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Spatiotemporal Analysis of Highway Traffic Patterns in Hurricane Irma Evacuation

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Abstract

The State of Florida is significantly vulnerable to catastrophic hurricanes that cause widespread infrastructural damage and claim lives annually. In 2017, Hurricane Irma, a Category 4 hurricane, took on the entirety of Florida, causing the state's largest evacuation ever as 7 million residents fled the hurricane. Floridians fleeing the hurricane faced the unique challenge of where to go, since Irma made an unusual landfall from the south, enveloping the entire state, forcing evacuees to drive farther north, and creating traffic jams along Florida's evacuation routes that were worse than during any other hurricane in Florida's history. This study aimed to assess the spatiotemporal traffic impacts of Irma on Florida's major highways based on real-time traffic data before, during, and after the hurricane made landfall. First, we conducted a time-series-based analysis to evaluate the temporal evacuation patterns of this large-scale evacuation. Second, we developed a metric, namely the congestion index (CI), to assess the spatiotemporal evacuation patterns on I-95, I-75, I-10, I-4, and turnpike (SR-91) highways with a focus on both evacuation and returning traffic. Third, we employed a geographic information system-based analysis to visually illustrate the CI values of corresponding highway sections with respect to different dates and times. Findings clearly showed that imperfect forecasts and the uncertainty surrounding Irma's predicted path resulted in high levels of congestion and severe delays on Florida's major evacuation routes.

Every year, hurricanes in the United States devastate entire regions, cause widespread major infrastructural damage (e.g., roadway/bridge closures, power outages), and claim lives (*1*, *2*). Between 1980 and 2019, the National Oceanic and Atmospheric Administration (NOAA) estimated the damage associated with weather- and climate-related disasters totaled $1.75 trillion in the United States (*3*). The State of Florida, which is surrounded by subtropical waters from three sides because of its unique geography, is one of the southern states that is significantly vulnerable to hurricanes (*4*, *5*). Many Floridians have to evacuate to safer locations under mandatory or voluntary evacuation orders before these hurricanes hit. Major congestion and massive delays on the evacuation routes make the problem even more challenging for the residents of affected regions as they need to evacuate in a timely manner (*6*, *7*). For example, recent hurricanes such as Hermine (2016), Irma (2017), and Michael (2018) have clearly shown that evacuee demand and roadway capacities and characteristics significantly affect the efficiency and timeliness of overall evacuation operations.

In 2017, Hurricane Irma, a Category 4 hurricane, took on the entirety of Florida, causing the state's largest evacuation ever as 7 million residents fled the hurricane, costing $50 billion in damage (*8*). Such hurricanes usually hit the state from the east or west, allowing residents to flee north or south (*9*). However, Floridians fleeing Irma faced the unique challenge of where to go, since the hurricane made an unusual landfall from the south, enveloping the entire state and forcing evacuees to drive farther north, creating traffic jams along Florida's evacuation routes that were worse than during any other hurricane in Florida's history (*10*). Many people living in Miami actually evacuated to the west, based on the initial projected path of Irma; however, they were forced to go back

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when Irma turned to the west rather than hitting the Miami area. Many drove north along major evacuation routes such as I-95 and I-75 to flee the storm. However, traffic jams and fuel shortages slowed them down and thousands of motorists were gridlocked along these routes for hours; this increased the loss of life risk, especially among vulnerable roadway users such as seniors (*4*, *11*).

In literature, several studies have focused on evacuation patterns with a specific focus on hurricanes (*12–16*). However, over the years, the focus of evacuation studies has changed, mainly resulting from changes in the frequency, impact area, and the unpredictability of these extreme events that require evacuation (*17–20*). Please refer to Lindell et al. (*21*), Huang et al. (*22*), and Thompson et al. (*23*) for more information on evacuation studies. However, research assessing the spatiotemporal traffic impacts of hurricanes using real-time traffic data before, during, and after the hurricane hits is still limited.

Using data obtained from surveys is one of the most common approaches in hurricane evacuation studies. For example, Wolshon et al. conducted surveys in hurricane-prone states in the United States to evaluate current practices and policies for hurricane evacuation management (*24*). This included the application of intelligent transportation systems technologies as well as contraflow traffic operations. Murray-Tuite et al. used a panel survey to compare the evacuation behavior of Hurricanes Ivan and Katrina via statistical analyses (*25*). Their findings indicated that evacuations from both hurricanes involved the same number of vehicles. Wolshon et al. also analyzed the spatial and temporal impacts of Katrina in Southeast Louisiana from August 26 to August 28, 2005 (*26*). Their findings showed that the evacuation increased traffic volumes on Louisiana highways for a period of about 60 h. The highest traffic congestion was observed on Saturday 27 and Sunday 28 August, 2 days and 1 day, respectively, before landfall.

In addition to survey data, simulation models have been widely used in literature to evaluate hurricane evacuations. For example, a traffic simulation model, the TRansportation ANalysis and SIMulation System (TRANSIMS), was proposed by Wolshon et al. to investigate the traffic conditions under different hurricane events (*27*). Transportation Interface for Modeling Evacuations, a software developed for the Florida Department of Transportation (FDOT) and Florida Department of Emergency Management by CDM Smith, was used for evaluating the evacuations of vulnerable citizens such as aging populations in South Florida (*28*, *29*). Archibald and McNeil used real-time traffic data to investigate the evacuation patterns of Hurricane Irene (August 2011) in Delaware (*30*). This study revealed that many people evacuated from the beach areas of coastal Delaware to flee the hurricane and that the evacuation patterns were very similar to those on summer weekends. Recently, Marasco et al. used Google Maps' travel time estimates and power outage data to assess the evacuation behavior in Florida, Georgia, and South Carolina during Hurricane Irma (*31*).

Several studies have focused on the State of Florida because of its vulnerability to hurricanes. For instance, Sadri et al. applied a mixed logit model to identify the factors affecting the hurricane evacuations of Miami Beach residents in Florida via one of the six major bridges (*32*). The authors used survey data that included a hypothetical Category 4 hurricane scenario to develop the model. In another study, Zhu et al. measured the accessibility of evacuation destination sites to Floridians during the Hurricane Irma evacuation (*4*). To achieve this goal, they estimated the evacuation demand using the hurricane's track and wind radius. They defined the potential crowdedness index metric to compute the level of crowdedness for the roadway segments and the level of accessibility for each subcounty accordingly. The findings of this study revealed a high level of traffic congestion in the northbound direction of interstates I-75 and I-95 and identified the least accessible locations along the northbound I-95. However, Zhu et al. focused on a specific region, not Florida in its entirety, and investigated how the counties in that region were affected (*4*).

