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ABSTRACT

This study analyzes spatio-temporal evacuation traffic patterns based on traffic data collected during Hurricanes Irene and Sandy in New Jersey. The temporal analysis shows that the total number of evacuees in Sandy was less than 30 percent of those in Irene. This is possibly due to the late-summer season, differences in background traffic, as well as so called “crying wolf” effect. However, similar to the evacuation departure behavior during Hurricane Irene, people who evacuated during Hurricane Sandy responded very quickly to the mandatory evacuation order. Traffic volumes increased significantly when the official mandatory evacuation order was issued. The spatial analysis shows that the most significant evacuation movements were located in the southern portion of the State, closest to the shore areas. The vast majority of this evacuation traffic moved westward, instead of traveling northbound along the shore areas made vulnerable by the storm. These evacuation traffic patterns are similar to the typical outbound traffic patterns seen in the shore areas at the end of a summer weekend but with departure times that were three to four hours earlier than usual. Moreover, in examining the evacuation traffic patterns and collected travel time data, this study was also able to identify traffic bottlenecks that arose during Hurricane Irene and Sandy evacuations. The results show that the bottlenecks were generally located at merging areas in the vicinity of on/off ramps or interchanges. These empirical observations can be used to improve real-world emergency response operations and evacuation models.
INTRODUCTION

Hurricanes Irene (2011) and Sandy (2012) crossed and affected much of the East Coast of the United States causing severe damage particularly in New Jersey and New York. Storm surge flooded roadways, tunnels and transit lines; high speed winds took down trees and power lines, and caused significant damage and disruptions during the post-hurricane days. Despite the adverse conditions, thanks to the proactive hurricane evacuation plans (1) developed by emergency management authorities as well as relatively early evacuation order declarations (2), both Irene and Sandy evacuation processes went smoothly with little traffic disturbance in New Jersey (3-4).

The main objective of this study is to quantify and illustrate the evacuation traffic patterns during Hurricanes Irene and Sandy in New Jersey, using observed traffic and demand data. Such patterns indicate how people respond to a mandatory evacuation order and the subsequent traffic congestion and bottlenecks that arise along the evacuation routes. The major highlights of this study are presented below.

First, this study utilized real-world traffic data obtained from different agencies instead of traditional post-hurricane survey data used in previous studies (5-10). The data used in this study included hourly traffic volumes from toll plazas, traffic detectors and Weight-in-Motion (WIM) stations at various geographically diverse locations, as well as historical travel time data collected by a commercial traffic data provider.

Second, the rich data enabled us to discuss more practical and also interesting issues. For example the possible changes of temporal and spatial patterns of evacuation traffic between two consecutive hurricanes based on statewide traffic volume data; the comparison of travellers’ evacuation decisions to regular daily departure decisions based on historical and evacuation traffic data; the bottlenecks during hurricane evacuations based on historical and evacuation travel time data.

Third, the summarized empirical evacuation traffic patterns in this study can be used as a reference to better mitigate hurricanes in the future, especially for Mid-Atlantic states along the Atlantic Coast that receive less attention compared with hurricane prone states such as Southeastern Atlantic or Gulf Coast states (11-14). In addition, with the increasing number of sensors being deployed on our roadways, this study also illustrates how to use empirical data sources as a useful feedback to evacuation planning.

BACKGROUND

New Jersey is a state in the Northeastern and Middle Atlantic regions of the United States. As a state with coastline along the Atlantic coast, storm threats have always been a problem. When storms are approaching, tides are often impacted by the storm surge. Moreover, much of this area is only slightly above sea level. During periods of heavy rain many low-lying areas and roadways could be flooded temporarily.

Hurricane Irene made landfall in NJ on August 28, 2011, and led to historic inland flooding after that month’s record rainfalls (15). The Irene-induced intense rainfalls caused significant inland flooding in NJ due to the saturated ground. Sandy made landfall on October 29, 2012, and because of its tremendous size and wind speed, drove a catastrophic storm surge, downed lots of trees and caused power outage. About 5 million residences lost electrical power across this region, with power outages commonly lasting for several weeks (16). A summary of Irene and
Sandy landfalls in NJ can be seen in Table 1. The timelines and paths of Irene and Sandy can be seen in FIGURE 1.

