON-ramps [L to R; top to bottom – LINDERO 2, WESTLAKE; HAMPSHIRE] (Source: PeMS)

4.2.2. US-101 SB

The mainline detectors for the southbound direction of US-101 received steady flows through the night between November 8th and November 9th indicating that people were using this facility to evacuate towards Los Angeles. The KANAN SB mainline detector experienced a sudden spike in evacuees occurred just after midnight (on November 9) and following this, just prior to 4 AM, the flowrates dropped dramatically (as shown in Figure 66). The plot is based on 1-hour increments, however, further inspection on 5-min data revealed small flow values which may have been emergency personnel. This also coincides with Ferreira (2018) indicating the roadway was closed early hours of Nov 9.

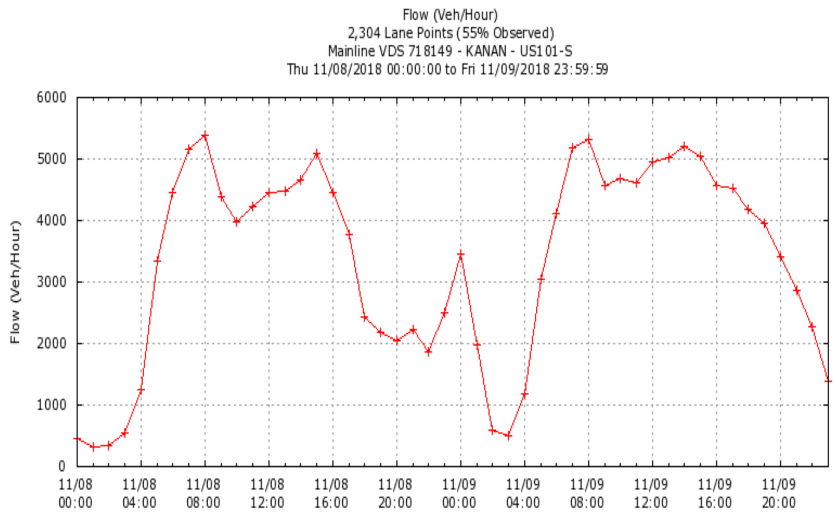


Figure 66 Flows on US-101 SB KANAN Mainline MM 36.2 (Source: PeMS)

Observing the ON-ramps starting south of SR-23 at RANCHO, moving southbound to LINDERO 1 (see Figure 67), there is an observable trend for evacuation during the early hours of November 9. Additionally, the ON-ramps at KANAN, PALO COMADO CYN, LOST HILLS, **Error! Reference source not found.**LAS VIRGENES, and CALABASAS – which w ere either in the fire's path or blocked by the fire from being accessed – went offline around the same time, just before 4 AM on November 9 (as evidenced by observations in Figure 68).

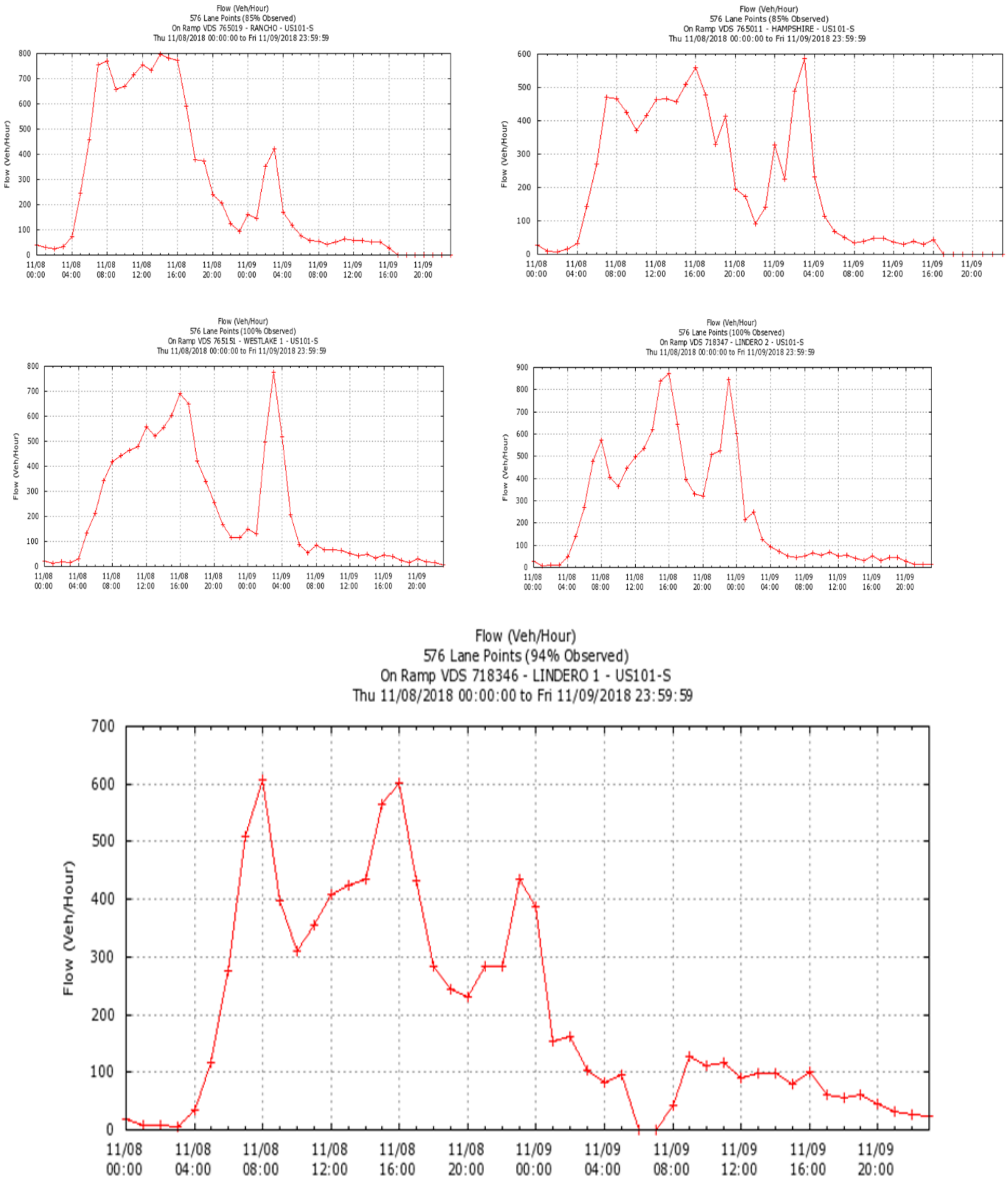


Figure 67 Flows on US 101 SB ON-ramps [L to R; top to bottom – RANCHO, HAMPSHIRE; WESTLAKE, LINDERO 2; LINDERO 1] (Source: PeMS)