To the best of our knowledge, no previous study has used real-time traffic data to investigate the traffic impacts of a large-scale hurricane evacuation such as Hurricane Irma. According to the literature, an assessment of the spatiotemporal traffic patterns of the Irma-induced large-scale evacuation for the entire state, using real-time traffic data before, during, and after the hurricane, is lacking. This is the key contribution of this study. The objective was to provide a spatiotemporal assessment of the Hurricane Irma evacuation patterns focusing on both the evacuation and returning traffic using a time-series analysis and the development of a metric, namely the congestion index (CI). We conducted this assessment using real-life traffic data obtained for the major evacuation routes of Florida, specifically I-95, I-75, I-10, I-4, and turnpike (SR-91) highways during a daily interval of 6 h starting on Tuesday, September 5, through Friday, September 15, 2017. Note that Irma's landfall was on September 10, 2017. The proposed methodology and findings will be presented in detail in the following sections.

Methodology

This study provides a spatiotemporal assessment of evacuation patterns on Florida's major highways before,

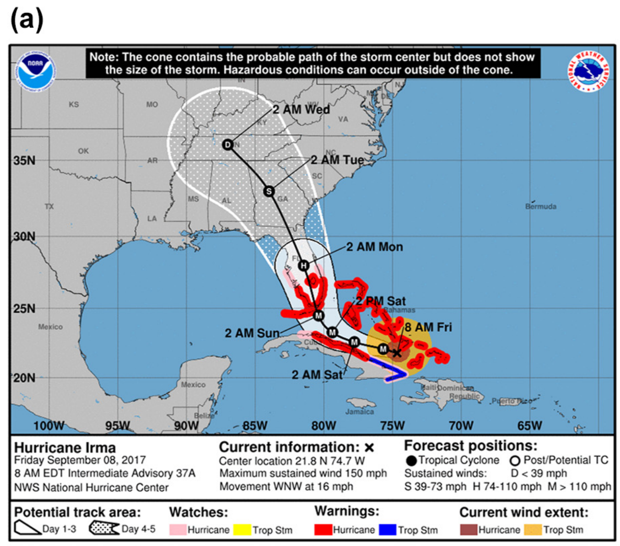

Figure 1. Hurricane Irma's track: (*a*) September 8, 2017 and (*b*) September 10, 2017 (*37*).
Note: DBZ = decibels of Z.

during, and after Hurricane Irma's landfall. Hurricane Irma, with winds of 185 mph, was the most powerful Atlantic Ocean hurricane ever recorded in U.S. history. Irma hit Florida as a Category 4 hurricane on the morning of September 10, 2017 (*33–35*). Approximately 6.8 million people were ordered to evacuate, which is the largest evacuation in the history of the State of Florida. The evacuation orders were issued in 54 of Florida's 67 counties. In 42 counties, mandatory evacuation orders were issued and the remaining 12 counties had voluntary evacuation orders (*34*, *36*). The unpredictability of the hurricane's path seriously challenged this evacuation, leaving many evacuees clueless-regarding where to go. Although evacuees were mobilized pretty quickly, those that traveled to the west coast were forced to go back as the hurricane path changed direction toward the west in a matter of hours. Such a quick mobilization of people caused extreme traffic congestion and delays throughout the state.

Figure 1, *a* and *b*, obtained from the National Hurricane Center and NOAA, illustrate Hurricane Irma's track at 8:00 a.m. on September 8, 2017, and September 10, 2017, respectively (*37*). Figure 2 presents the radar images and paths of Hurricane Irma over the State of Florida on September 10, 2017 (*38*). DBZ in this figure stands for decibel relative to Z (radar reflectivity factor) and the colors indicate the power of the returned energy to the radar (*39*). These figures clearly show the unpredictability of the hurricane's path. Although initial projections suggested that it would hit the Miami area, in just 2 days, Hurricane Irma's path shifted west.

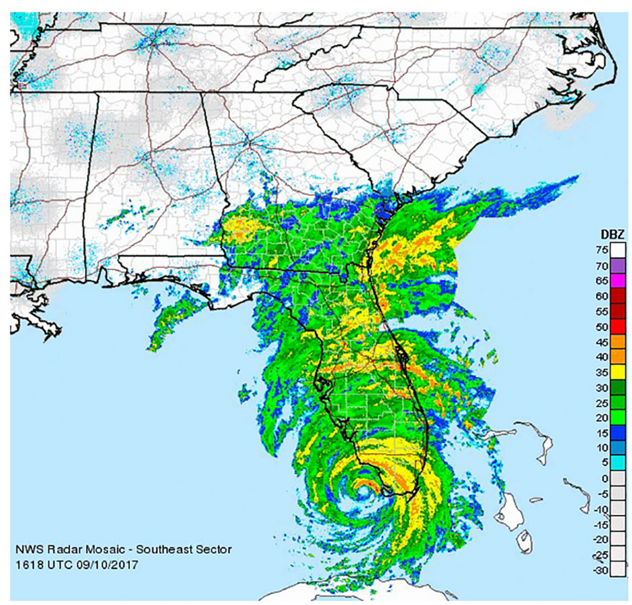

Figure 2. Hurricane Irma's path over the State of Florida (September 10, 2017) (*38*).
Note: DBZ = decibels of Z.

We considered both evacuation traffic (evacuation traffic before the hurricane made landfall for the period of September 5 to 10, 2017), and returning traffic (traffic resulting from the evacuees returning after the hurricane, between September 11 and 15, 2017). Real-time hourly traffic data recorded by FDOT's telemetered traffic monitoring sites (TTMS) were used in the proposed assessment (*40*). In total, there are 63 TTMS located on the specified highways. However, in this study, eight TTMS were strategically selected for further analysis based on their proximity to large cities such as Miami, Jacksonville, Orlando, and Tampa. Figure 3 illustrates Florida's highways along with the TTMS locations, and those that were selected for the assessment.

The overall approach consists of three steps. First, we conducted a time-series-based analysis to evaluate the temporal evacuation patterns of this large-scale evacuation. The results of this analysis are illustrated in Figure 4 for the eight selected TTMS (shown in Figure 3). We also present a comparative analysis for both the evacuation and returning traffic patterns at these selected TTMS locations.