<table>
<thead>
<tr>
<th></th>
<th>Irene</th>
<th>Sandy</th>
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<tbody>
<tr>
<td>Landfall Time</td>
<td>5:35 a.m. EDT 28 August 2011</td>
<td>7:30 p.m. EDT 29 October 2012</td>
</tr>
<tr>
<td>Landfall Location</td>
<td>Little Egg Inlet, NJ</td>
<td>Brigantine, NJ</td>
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<tr>
<td>Category</td>
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<tr>
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<td>Maximum Wind Speed (mph)</td>
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<tr>
<td>Maximum Precipitation (inch)</td>
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<tr>
<td>Maximum Storm Surge (ft)</td>
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<tr>
<td>Casualty</td>
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<td>12</td>
</tr>
<tr>
<td>Total Damage in U.S. (billion)</td>
<td>15.8</td>
<td>50</td>
</tr>
</tbody>
</table>

Source: 15–16
Hurricane Irene

Sat, Aug 20
- Tropical Storm Irene formed in east of Leeward Islands.

Mon, Aug 22
- Irene became a Category 2 hurricane, and affected significantly in Puerto Rico.

Wed, Aug 24
- Irene strengthened to a major Category 3 hurricane as it heads towards the east coast of North America.

Thu, Aug 25
- In the morning, NJ Governor Chris Christie declared state of emergency.
- In the afternoon, mandatory evacuation for the barrier islands in Cape May County became effective.

Fri, Aug 26
- In the morning, mandatory evacuation of Atlantic County and Cape May County became effective.

Sun, Aug 29
- 5:35 AM EDT. Irene made landfall in Little Egg Inlet, NJ.

Hurricane Sandy

Mon, Oct 22
- Tropical wave Irene formed in the western Caribbean Sea.

Wed, Oct 24
- Sandy became a hurricane, and made landfall near Kingston, Jamaica.

Thu, Oct 25
- Sandy hit Cuba as a Category 3 hurricane.

Fri, Oct 26
- Sandy moved through the Bahamas as a Category 1 hurricane.
- Voluntary evacuation order of Cape May County became effective.

Sat, Oct 27.
- In the morning, NJ Governor Chris Christie declared state of emergency, and issued mandatory evacuation order for all barrier islands in NJ (from Sandy Hook down to Cape May). Residents and visitors were asked to evacuate by 4:00 PM EDT on Sun, Oct 28.

Mon, Oct 29
- 7:30 PM EDT. Sandy made landfall in Brigantine, very near Atlantic City, NJ.

FIGURE 1 Hurricane Irene evacuation and highway operations in NJ (Sources:15-18)
This study utilized real-world traffic and demand data obtained from different agencies (see Table 2). The data included hourly traffic volumes from toll plaza counts, Traffic Volume Station (TVS) and Weight-in-Motion (WIM) stations at various geographically diverse locations, as well as historical travel time data collected by a traffic service provider. Compared with post-hurricane surveys, the observed traffic data offer more realistic results, and avoid the general “problem of recall” frequently encountered in social science surveys.

### Table 2 Data description

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Purpose</th>
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<tbody>
<tr>
<td>Traffic volume</td>
<td>Highway toll plazas</td>
<td>Evacuation departure curves</td>
</tr>
<tr>
<td></td>
<td>Weight-in-Motion (WIM) stations</td>
<td>Evacuation traffic patterns</td>
</tr>
<tr>
<td></td>
<td>Traffic Volume Station (TVS)</td>
<td>Evacuation safety margin</td>
</tr>
<tr>
<td>Travel time</td>
<td>Traffic service provider</td>
<td>Evacuation bottlenecks</td>
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</table>

The toll plaza data were extracted from the electronic toll collection (ETC) database provided by New Jersey Turnpike Authority and Atlantic City Expressway. ETC database includes individual vehicle records at each toll plaza with the corresponding vehicle information such as entry date and time, vehicle class, payment type (i.e. cash or EZ-pass), number of axles. In order to extract hourly toll plaza volume, a computer program is coded in C programming language for parsing the dataset (one month of data are approximately 1GB in text file format). Each vehicle record is sorted based on toll plaza, date and time.

The TVS and WIM data were extracted from traffic monitoring program by New Jersey Department of Transportation (NJDOT). TVS and WIM database includes traffic volume, classification and speed using loop detectors.

Travel time data were from commercial traffic data provider, who provides a variety of mobile applications and internet services to transportation applications. This company provides historical and real-time traffic information, traffic forecasts and travel times. The data used in this study was collected from a corridor monitoring site which covers the major highways and arterials in New Jersey.