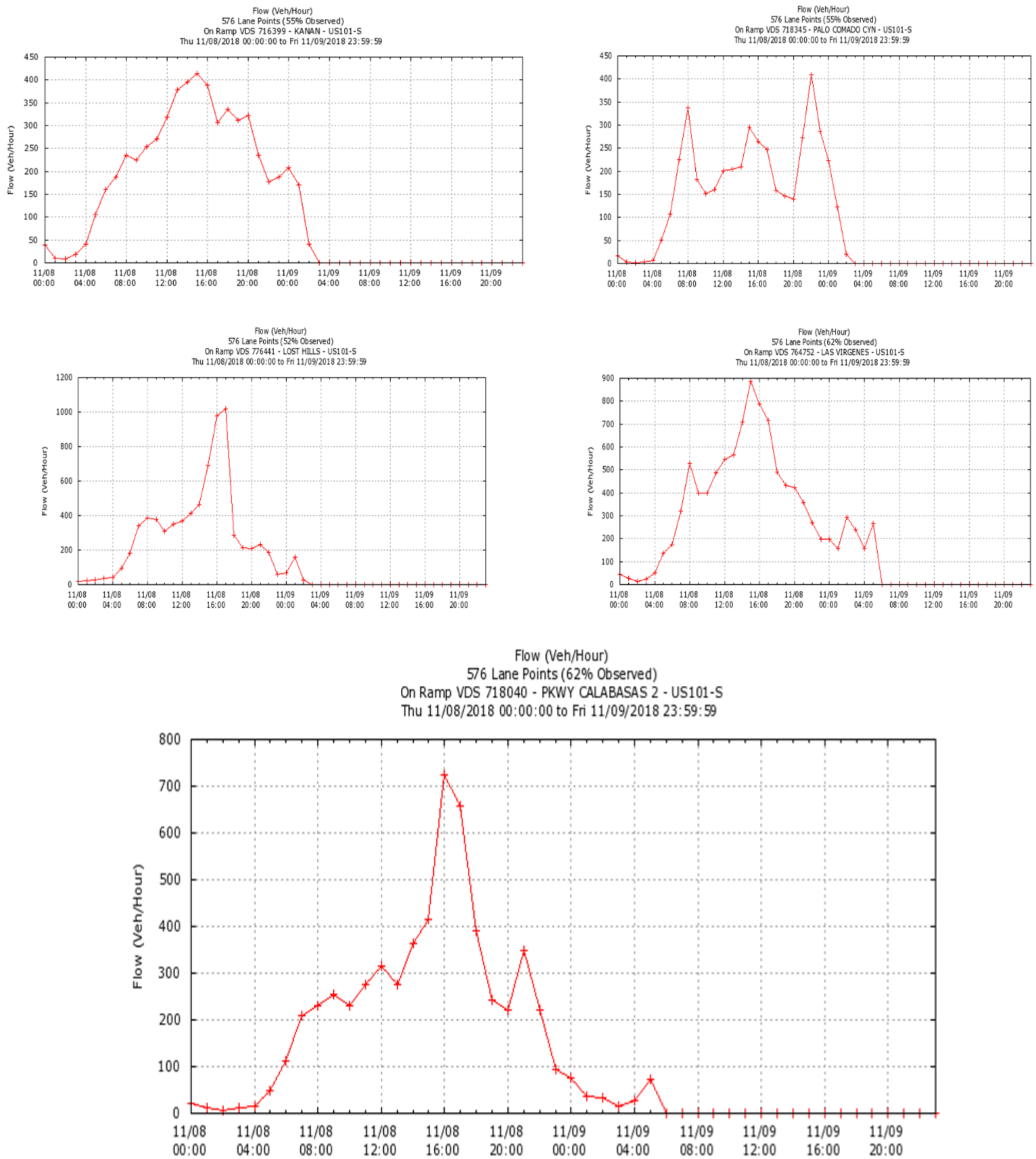


Figure 68 Flows on US 101 SB ON-ramps [L to R; top to bottom – KANAN, PALO COMADO CYN; LOST HILLS, LAS VIRGENES; CALABASAS] (Source: PeMS)

4.2.3. SR-23NB

Two plots were extracted from PeMS to depict the volume of evacuees – (i) traffic moving southbound from US-101, north of SR-23, due to the Hill Wildfire, and (ii) traffic moving northbound on US-101, south of SR-23. We assume that the volumes observed from US-101 SB to SR-23 NB would capture individuals using SR-23 NB to evacuate. After inspecting these visualizations, however, it became evident that few individuals used this route to evacuate from the Hill Fire – who were captured by the detectors further downstream on US-101SB (Figure 69).

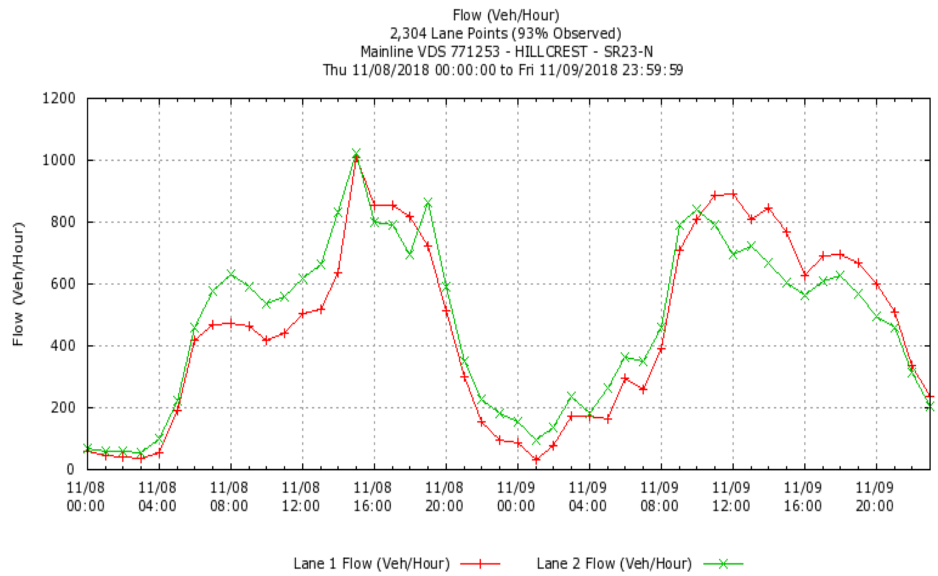


Figure 69 US-101 SB to SR-23 NB HILLCREST ON-ramp MM 12.5 (Source: PeMS)