Second, we developed a metric, CI, to assess the spatiotemporal evacuation patterns on I-95, I-75, I-10, I-4, and turnpike (SR-91) highways during a daily interval of 6 h starting on Tuesday, September 5, through Friday, September 15, 2017. This metric was defined to measure the level of congestion for each roadway section on the studied highways. A section here is defined as a specific segment of the roadway as determined by FDOT, whereas the CI for a roadway section is defined as follows (Equation 1):

$$CI = \frac{\text{Evacuation/Returning Traffic} - \text{Normal Daily Traffic}}{\text{Normal Daily Traffic}} \times 100 \quad (1)$$

Here, the CI is simply a metric of the percentage change in traffic. We basically compared the evacuation or returning traffic with normal daily traffic levels. For normal daily traffic, we used data for the same days in September 2018. It is worth mentioning that 2018 hourly traffic volumes constituted the most up-to-date dataset at the time of this study (*41*).

Third, a GIS-based analysis was employed to visually illustrate the CI values of corresponding highway sections with respect to different dates and times. Figures 5 and 6 illustrate the CI values of the evacuation and returning traffic patterns on I-95, I-75, I-10, I-4, and turnpike (SR-91) highways in the State of Florida. We present these results using GIS-based illustrative maps for two time periods: 3:00 to 6:00 p.m. and 6:00 to 9:00 p.m. Negative CI values indicate that there is no traffic congestion on that specific highway segment. Conversely, positive percentages show the level of congestion and how much extra traffic was on the highways in comparison to a normal day without evacuation traffic. Note that this approach was used for both evacuation and returning traffic.

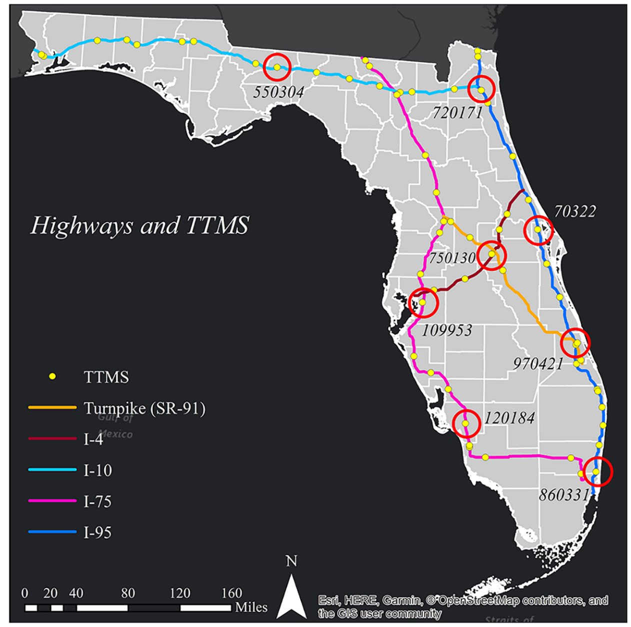

Figure 3. Highways and telemetered traffic monitoring sites (TTMS) locations.

Results

Time-Series-Based Analysis

Findings of the time-series-based analysis for selected highways are shown in Figure 4 for the eight selected TTMS located on the highways. Note that the temporal traffic patterns are presented for both evacuation and returning traffic, and for northbound (NB), southbound (SB), westbound (WB), and eastbound (EB) directions.

We will first focus on the evacuation traffic temporal patterns. After the evacuation orders were issued on September 6 and September 7, 2017, we observed a spike in traffic volumes at all TTMS locations, which seemed to dissipate a few days before the hurricane made landfall. These spikes happened in NB and WB directions for all TTMS, and in an EB direction for TTM 750130 only. This indicated that people were mostly traveling to the north and west to flee the hurricane. The maps in Figure 4 revealed similar traffic patterns for all the selected TTMS on September 10, 2017. This was the day of the landfall and no traffic was observed in any direction. This was anticipated as either people had already evacuated or were sheltering in place while the hurricane approached land. TTMS 860331 on I-95, which is located near Miami, had the highest traffic volumes for both evacuation and returning traffic in comparison to the other TTMS (Figure 4*a*). After landfall, the traffic volumes gradually started increasing in all NB and WB directions