### EVACUATION TRAFFIC PATTERNS

In the first part of this section, we select Cape May County, the southernmost county in New Jersey (see FIGURE 1), as a representative sample of vulnerable areas to illustrate the temporal evacuation traffic patterns during Hurricane Irene and Sandy in New Jersey. The analysis is based on hourly traffic volumes data from toll plazas on the evacuation route along the shore area.

In the second part of this section, we analyze the spatial evacuation traffic patterns prior to Hurricanes Irene and Sandy making landfall throughout statewide New Jersey. The analyses included in this section are based on hourly traffic volumes during Irene and Sandy evacuations from the permanent continuous TVS and WIM sites in statewide New Jersey.
Temporal Evacuation Traffic Patterns in Cape May County, NJ

The temporal progressions of Hurricane Irene and Sandy evacuation traffic at Cape May toll plaza on Garden State Parkway (GSP) Northbound are illustrated in FIGURE 2. FIGURE 2(a) shows the hourly traffic volume during Hurricane Irene from Wednesday, August 24, through Sunday, August 28, 2011. FIGURE 2(b) shows the hourly traffic volume during Hurricane Sandy from Friday, October 26, through Tuesday, October 30, 2012. The time stamps of mandatory evacuation orders and Hurricane Irene and Sandy landfall times are shown as dashed vertical lines. As a reference, traffic flows for the same days during the prior week are also included in FIGURE 2(a) and FIGURE 2(b), to illustrate typical traffic conditions.

The volume trend lines in FIGURE 2(a) show the Irene evacuation process in Cape May County. The process started around 9:00am on Thursday, August 25. Approximately 6 percent of the evacuees had already evacuated by the time the mandatory evacuation order was issued. The major part of the evacuation, which comprised more than 85 percent of the evacuees, continued into the midnight of Friday, August 26. Only less than 8 percent of the evacuees chose to evacuate on Saturday, August 27.

The Hurricane Sandy evacuation pattern is shown in FIGURE 2(b). The process started around 12:00pm on Friday, October 26, when traffic volumes started to become higher than the prior week’s volumes. Approximately 6 percent of the evacuees had already evacuated by the time the mandatory evacuation order was issued. Similar to Irene, the major Sandy evacuation happened within two days after the mandatory evacuation order issued. More than 90 percent of the evacuees evacuated during October 27-October 28, 2012. Only less than 3 percent of the evacuees chose to evacuate on Monday, October 29. This evacuation behavior may be in part caused by an easily mobilized tourist population, lack of hurricane evacuation experience, and/or the nature of the affected region, which in this case is a rural area with limited evacuation routes (19).

The observations from Hurricane Sandy were consistent with the findings for Hurricane Irene reported in Li et al. (19). The evacuees in Cape May County responded very quickly to the mandatory evacuation order. Traffic volumes increased significantly when official mandatory evacuation order was issued. Two peak evacuation demand periods were observed around the start times of the mandatory evacuation orders for Hurricane Irene (3:00 pm Thursday, August 25, 2011) and Sandy (12:00 pm Saturday, October 27, 2012), respectively.

However, despite the quick response behavior, the total number of evacuees during Hurricane Sandy was much less than the number of evacuees during Hurricane Irene. In other words, the data show that fewer people chose to evacuate during Hurricane Sandy compared with Irene. The total number of evacuees during Irene evacuation (August 25-26, 2011) is 62,397, which is a 30 percent increase compared with prior week. On the other hand, the total number of evacuees during Sandy evacuation (October 27-28, 2012) is 22,127, which is only 30 percent of the total number of evacuees during Irene evacuation. The total Sandy evacuation demand is even lower than the routinely observed traffic demand (prior week).

Several factors may have affected the evacuation demand during Hurricane Sandy in Cape May County. One critical factor is the tourist population. During the summer/hurricane season, more than 85 percent of the people in Cape May County are non-residents. However, Hurricane Sandy happened late in the summer season with fewer tourists remaining in Cape May County. Another factor affecting the Hurricane Sandy evacuation demand is the background traffic. “Background traffic consists of vehicles that are present during an evacuation but are not
associated with permanent residents, transients, special facility populations, or voluntary evacuees” (20). The major Hurricane Sandy evacuation process happened during the weekend (October 28-29, 2012) instead of weekdays (August 25-26, 2011) during Hurricane Irene. That may have eliminated some background traffic during Hurricane Sandy evacuation.