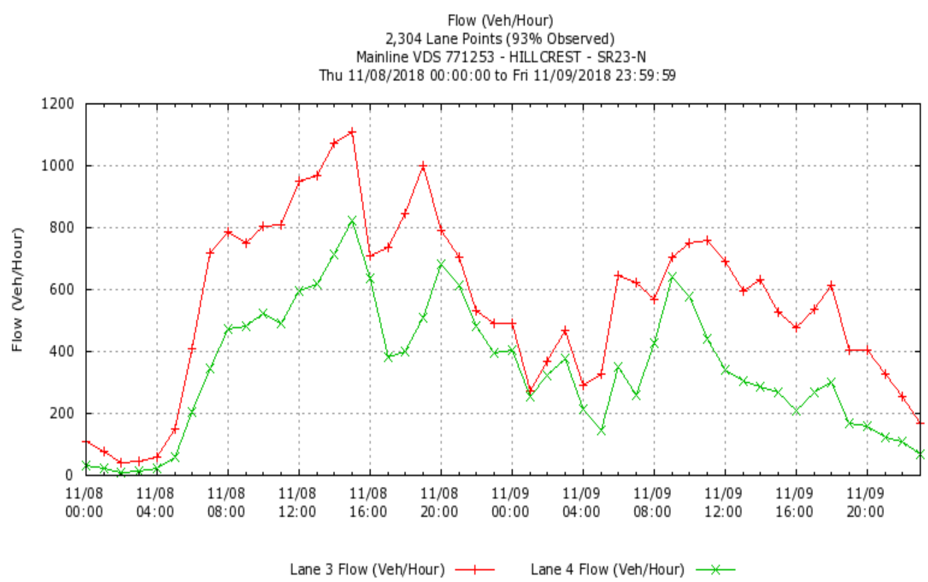


Figure 70 US-101 NB to SR-23 NB HILLCREST ON-ramp MM 12.5 (Source: PeMS)

A more interesting observation, was the volume of individuals that evacuated from US-101 NB to SR-23 NB. As shown above, a steady volume of individuals merged on SR-23 from US-101 NB during the night of the fires (Figure 70).

4.3. Data Limitations and Challenges

The current study, like any other study involving the collection of large-scale loop detector data, suffers from some limitations that are beyond the control of the research team. As seen in the earlier sections, there were roadway detectors that were offline either for a lot of time during a day or were offline for a significant time period considered for the analysis. In some cases, for instance, certain detectors only produced a tiny percentage of the output with respect to the number of timestamps in a day. In other cases, such as I-75 in District 2, there were only a few detectors working for a stretch of roadway that spanned more than 150 miles. The research team reserved judgement in determining data validity by analyzing each individual roadway facility.

In order to validate this exercise, the research team utilized available capacity-based measures to capture detector coverage, and the percentage day captured in addition to those that were earmarked for examining the characteristics of the traffic stream. If either of these parameters resulted in erroneous measures – high, in the case of detector coverage (i.e., when the spacing between the detectors was too large), or small, in the case of percentage day captured – those roadways were not considered in this study.

In addition to this issue, we found that every district in the state of Florida named their detectors differently. For instance, District 6 detectors included the mile marker in their naming convention whereas in District 2, the detector names only contained information on their nearest roadway. This non-homogeneity in naming detectors led to extra computational time to identify the exact mile marker location that was sought for the analyses.

In comparison with Hurricane Irma, it became quite evident that the Woolsey wildfire was vastly different spatiotemporal scale of the disaster and the ensuing evacuation. As such, the validity of data used was reassuring – the detectors were working near 100% of the time, or not at all. Additionally, since the researchers decided to utilize the existing PeMS visualizations to depict the evacuation movements over time and space, there was no need to empirically export and analyze the data. Future research in this regard would warrant more detailed investigations over time and space and could critically use econometric modeling techniques to understand the influence for some of the evacuation decisions undertaken during these mass evacuation events.

5. Conclusion and Recommendations

5.1. Conclusions

This study investigated two mass evacuation events – Hurricane Irma in Florida (2017), and the Woolsey Fire in California (2018) to determine spatial and temporal trends in roadway traffic and assess the performance of the transportation network during said events. The research team reviewed existing literature for hurricane and wildfire-based mass evacuations. A determination of the major data sources with relevant data from roadway detectors was made by the research team. Next, the research team embarked on data collection. A series of databases were used to collect all the data relevant to this study. In the case of Hurricane Irma, three datasets were used: (i) RITIS probe detector data was collected for each evacuation day across all FDOT districts in the state of Florida for assessing the performance of the roadways during the mass evacuation process; (ii) RITIS probe detector data was collected over three months of the year for average estimates; (iii) Florida Traffic Online hourly continuous data was collected to validate the findings from the probe detector dataset.

In order to accomplish this performance assessment, the research team developed hurricane-evacuation specific performance metrics (vehicle miles traveled while congested (%), vehicle miles traveled, % day captured, vehicle-hours of delay, mean speed of the traffic in the uncongested state, and mean speed of the entire traffic stream). These performance metrics provided a general overview of the performance of the traffic stream. The performance metrics were further supplemented by analyzing data from the hourly traffic count stations that provided an understanding of the evacuation trends pertaining to each FDOT district. The research team identified key detector issues that were encountered at each district and discussed key findings based on the analysis conducted for each FDOT district.

To summarize, this study found that the major interstates experienced severe congestion during the main evacuation days. Since the evacuation was unidirectional (all traffic moving up North, and out of the state of Florida), it presented a unique challenge for evacuation. The residents of the southern districts (D6, D4, and D1) evacuated first followed by their central (D7, and D5), and northern counterparts (D2, and D3). As a result, by the time, some of the residents from the central and northern districts had issued evacuation, the roadways had already exceeded capacity and it resulted in congestion across several regions. Once the southern districts evacuated, congestion along FL roadways shifted northward through the I-75 and I-95 with both these roadways periodically getting more and more congested (as shown by the increase in VMT, refer to Figure 71 to Figure 75).

Once the southern districts evacuated, congestion along FL roadways shifted northward through the I-75 and I-95 with both these roadways periodically getting more and more congested (with the increase in VMT up to 300% in some instances on I-95, see Figure 71 to Figure 75 in Appendix A). Additionally, our analysis also revealed how some other highways remained underutilized, in comparison to the major evacuation routes raising the possible conclusion that evacuees may have been experiencing lack of information (on fuel availability, resources along the facility, utilities, shelter information, as well as travel time information) which may have prompted the non-utilization of such roadways to evacuate out of harm's way.

We also found instances where roadway facilities that under normal conditions was never congested, ended up being heavily congested during the evacuation times, (sometimes leading to an increase in VMT of up to 300%). Such instances could also be attributed to possible lack of information provided to evacuees regarding roadway conditions (any roadway facility that typically moves along at near free-flow speeds may provide an obvious motivation for evacuees to utilize the facility to evacuate, unbeknownst to the potential issues that the roadway facility was undergoing during the evacuation process).

In the case of the Woolsey wildfire, the research team collected data from the Caltrans' web-based transportation data portal (PeMS). After thoroughly studying the evacuation surrounding the Woolsey wildfire, the research team embarked on identifying specific ON-ramps, and mainline detectors that would provide the main evacuation characteristics for the public moving out of harm's way from the fires. The PeMS-generated visualizations along the chosen detectors and ON-ramps were used to conduct the performance assessment during the Woolsey wildfire evacuation and its impacts over the three major roadways: US 101 NB, US 101 SB, and SR-23 NB. The visualizations describing traffic flow provided a general understanding of the evacuation trends for people from the Woolsey wildfire along all the chosen roadways.