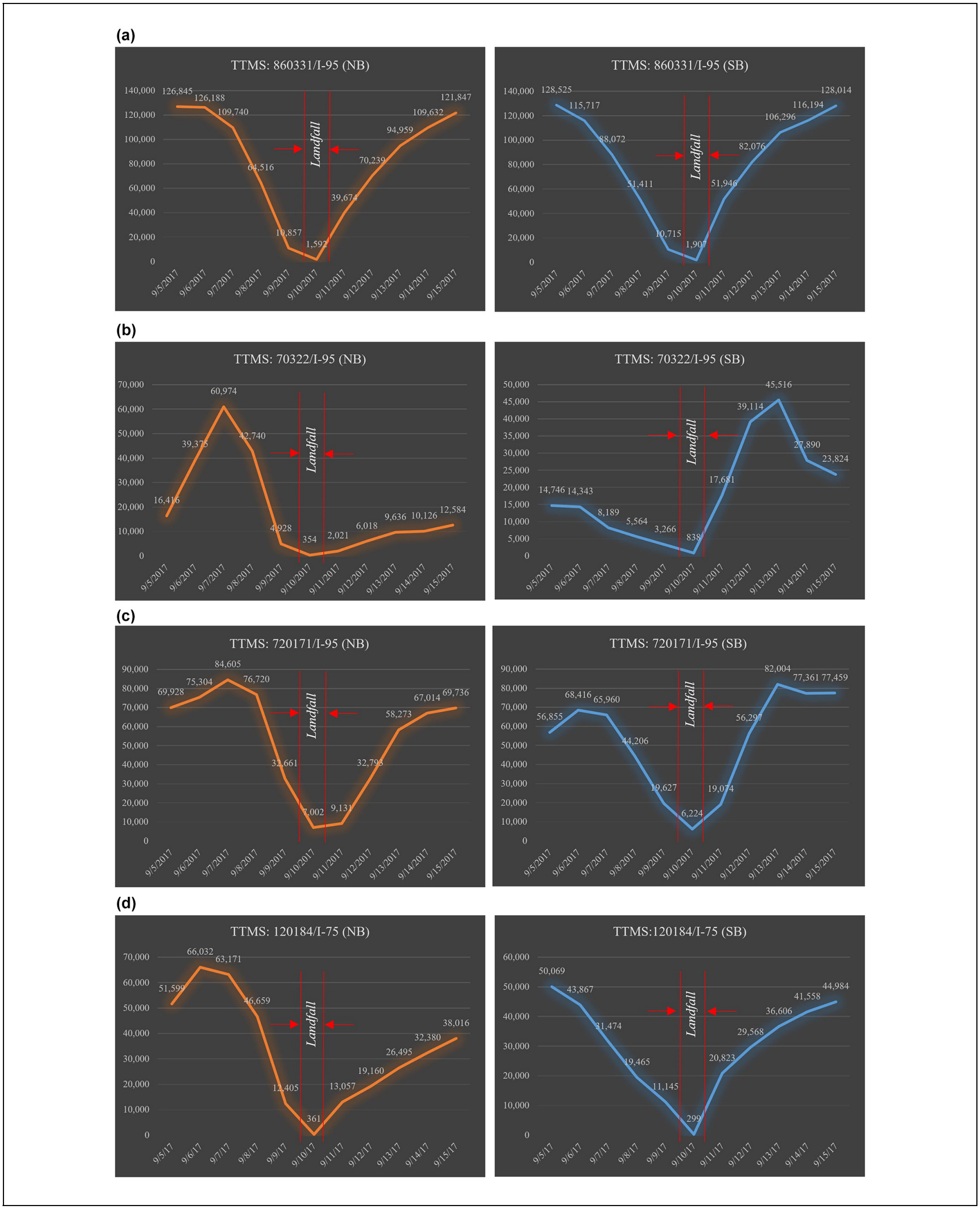

Figure 4. Time-series-based analysis for the selected telemetered traffic monitoring sites (TTMS) (daily traffic volumes): (*a*) TTMS 860331, (*b*) TTMS 70322, (*c*) TTMS 720171, (*d*) TTMS 120184, (*e*) TTMS 109953, (*f*) TTMS 550304, (*g*) TTMS 750130, and (*h*) TTMS 970421.
Note: NB = northbound; SB = southbound; WB = westbound; EB = eastbound.

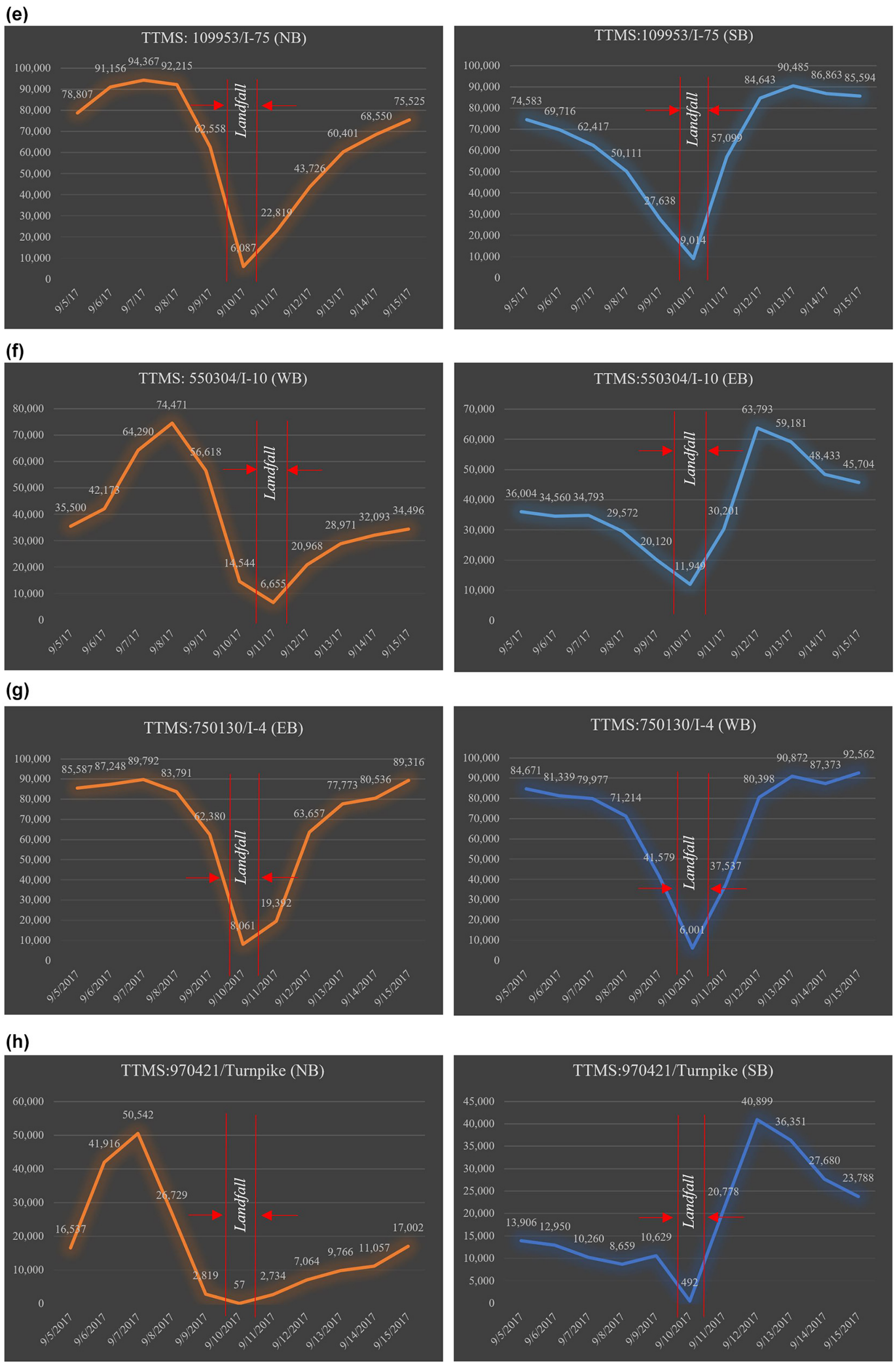

Figure 4. (*continued*)

and in an EB direction on TTMS 750130 only. This was also expected since regular traffic conditions resumed once the hurricane threat was gone. SB and EB directions, conversely, revealed a downward traffic trend before the hurricane made landfall. This assessment also held for the WB direction on TTMS 750130, which is located on I-4.