The reduced total evacuation demand during Hurricane Sandy may also have been due to so-called “crying wolf” effect (21). Repeated false alarms reduce the credibility of warning information, and change the evacuation response behavior. During Hurricane Irene, evacuees responded to the mandatory evacuation order very quickly. At least 90 percent of the residents in the most-impacted counties left the shore area over 36 hours after the declaration of mandatory evacuation order (22). However, it turned out that Hurricane Irene did little damage to Cape May County. Some people came back from Irene evacuation only found a few leaves on the ground (23). Thus, it is possible that some residents and tourists decided to stay back during Hurricane Sandy after the experience of Hurricane Irene evacuation.

FIGURE 2 Irene and Sandy evacuation traffic counts from in Cape May toll plaza on GSP

(a) Hurricane Irene (2011)

(b) Hurricane Sandy (2012)
The spatial progression of Irene and Sandy evacuation traffic are illustrated in FIGURE 3 and FIGURE 4, respectively. FIGURE 3 shows the hourly traffic volume at each TVS or WIM site from Thursday, August 25, through Friday, August 26, 2011. FIGURE 4 shows the hourly traffic volume at each TVS or WIM site from Friday, October 26, through Saturday, October 27, 2012. As a reference, traffic flows for the same days during the prior week are also included in FIGURE 3 and FIGURE 4, to illustrate typical traffic conditions. In addition to the TVS and WIM data, the hourly traffic volumes from the Cape May and Gretna toll plazas on GSP are also included in FIGURE 3 and FIGURE 4.

The area of New Jersey that was vulnerable to both Hurricanes Irene and Sandy can be broadly divided into two geographic regions: northeastern NJ and the shore. Northeastern NJ was potentially vulnerable to damage caused by a storm surge and flooding. The NJ shore along the Atlantic Coast, a stretch of 130 miles of coastline along the central-east and southeast regions of the state had significant damage potential. In addition, high seasonal population along the shore make hurricane evacuation an issue of critical concern for this region.

FIGURE 3 shows that the major Irene evacuation happened in the shore region, the central-east and southeast region of the state closet to the Atlantic Coast. In data sites 6-15, the traffic volumes during Irene evacuation are significantly higher than the prior week’s counts. In addition, the evacuation traffic patterns at different locations also confirm the quick evacuation response behavior observed in Cape May County. Moreover, there was little evacuation traffic observed in the data sites in the northeast region of NJ. In other words, no significant evacuation traffic from New York City was observed during Hurricane Irene.

Another observation shown in FIGURE 3 is that the major evacuation traffic moved to the western regions, instead of traveling to the northern area along the shore. For example, NJ-55 and GSP are two major evacuation outbound routes in Cape May County. However, during Irene evacuation, the westbound evacuation traffic along NJ-55 is 25,242, while the northbound traffic along the GSP is only 14,450. This is possibly due to the risk perception and proximity of evacuees along the shore. As stated by Carnegie and Deka (24), the distance to a threat is a critical factor affecting evacuation behavior. Evacuees preferred to choose the destinations and corresponding evacuation routes away from the potential risk.

FIGURE 4 shows that the spatial evacuation traffic patterns during Hurricane Sandy are similar to those of Hurricane Irene. The major evacuation happened in the southern New Jersey along the shore region, and no significant traffic from New York City was observed during Hurricane Sandy. However, similar to the observation in Cape May toll plaza along the GSP, the total number of evacuees during Hurricane Sandy was much less than the number during Hurricane Irene.
FIGURE 3 Statewide evacuation traffic in NJ prior to the landfall of Hurricane Irene
FIGURE 4 Statewide evacuation traffic in NJ prior to the landfall of Hurricane Sandy
Evacuation response behavior can also be analyzed in terms of individual/household departure time choices. During hurricane evacuations, evacuees must determine the appropriate extra time required with regard to their departure time. Such extra time needed to ensure their timely arrival to a safe region is called safety margin (25-26). The safety margin is discussed for daily traffic conditions such as morning commute and airport trips (27-29). In addition to daily traffic patterns, the evacuation departure behavior can also be interpreted in terms of safety margin: on the one hand, evacuees have a deadline to leave the evacuation zones before the hurricane makes landfall. On the other hand, evacuees are likely to assume that transportation systems will be highly congested based on media reports and their own personal experiences.

The differences in the traffic patterns during the Irene and Sandy evacuations and typical summer weekends are illustrated in FIGURE 5. This data include toll plaza counts, WIM stations, and TVS. We chose to compare Irene and Sandy evacuation traffic with the summer weekend traffic because tourists dominate beach communities in the summer. Usually daily tourists and weekly renters travel to the beach on the weekends and drive back home on Sundays. Thus, the Sunday outbound traffic from the beach communities is often bumper-to-bumper traffic with peak traffic demand.