Results from this study are very timely and will be of invaluable assistance to local/regional/state entities that are looking to characterize the performance of the roadway network during such mass evacuations. The study is the one of the first works to comprehensively use customizable hurricane-specific performance metrics, that we believe, provide a much better insight into characterizing the performance of the roadway network. This is also a first-of-its-kind study to throw a lot of insight on two different types of mass evacuations – a short-notice evacuation (in the case of the evacuation from Hurricane Irma), and a no-notice evacuation (in the case of the evacuation from the Woolsey wildfire). Even though the extents of the two mass evacuation events are vastly different, this data-intensive study provides a comprehensive methodology to effectively characterize the performance of the roadway networks in both the events.

The wildfire evacuation, although much smaller in scale in comparison to the hurricane was exacerbated by a neighboring fire (the Hill wildfire) which propagated SW of the Woolsey fire. Therefore, considerations emanating out of this wildfire also constrained the evacuation process and were considered by the research team during the performance assessment. Since wildfires are so unpredictable, resulting mostly in no-notice forced evacuations, considerations made as a part of this study will serve as an important benchmark for future studies in this arena.

5.2. Recommendations

Based on the findings from this study, the research team would like to present the following recommendations:

- **Agencies should ensure that roadway detectors are in working condition through routine maintenance and quality control measures:** Studies of this nature are highly data intensive and the findings are entirely based on the quality of data available for collection and eventual analysis. Many a time, the research team witnessed significant obstacles in acquiring all eligible roadway detector data as several detectors in most districts were either offline during the analysis period or experienced significant disruptions in data quality and output. Therefore, it is imperative to ensure that the roadway detectors are in working condition through timely maintenance and quality checks. This is a resource-intensive exercise but a timely one, so as to ensure data quality and the validity of the subsequent analysis. A lot of policymaking decisions hang in the balance of such analysis and therefore, this is our primary recommendation to transportation agencies and decisionmakers.
- **Agencies should promote the use of hurricane/wildfire-specific performance measures to assess the performance of the transportation network:** Many past studies have been conducted in the field of mass evacuations by using traditional transportation performance measures such as travel time reliability. Although travel time-based performance measures depict the typical congestion occurring on roadways and the variability in this congestion, in the context of a hurricane/wildfire evacuation that has extremely low probabilities to impact the exact same areas as previous hurricanes/wildfires with the same intensities, using performance measures that are based on normal operating conditions would result in erroneous conclusions. Additionally, a comparing the network characteristics observed from other hurricanes/wildfires may also lead to vastly different outcomes due to limited observations that are similar spatially and temporally. The study was also able to describe how no-notice events and short-notice events warranted different kinds of treatments to assess performance of the transportation network.
- **Agencies need to be prepared for evacuations at any point during the day:** Given the dynamic nature of no-notice events, in comparison to short-notice events, agencies should always be prepared to conduct evacuations at any time of the day. This can be accomplished by making physical as well as human resources available at very short notice to assist with the evacuation activities and devising ways to stay in touch with residents at all times during the day.
- **Agencies should develop detailed evacuation plans, communication materials, and alert residents in high-risk regions to be available for evacuating at any given time:** Impending a natural disaster, residents of high-risk regions should be identified in

advance to the most granular level possible, notified about the need to be ready to evacuate at any point in time, and should be provided resources on potential evacuation routes, information on fuel availability as well as information on shelters, accommodation, utilities, and a concrete plan for reentry. These high-risk zones must also be engaged for evacuation purposes in a phased manner to mitigate all controllable instances of congestion.

- **Agencies should provide as much real-time information for evacuees as possible:** An analysis of the evacuation during Hurricane Irma and the Woolsey fire revealed that most evacuees ended up on the major roadways such as the I-75 and the I-95. Our analyses also revealed how certain other highways may not have been utilized to their fullest potential during the evacuation process. These highways, if used to their potential, may have relieved some congestion experienced along the major evacuation routes leading to system-wide benefits. While there has been no empirical study conducted to analyze the reasons why some of the other highways were not used to their potential, previous literature has pointed to the non-availability of complete information during evacuation process. For instance, not receiving information about the status of fuel availability (a common problem during evacuations) along these highways may have been detrimental to their use as an evacuation route. Some of these issues could have been mitigated by providing as much real-time information as possible – either through existing roadway infrastructure or through the effective deployment of agency resources to provide information.
- **Agencies need to strive for equitable outcomes in disaster evacuation:** There are likely many residents who may not have been able to evacuate from their residences to safer places. This may have been due to many existing constraints – physical, economical, logistical, and others. Agencies and decisionmakers need to be cognizant of the challenges of these disadvantaged groups and ensure equitable outcomes in the disaster evacuation paradigm. Where resources for evacuation are non-existent, agencies should ensure that these groups are provided with an option to evacuate to safer zones – by planned, systematic allocation of resources. Equity is often an unexplored topic for discussion in such scenarios and studies like this and other provide opportunities to explore these realms. For instance, agencies should be ready to deploy buses or vans to assist evacuees who may need assistance of that nature to shelters. County emergency management plans must be updated periodically to account for more equitable outcomes in disaster evacuation processes.

5.3. Future Work

There are many future directions that this study could take: One potential direction is to enhance the results from this study. The performance metrics developed as part of this research study are validated using comparisons made on 3-month 5-minute 85th percentile speed data from RITIS probe detectors. There is room for improvement to further enhance the period of comparison to a

12-month period to account for seasonality in our analyses. While this requires higher computational resources, that is a potential direction in which the research team aspires to proceed in future studies.

Data visualization techniques used in this study could be enhanced. Given the large-scale data that was collected as part of this study, there could be the potential to apply computationally intensive methodological approaches such as statistical and econometric models. This may assist analysts and agencies to understand the factors that influenced the evacuation decisions undertaken by the residents. While this may need further data collection in the form of stated/revealed preference surveys understanding respondent experiences from the evacuation process, this is a very insightful potential direction for studies of this nature. The application of machine learning and deep learning approaches with this data may also provide ways to predict speeds on freeways/interstates during future evacuations.

Lastly, future work in this field could explore equity-related issues that were experienced during mass evacuations. Studies of this nature are very timely and would provide an innumerable resource to further our understanding of some of the prevailing challenges from mass evacuations. This will go a long way in informing agencies and decisionmakers of the challenges experienced by disadvantaged groups in mass evacuations and provide an opportunity to assess the performance of agencies in striving for equitable outcomes during such stressful times. In an era of performance measurement, it is the belief of the authors that studies like the this are timely and well-intentioned with a vision for harboring equitable, safe, positive, healthful outcomes.