When we studied the returning traffic patterns, I-95, I-75, and I-4 had the highest traffic volumes at the following locations: TTMS 860331 (for both NB and SB directions), TTMS 109953 (SB) on I-75, and TTMS 750130 (WB) on I-4. More specifically, TTMS 860331 and TTMS 750130 had the highest returning traffic on September 15, 5 days after the hurricane made landfall (Figure 4, *a* and *g*). On TTMS 109953, however, the highest returning traffic was observed on September 13, 2017 (Figure 4*e*). Another interesting finding was that we observed significant traffic volume differences between evacuation and returning traffic at the following locations: NB–SB and WB–EB directions for TTMS 70322 on I-95, TTMS 550304 on I-10, and TTMS 970421 on the turnpike (Figure 4, *b*, *f*, and *h*). This may have been because of the drastically increased traffic volumes from the evacuation, which were much higher than the average daily traffic.

Impact of Evacuation Traffic

To analyze the spatiotemporal traffic impacts of Hurricane Irma, CI, was used to measure the congestion level of different roadway sections. Using GIS-based techniques, these CI values were illustrated on maps to show the level of traffic congestion on the highway sections for both evacuation and returning traffic. For this purpose, we focused on two time intervals every day from Tuesday, September 5, through Friday, September 15, 2017: 3:00 to 6:00 p.m. and 6:00 to 9:00 p.m. We will now present our findings for the selected highways.

Figure 5, *a* and *b*, show the CI-based traffic levels between 3:00 and 9:00 p.m. on September 5, and September 6, 2017, respectively. On these figures, we observed that the roadway sections shown experienced higher traffic volume than usual. On September 5, the highest traffic level was observed between 6:00 and 9:00 p.m., where the traffic was up to 75% higher than that of an average day. Similar patterns were seen on September 6. The highest percentage changes in congestion on this day were in the NB direction of I-95 and I-75 as well as the northwest direction on SR-91. We observed a 350% increase in traffic volumes between 6:00 and 9:00 p.m. compared with an average day. This clearly indicated that people started evacuating toward safety in a northly direction. Figure 5*c* presents similar patterns on September 7, and all the studied roadway sections except I-4 were congested with traffic volumes that were considerably higher than those of a normal day. We also started to see substantial congestion on I-10, which had not happened on the previous days. The highest levels of evacuation traffic were still observed between 6:00 and 9:00 p.m.

Figure 5, *d* and *e*, however, revealed different patterns for September 8 and 9 compared with previous days. All highways except I-10 are shown as green, which indicates that these routes were not experiencing congestion. However, I-10 was still congested. This indicated that some of the Floridians fleeing north had reached the I-10 and preferred to travel west to flee the hurricane rather than going further north. On September 9, 1 day before Hurricane Irma made landfall, evacuation traffic on some sections of I-10 was 200% higher than typical daily traffic. Between 6:00 and 9:00 p.m., the CI value was approximately 350%. On the day of landfall (September 10, 2017), there was no congestion on any of the studied highways, as seen in Figure 5*f*. This indicated that many Floridians had already evacuated before the hurricane made landfall and others were sheltering in place, given the order of the governor.

To sum up, on September 6, and September 7, 2017, the NB lanes of I-95 and I-75 had the highest levels of evacuation traffic (up to 350% greater than regular traffic levels). I-10 started to experience more traffic on the WB lanes when evacuees reached the interstate on September 8. Compared with I-95 and I-75, I-10 started experiencing evacuation traffic considerably later, as it took a couple of days for evacuees to reach I-10 near Jacksonville. Therefore, I-10 had the highest levels of congestion on September 8, and September 9. Furthermore, the northeast direction of I-4 had almost no traffic congestion before the hurricane made landfall. Comparing the time-series analysis (Figure 4) and the levels of congestion calculated using the CI values (Figure 5), we can also conclude that higher evacuation traffic volume did not necessarily indicate traffic congestion. Some highway sections such as southern parts of I-95 (TTMS 860331) were sufficient to handle the evacuation traffic and therefore did not experience congestion and delays (Figure 5). Conversely, Figure 4 shows that TTMS 860331, which is the closest location to Miami, had the highest number of vehicles of all TTMS for the NB direction.

Impact of Returning Traffic

We also studied the impact of returning traffic from Monday, September 11 through Friday, September 15, 2017 focusing on the same two time intervals: 3:00 to 6:00 p.m. and 6:00 to 9:00 p.m. On September 11, 1 day after Hurricane Irma made landfall, we observed that

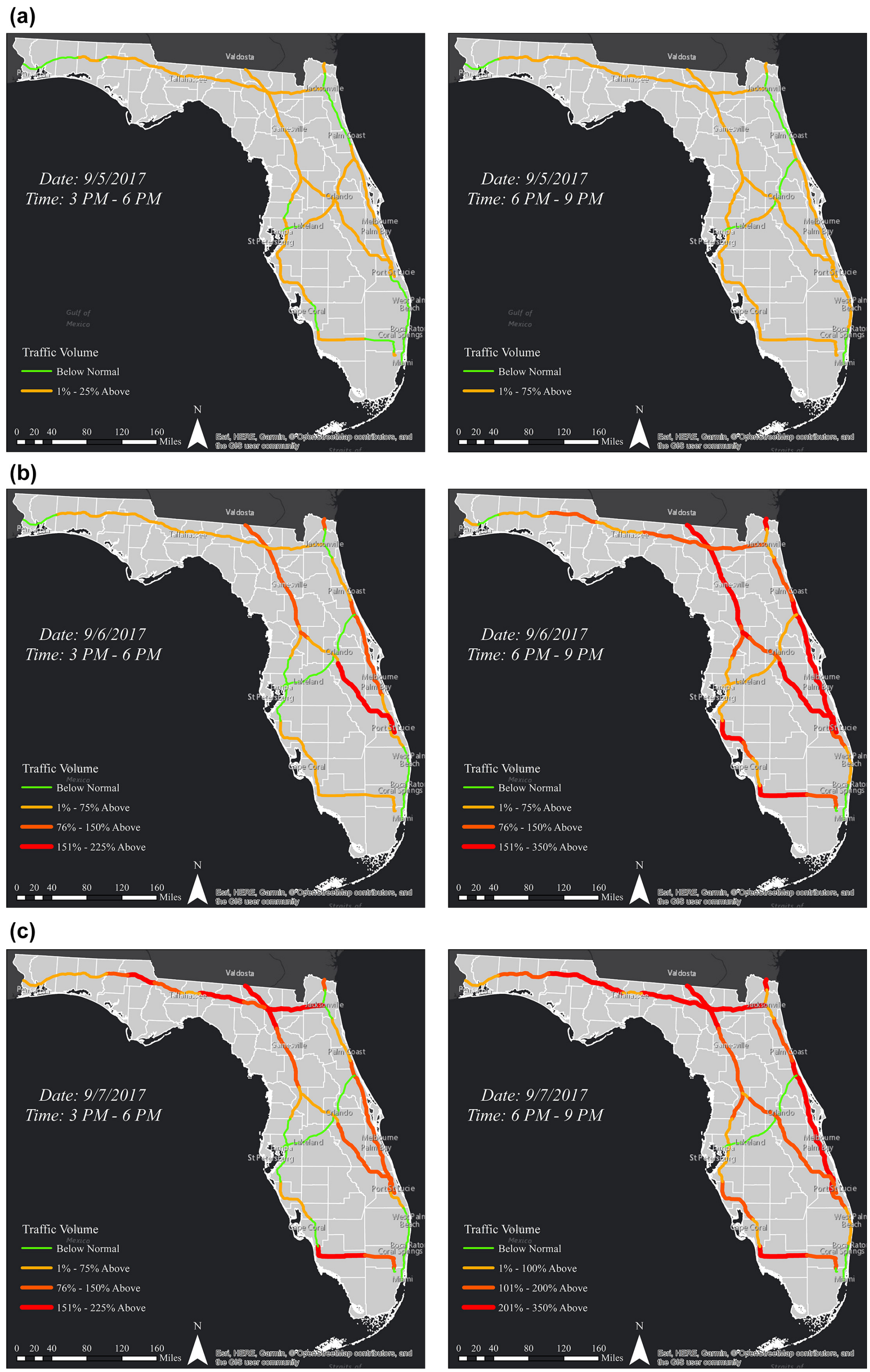

Figure 5. Impact of evacuation traffic between 3:00 and 9:00 p.m.: (*a*) September 5, (*b*) September 6, (*c*) September 7, (*d*) September 8, (*e*) September 9, and (*f*) September 10, 2017.

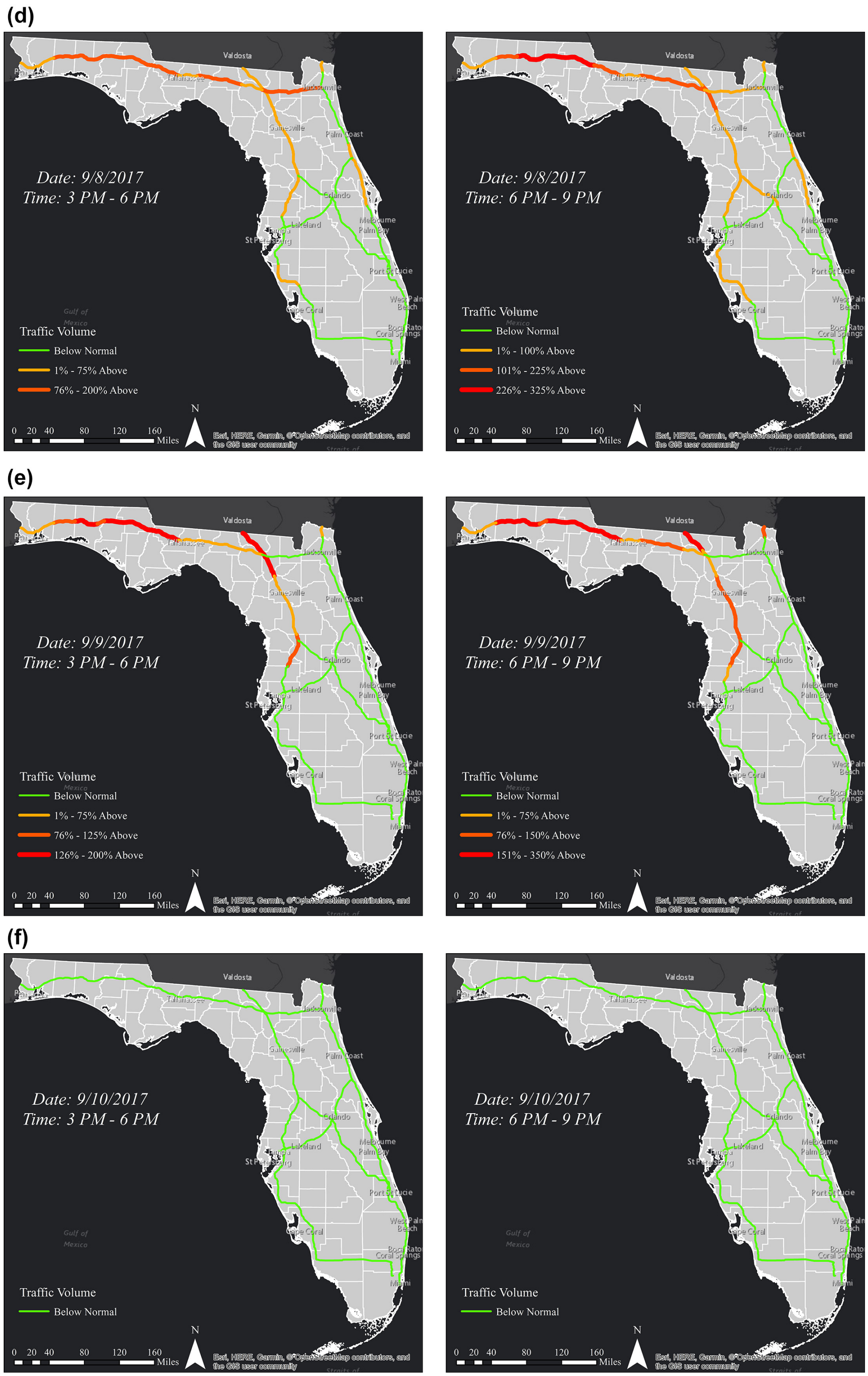

Figure 5. (*continued*)

many sections of the studied highways were congested, as seen from Figure 6*a*. More specifically, the EB lanes of I-10 had the highest level of congestion, which was up to 500% from 6:00 to 9:00 p.m. Also, the SB direction of I-95 and I-75 had a 150% and 300% increase in traffic volumes, respectively. These increases are understandable since evacuees fleeing north and northwest started returning right after the hurricane left Florida. Figure 6*b* shows similar patterns for September 12, 2017. CI values for the EB direction on I-10 reached 550%, whereas the SB lanes of I-75 and I-95 had CI values of up to 400% and 250%, respectively.