References

1. Bertini, R.L. (2003). Toward the systematic diagnosis of freeway bottleneck activation. *Proceedings of the 2003 IEEE International Conference on Intelligent Transportation Systems, 1*, 442-447 vol.1.
2. Cal Fire. (2018). Woolsey Fire Incident Information. Cal Fire. https://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=2282
3. Cambridge Systematics, Texas Transportation Institute. (2005). Traffic Congestion and Reliability, Trends and Advanced Strategies for Congestion Mitigation. Federal Highway Administration.
4. Cassidy, M. J., & Bertini, R.L. (1999). Some traffic features at freeway bottlenecks. *Transportation Research B,* 33B:25-42, 1999.
5. Chen, C., Varaiya, P., & Kwon, J. (2008). An Empirical Assessment of Traffic Operations. DOI: 10.1016/B978-008044680-6/50008-8.
6. Chen, C., Skabardonis, A., & Varaiya, P. (2003). Systematic Identification of Freeway Bottlenecks. In Proceedings of 83rd Transportation Research Board Annual Meeting, Washington, D.C., January 2004b.
7. Clark, K., & Bousque, S. (2018). *Irma's here. But if you're still leaving by car, this is what traffic is like.* Miami Herald, 09-Sep-2017. [online]. Available: http://www.miamiherald.com/news/weather/hurricane/article172240962.html. [Accessed: 16-Nov-2018].
8. Cosgrove, J. (2019). *Must Reads: Firefighters' fateful choices: How the Woolsey fire became an unstoppable monster.* Los Angeles Times, 06-Jan-2019. [online], Available: https://www.latimes.com/local/lanow/la-me-woolsey-resources-20190106-htmlstory.html. [Accessed: 12-Mar-2020]
9. Dixit, V., Montz, T. & Wolshon, B. (2011). Validation Techniques for Region-Level Microscopic Mass Evacuation Traffic Simulations. *Transportation Research Record: Journal of the Transportation Research Board 2229*, pp. 66–74. DOI: 10.3141/2229-08
10. Dixit, V. & Wolshon, B. (2014). Evacuation traffic dynamics. *Transportation Research Part C*, 49 (2014) 114-125.

11. Forecasting & Trends Office (FTO). (2018). The FDOT Source Book: A Technical Report – 2018. Florida Department of Transportation Forecasting and Trends Office.
12. Florida Department of Transportation (FDOT). (2017). Level of Service Targets for the State Highway System. Systems Planning, Topic No.: 000-525-006-c.
13. Federal Highway Administration (FHWA). (2018). Traffic Data Computation Method, POCKET GUIDE. U.S. Department of Transportation. No. FHWA-PL-18-027.
14. Ferreira, G. (2018). *Highway 101 reopens in Woolsey Fire area.* The Tribune, 11-Nov-2018. [online]. Available: https://www.sanluisobispo.com/news/local/article221505045.html. [Accessed: 12-Mar-2020].
15. Harten, E., Patel, R., Ryan, L., &Sawyer, J. (2018). Evaluation of Traffic Mitigation Strategies for Pre-Hurricane Emergency Evacuations. https://ieeexplore-ieee-org.ezproxy.lib.usf.edu/stamp/stamp.jsp?tp=&arnumber=8374739
16. Jha, M., Moore, K., and Pashaie, B. (2004). Emergency evacuation planning with microscopic traffic simulation. *Transportation Research Record 1886*, Transportation Research Board, Washington, DC, 40–48
17. Jin, S., Luo, X. & Ma, D. (2018). Determining the Breakpoints of Fundamental Diagrams. *IEEE Intelligent Transportation Systems Magazine*, vol. 12, no. 1, pp. 74-90, Spring 2020.
18. Li, J, & Ozbay, K. (2015). Hurricane Irene Evacuation Traffic Patterns in New Jersey. *Nat. Hazards Rev., 10.1061*/(ASCE)NH.1527-6996.0000154. 16(2)
19. Liu, Y., Chang, G.-L., Liu, Y., and Lai, X. (2008). Corridor-based emergency evacuation system for Washington, DC: System development and case study. *Transportation Research Record 2041*, Transportation Research Board, Washington, DC, 58–67.
20. Lindgren, R. (2005). Analysis of Flow Features in Queued Traffic on a German Freeway. Ph.D. dissertation, Dept. Civil & Envir. Eng. Portland State Univ., 2005.
21. Lyman, K. & Bertini, R. L. (2008). Using Travel Time Reliability Measures to Improve Regional Transportation Planning Operations. *Transportation Research Record 2046*. 10.3141/2046-01.

22. Naghawi, H., and Wolshon, B. (2012). Performance of traffic networks during multimodal evacuations: Simulation-based assessment. *Nat. Hazards Rev*., 10.1061/(ASCE)NH.1527-6996.0000065, 196–204

23. Office of Operations. (2006). Travel Time Reliability: Making it There on Time, All the Time, Report No. FHWA-HOP-06-070, *Federal Highway Administration*, Washington, DC. online: https://ops.fhwa.dot.gov/publications/tt_reliability/brochure/ttr_brochure.pdf, [Accessed: 24-Feb-2020].

24. Office of Research, Development, and Technology. (2005). Fiscal year 2004 Performance Report. Report No. FHWA-HRT-05-040, *Federal Highway Administration*, Washington, DC.

25. PeMS. PeMS website. http://pems.dot.ca.gov/

26. Schleuss, J., & Krishnakumar P. (2018). *Here's where the Woolsey fire burned through the hills of Southern California.* Los Angeles Times, 13-Nov-2018. [online]. Available: https://www.latimes.com/projects/la-me-woolsey-fire-progression/. [Accessed: 12-Mar-2020].

27. Songchitruska, P., Henk, R., Venglar, S. & Zeng, X. (2012). Dynamic Traffic Assignment Evaluation of Hurricane Evacuation Strategies for the Houston-Galveston Texas, Region. *Transportation Research Record: Journal of the Transportation Research Board.* https://doi.org/10.3141/2312-11

28. Transportation Research Board, Highway Capacity Manual (HCM) (2010). Washington DC, USA: National Research Council.

29. Wolshon, B., & McArdle, B. (2010). Traffic Impacts and Dispersal Patterns on Secondary Roadways during Regional Evacuations. *Natural Hazards Review, 12(1).* https://doi.org/10.1061/(ASCE)NH.1527-6996.0000026

30. Wolshon, B., Urbina, E., Wilmot, C., and Levitan, M. (2005). Review of policies and practices for hurricane evacuation. I: Transportation planning, preparedness, and response. *Nat. Hazards Rev.*, 10.1061/(ASCE) 1527-6988(2005)6:3(129), 129–142

31. Wolshon, B., Hamilton, E. U., Levitan, M., and Wilmot, C. (2005a). “Review of policies and practices for hurricane evacuation. II: Traffic operations, management, and control.” Nat. Hazards Rev., 10.1061/ (ASCE)1527-6988(2005)6:3(143), 143–161

32. Wolshon, B., and McArdle, B. (2009). “Temporospatial Analysis of Hurricane Katrina Regional Evacuation Traffic Patterns” Journal of Infrastructure Systems, 10.1061/(ASCE)1076-0342(2009)15:1(12)

33. Wolshon, B., Herrera, N., Zhang, Z., & Parr, S. (2019). Assessment of Post-Disaster Reentry in Megaregions: A Pilot Study. Cooperative Mobility for Competitive Megaregions.

34. Zhang, Z., Wolshon, B. & Dixit, V.V. (2015). Integration of cell transmission model and macroscopic fundamental diagram: Network aggregation for dynamic traffic models. *Transportation Research Part C, 55* (2015) 298 – 309.