On September 13, 2017, 3 days after the hurricane made landfall, the level of congestion decreased on all the roadway sections, as seen from Figure 6*c*. Some heavy traffic was still evident on EB I-10 and the SB lanes on I-75 in the north. This indicated that there were still evacuees trying to return home. Figure 6*d* reveals a similar pattern, with some sections still experiencing traffic on I-10 and I-75. On September 15, 2017, the lowest levels of traffic on the studied highways after Irma made landfall were observed (Figure 6*e*). The highest congestion levels, which were up to 65%, were observed on the SB lanes of I-95 and I-75, and the EB lanes of I-10. It is important to note that I-4 did not experience congestion after landfall.

Conclusions and Future Work

This study aimed to assess the spatiotemporal traffic impacts of Irma on Florida's major highways based on real-time traffic data before, during, and after the hurricane made landfall. First, we conducted a time-series-based analysis to evaluate the temporal patterns of this large-scale evacuation. Second, we developed a metric, CI, to assess spatiotemporal evacuation patterns on I-95, I-75, I-10, I-4, and turnpike (SR-91) highways with a focus on both evacuation and returning traffic. Third, we employed a GIS-based analysis to visually illustrate the CI values of corresponding highway sections with respect to different dates and times.

The findings clearly showed that imperfect forecasts and the uncertainty surrounding Irma's predicted path resulted in high levels of congestion and severe delays on Florida's major evacuation routes. On September 6 and September 7, 2017, the NB lanes of I-95 and I-75 had the highest levels of evacuation traffic (up to 350%). I-10 started to experience more traffic on the WB lanes when evacuees reached the interstate on September 8. Compared with I-95 and I-75, I-10 started experiencing evacuation traffic considerably later as it took a couple of days for evacuees to reach I-10 near Jacksonville. Therefore, I-10 had the highest levels of congestion on September 8 and 9, 2017. Furthermore, the northeast direction of I-4 had almost no traffic congestion before the hurricane made landfall. On September 11, 1 day after Hurricane Irma made landfall, we observed that many sections of the studied highways were congested. More specifically, the EB lanes of I-10 had the highest level of congestion compared with the others, which was up to 500% from 6:00 to 9:00 p.m. The SB direction of I-95 and I-75 had a 150% and 300% increase in traffic volumes. These are understandable since evacuees fleeing north and northwest started returning immediately after the hurricane left Florida. Similar patterns were observed until September 15, when the returning traffic was almost over. It is important to note that I-4 was not congested during either evacuation or returning traffic, which clearly showed that it was not utilized sufficiently.

It is critical to accurately model emergency evacuations, focusing on the wide-ranging effects of evacuation assumptions (including, for example, the starting time, passengers per vehicle, background traffic, inbound/outbound and internal trips, and shadow evacuations) and traffic conditions (delays and queues). This research could serve as a first step in achieving this goal. For a state like Florida, where populations that live independently and in urban areas comprise a high percentage of the total population, dynamic- and static assignment-based models could be used to evaluate the time-varying effects of traffic volume, delays, and queues on evacuations. The results presented in this paper could inform these simulation models significantly. From an evacuation traffic control perspective, this type of analysis would be especially appropriate for slow onset disasters such as Hurricane Irma, for which emergency officials can decide on an advanced notice and staged evacuation based on the spatial distribution of populations, transportation network conditions, and disaster characteristics. This could also be included as a vital decision component in comprehensive evacuation plans.

To fully support emergency evacuation plans and policies, new hypothetical scenarios could be developed based on the findings of this study. This should be achieved by changing the scenario parameters such as the demand loading time (the amount of time available for the evacuation), and the departure window (the time the evacuation starts—different hours during the day or day versus night). This type of study could be extended to include vulnerable populations including seniors, mobile home residents, and seasonal populations (such as people who travel with recreational vehicles). However, the first step is to understand evacuation behaviors and performance through a spatiotemporal assessment based on real-life data, as presented in this paper.

Studying the transportation-based accessibility of evacuees, particularly those living in vulnerable coastal areas and those that need special assistance would be a worthwhile direction for future research. For large-scale

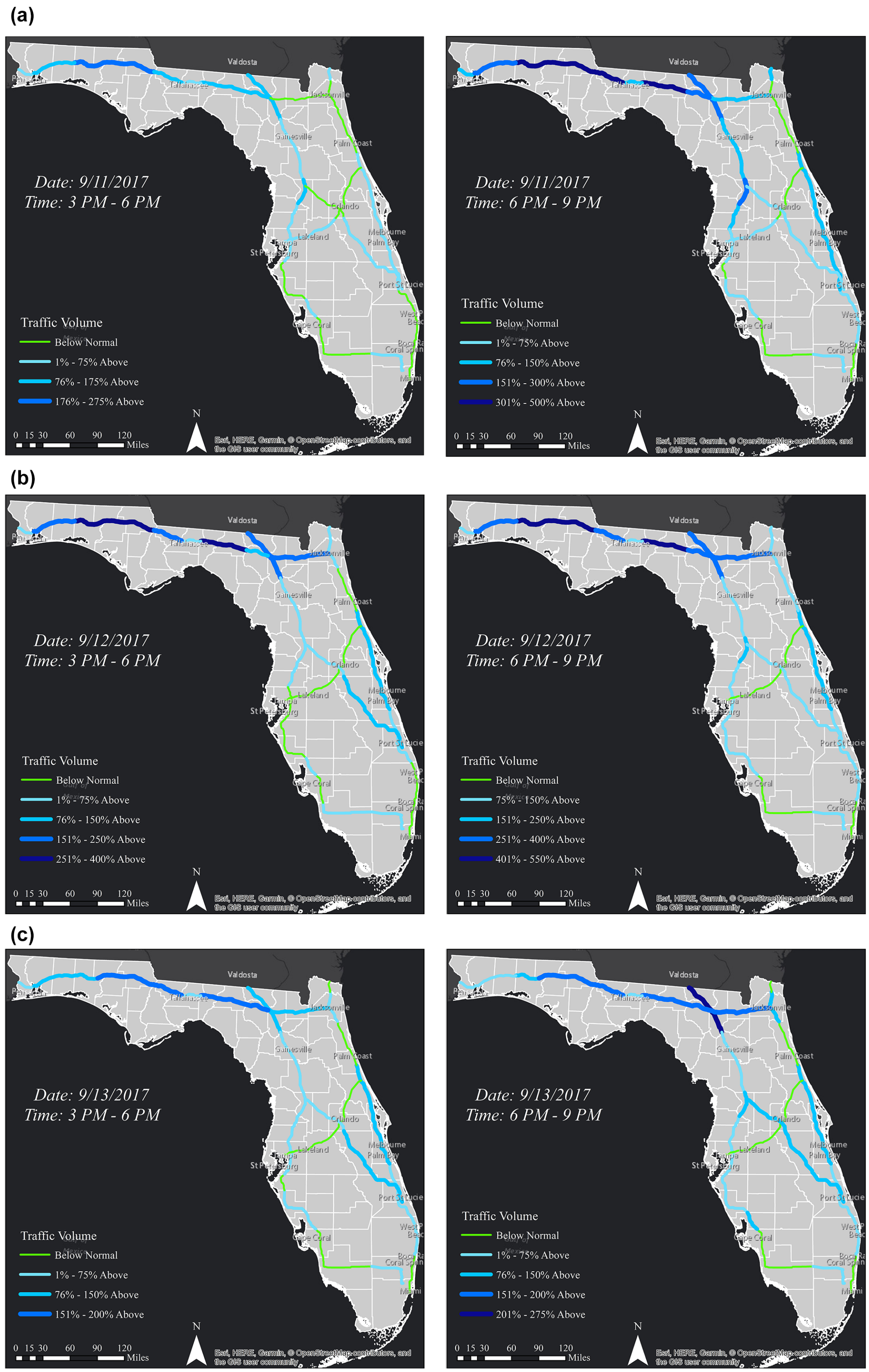

Figure 6. Impact of returning traffic between 3:00 and 9:00 p.m.: (*a*) September 11, (*b*) September 12, (*c*) September 13, (*d*) September 14, and (e) September 15, 2017.

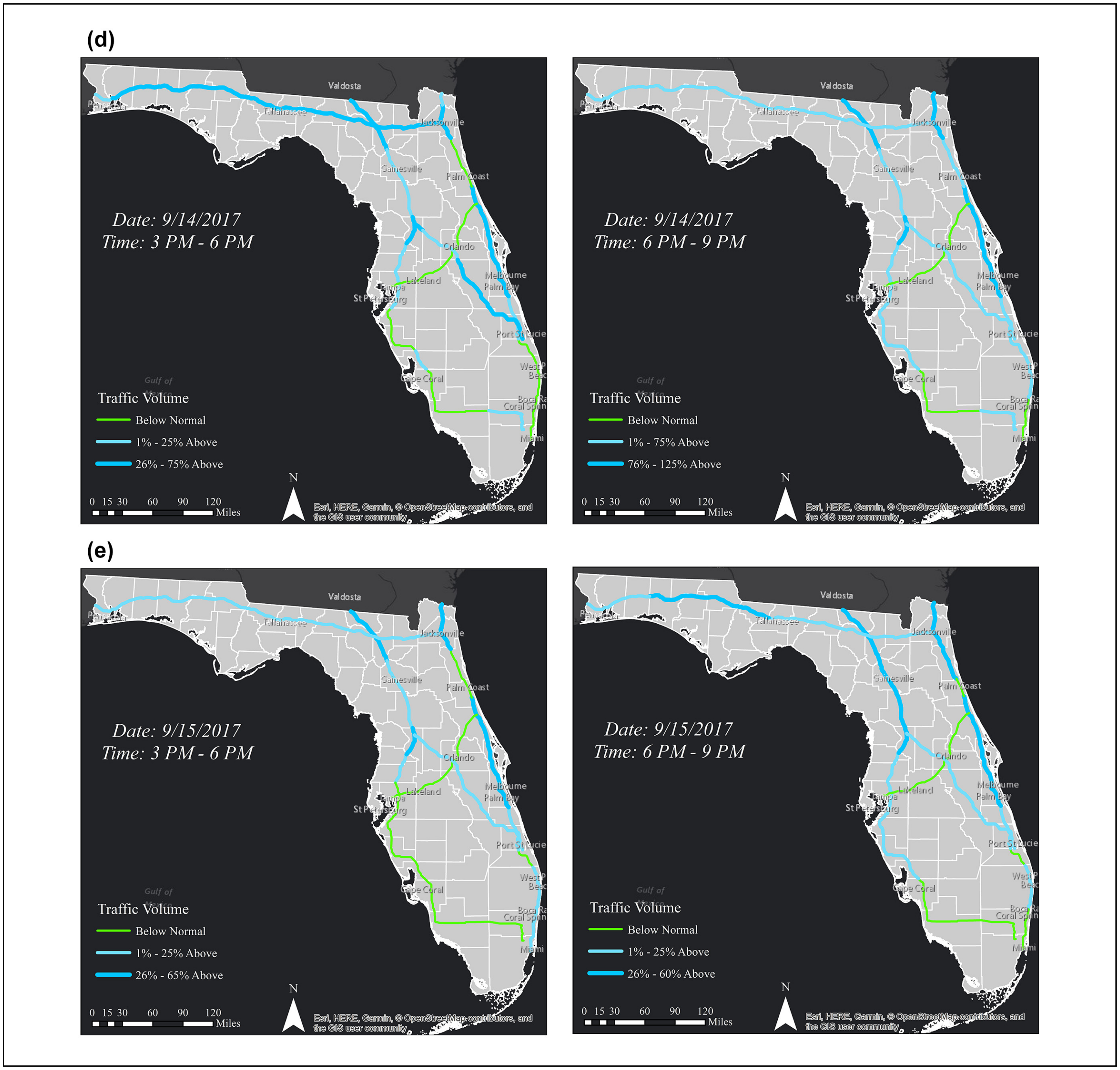

Figure 6. (*continued*)

hurricanes, storm surge modeling could be integrated with massive evacuation modeling by considering potential hurricane tracks bounded by the hurricane cone. Modeling such integrated simulations could provide the information people in hurricane-prone areas need to make the decision to evacuate or not before the mandatory evacuation order is given, potentially avoiding traffic congestion.

The approach used in this paper could be extended to other disasters and locations given data availability. Qualitatively, however, the effectiveness of the methodology in a particular location for a given disaster could be affected by the following critical variables: (a) type and duration of the disaster, (b) handling of the evacuation operations by the government organizations, (c) cultural traditions, (d) spatial characteristics, and (e) state of the evacuation routes and transportation infrastructure. An evaluation of the efficiency of the emergency evacuation operations would be an interesting area for future work.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: M. Ghorbanzadeh, E. E. Ozguven; data collection: M. Ghorbanzadeh, E. E. Ozguven; analysis and interpretation of results: M. Ghorbanzadeh, S. Burns, L. Vijayan, E. E. Ozguven, W. Huang; draft manuscript preparation: M. Ghorbanzadeh, E. E. Ozguven, W. Huang. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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