35. Zheng, Z., Ahn, S., Chen, D., & Laval, J. (2011). Applications of wavelet transform for analysis of freeway traffic: Bottlenecks, transient traffic, and traffic oscillations. (2011).

36. Zou, N., Yeh, S.-T., Chang, G.-L., Marquess, A., and Zezeski, M. (2005). “Simulation-based emergency evacuation system for Ocean City, Maryland, during hurricanes.” Transportation Research Record 1922, Transportation Research Board, Washington, DC, 138–148.

Appendix A: Hurricane Irma Evacuation Roadway Performance by Day

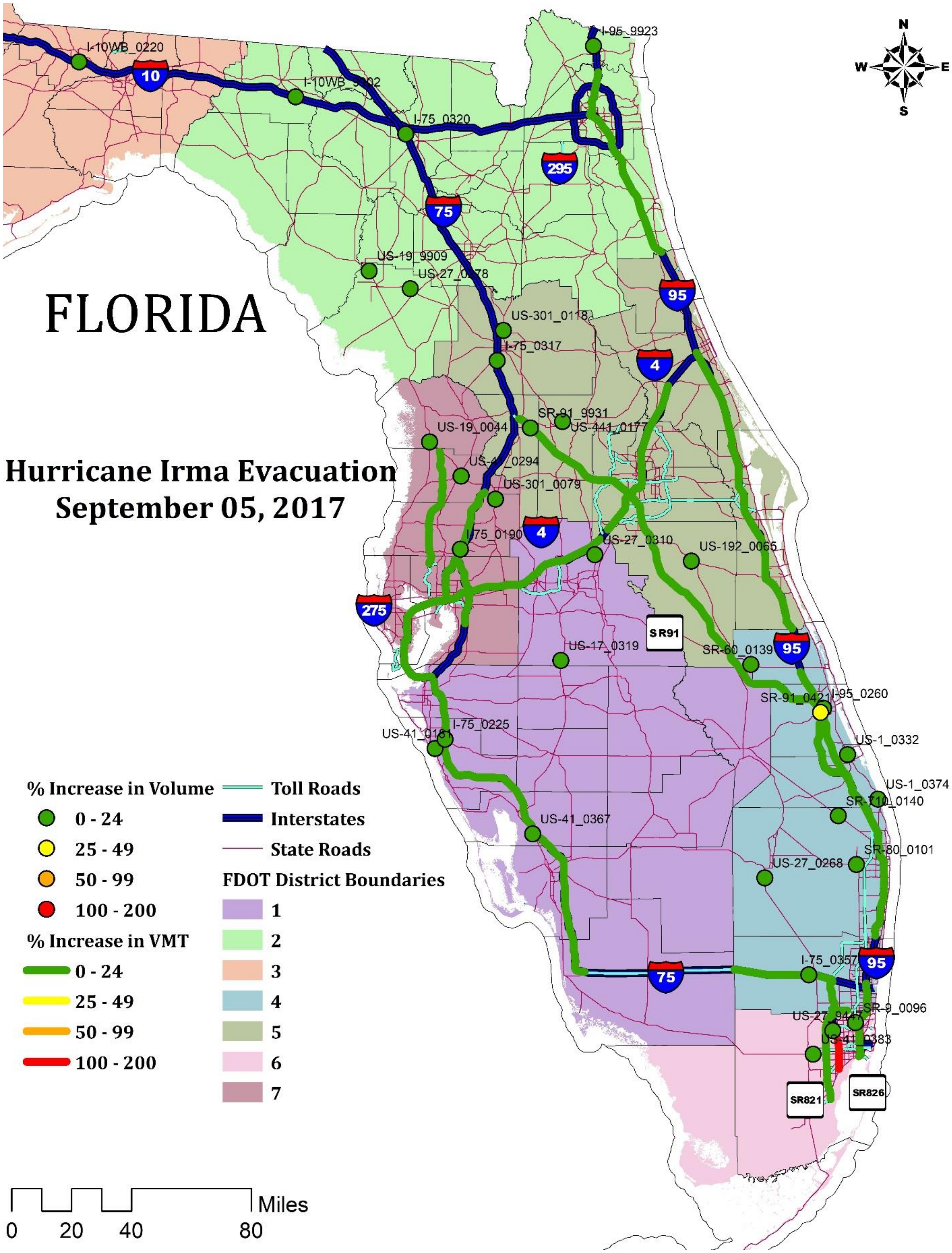


Figure 71 Hurricane Irma Evacuation – Roadway Performance – September 5, 2017

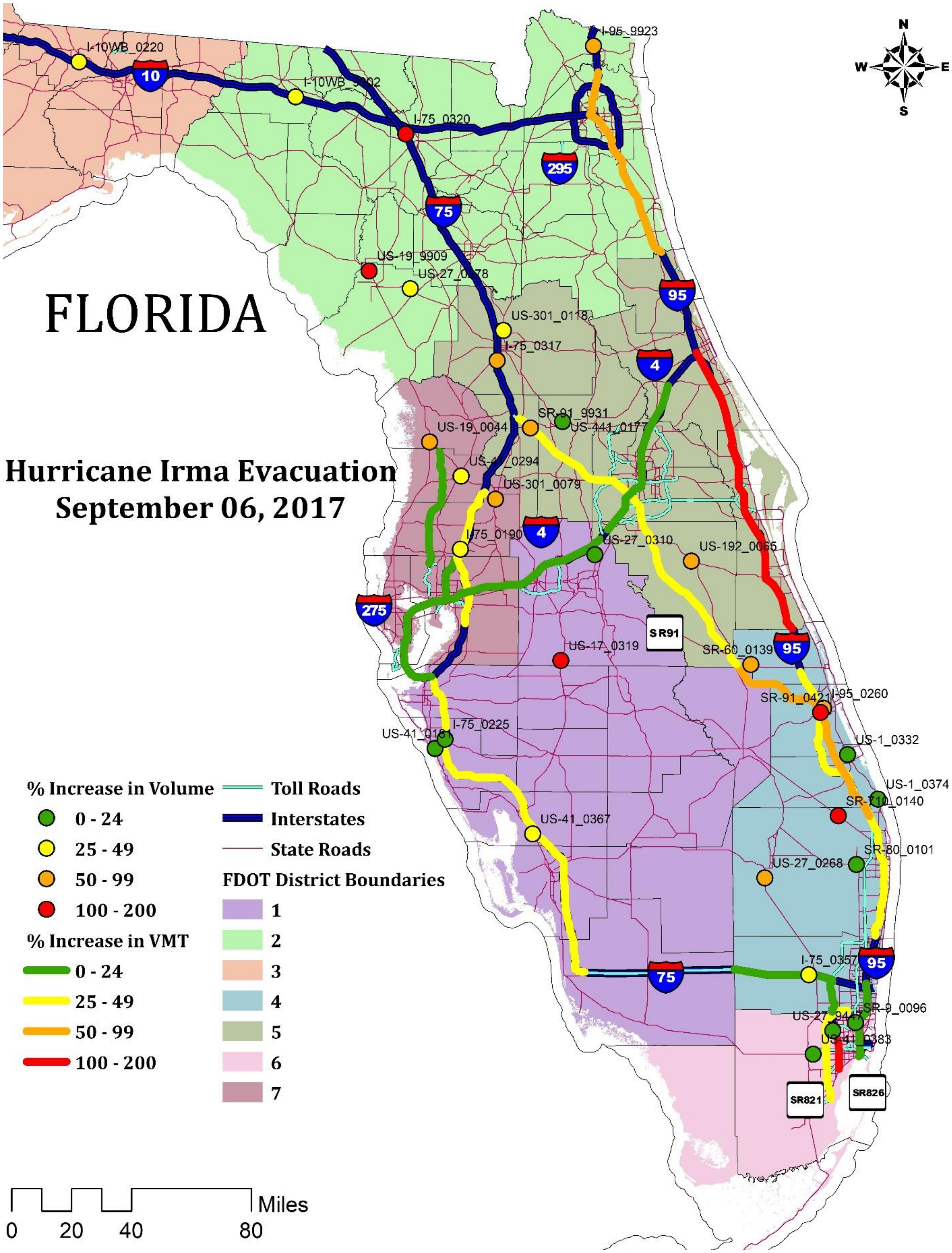


Figure 72 Hurricane Irma Evacuation – Roadway Performance – September 6, 2017

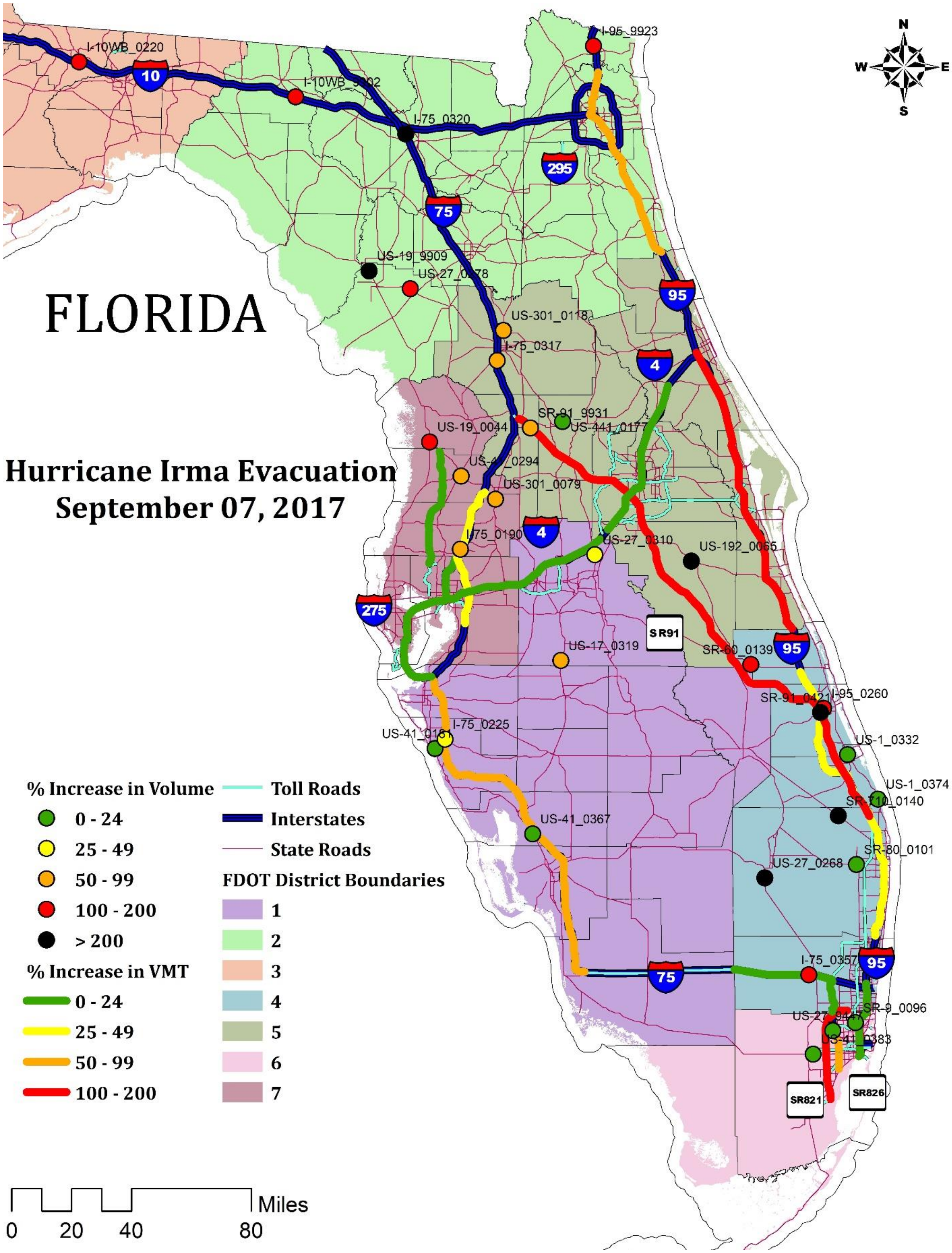


Figure 73 Hurricane Irma Evacuation – Roadway Performance – September 7, 2017

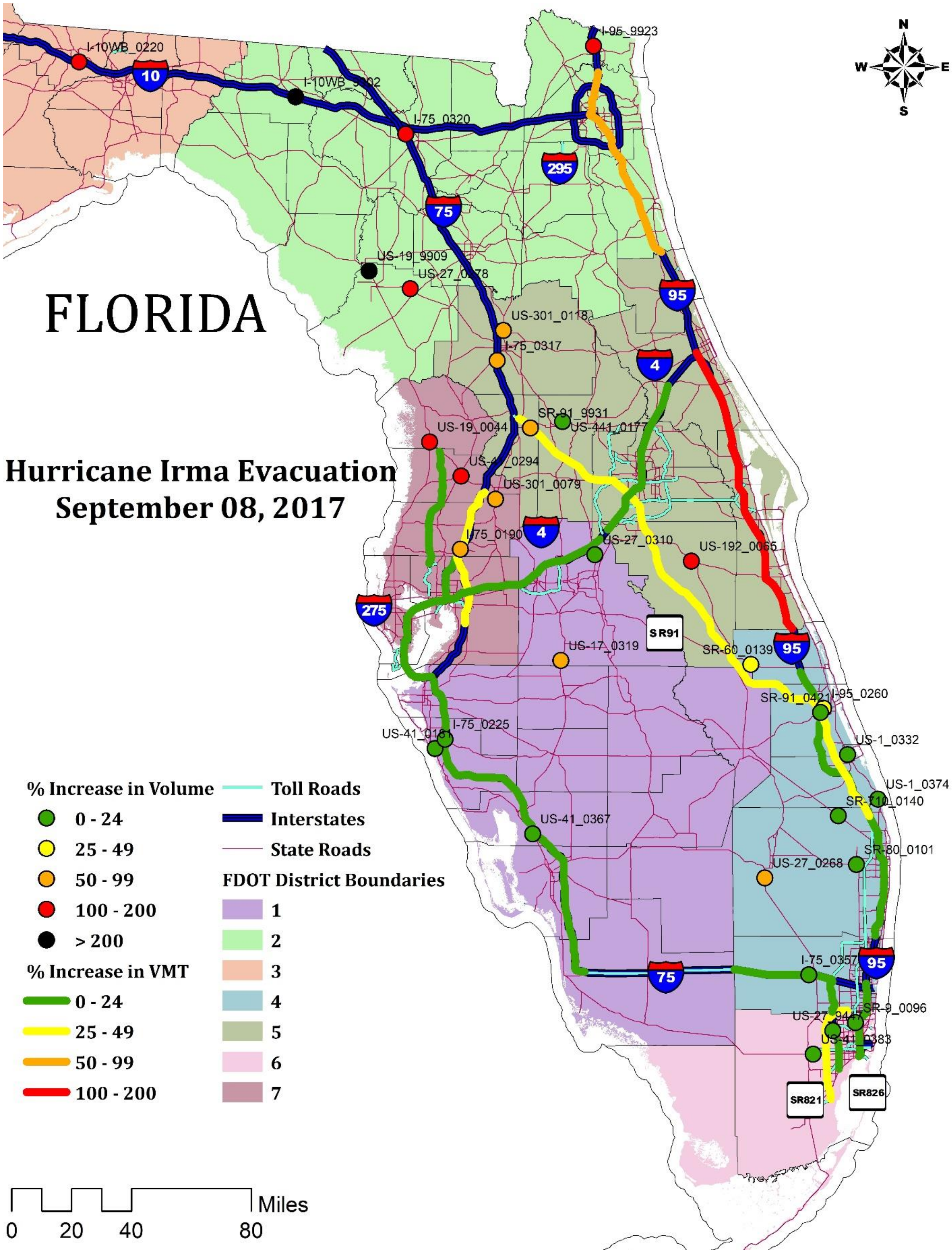


Figure 74 Hurricane Irma Evacuation – Roadway Performance – September 8, 2017

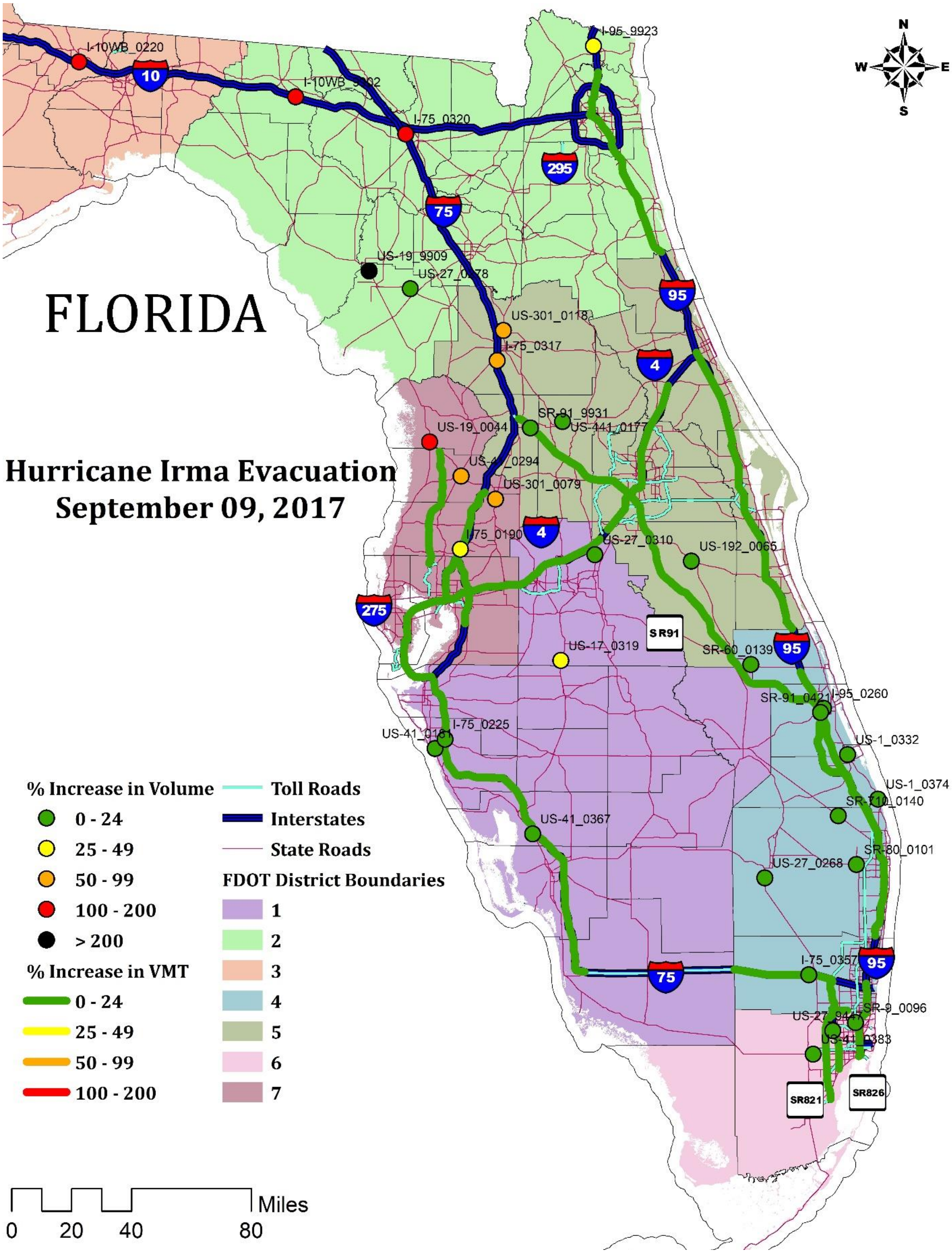


Figure 75 Hurricane Irma Evacuation – Roadway Performance – September 9, 2017

CENTER FOR TRANSPORTATION EQUITY, DECISIONS & DOLLARS

The **Center for Transportation, Equity, Decisions and Dollars (CTEDD)** is a USDOT University Transportation Center, leading **transportation policy research** that aids in **decision making** and **improves economic development** through **more efficient, and cost-effective use of existing transportation systems,** and offers **better access to jobs and opportunities.** We are leading a larger consortium of universities focused on **providing outreach** and **research to policy makers**, through **innovative methods** and **educating future leaders of the transportation field.**

UNIVERSITY OF TEXAS ARLINGTON

CAL POLY SAN LUIS OBISPO

Georgia Tech

USF UNIVERSITY OF SOUTH FLORIDA

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

C-TEDD@UTA.EDU | CTEDD.UTA.EDU | @UTACTEDD | @ C__TEDD | @ CENTER FOR TRANSPORTATION, EQUITY, DECISIONS AND DOLLARS | 817.272.5138