FIGURE 5 shows that the evacuees made their departures approximately 1-4 hours earlier than those leaving the shore on regular weekends at different sites. The peak period for departures on the weekends was between 10 a.m. and 5 p.m., while during Hurricane Irene the peak period was between 7 a.m. to 1 p.m. Moreover, the data collection sites along the beach revealed that travellers were adopting larger safety margins than the travellers at inland sites. The magnitude of the safety margin decreased with the increasing distance from the Jersey shore. For example, in Cape May County the safety margin was 3-4 hours, while the safety margin reduced to 1-2 hours in the inland areas. This may have been caused by the difference of risk perception and the proximity of the evacuees in different regions. The evacuees along the shore took larger safety margins mainly because they perceived a higher risk from the impending hurricane compared to those located further inland. The empirical evacuation safety margin observed during Hurricane Irene and Sandy shows that evacuation traffic is not totally unpredictable. Thus, with appropriate traffic management, those evacuees lacking prior evacuation experience can also be helped in an efficient manner.
FIGURE 5 Traffic patterns between hurricane evacuations and regular summer weekends.
The identification of bottlenecks is a critical component of emergency evacuation planning when evaluating the traffic operations during an evacuation. In this section, instead of simulation tools used in prior studies (30-32) for identifying evacuation bottlenecks, travel time data collected by commercial traffic data provider was used to identify traffic congestions and bottlenecks.

The travel time data used in this study was collected from I-95 monitoring sites, which cover the major highways and roads in New Jersey. For a specific section of road, the data includes average speed and travel time in 5-minute intervals.

FIGURE 7 shows the Irene and Sandy evacuation bottlenecks in NJ based on the travel times. The bottlenecks refer to the links with a 30% travel time increase as seen in the comparison of the Irene evacuation with the same time from the prior week. During Hurricane Irene evacuation, the bottlenecks first appeared in the afternoon of Thursday, August 25, along the southern section of the GSP. Then, on Friday, August 26, the bottlenecks spread to the northern section of the GSP and other major evacuation routes, such as the Atlantic City expressway. The worst network performance occurred between 12:00 P.M. to 6 P.M. on Friday, August 26, 2011. During the evening (6 P.M. to 9 P.M.) on Friday, August 26, the network congestion improved. While during Hurricane Sandy, probably because of the comparatively lower evacuation demand, little congestion was observed during evacuation process. The worst network performance occurred between 9:00 A.M. to 12 P.M. on Sunday, October 28, 2012.

FIGURE 7 also illustrates that the bottlenecks observed during Irene and Sandy evacuations were generally located at the merging sections. This is not surprising because freeway merge areas are critical segments that are known to cause congestions. When traffic volumes increase, there are numerous conflicts (e.g. lane changing, vehicle merging, etc.) in these merge areas.

Freeway ramp management is one of several important traffic management approaches that do not receive sufficient attention by emergency planning and management professionals. A recent study (33) shows that ramp closure can be an effective tool in reducing traffic congestion and increasing efficiency on the road. Recently, Machiani et al. (34) also examined the ramp closures in no-notice evacuation management. The results show that “ramp closures can speed the evacuation process by improving freeway flow. Blocking ramps could prohibit vehicles from entering freeways at their day-to-day locations and mitigate the congestion experienced by evacuees”. This may be a good start when considering ramp management for emergency management, especially during hurricane evacuation.
FIGURE 6 Observed bottlenecks during Hurricane Evacuations in Southern New Jersey
CONCLUSION

This study analyzed the evacuation traffic patterns during both Hurricanes Irene and Sandy that hit New Jersey in 2011 and 2012, respectively. Different sources of real-world traffic data were used for the analyses. The data included hourly toll plaza volume counts, Traffic Volume Station (TVS) traffic counts, Weight-in-Motion (WIM) traffic counts, and travel time data collected by a traffic service provider. Compared with traditional post-hurricane surveys and simulation studies, the use of extensive traffic data has several advantages, including a larger sample size, avoidance of the problem of recall common in social sciences, as well accuracy and reliability problems usually associated with data obtained from simulation models. The temporal and spatial evacuation traffic patterns were analyzed using hourly traffic volume data, and bottlenecks were identified using the travel time data. The major conclusions of this study based on these empirical observations are as follows:

(a) The evacuation demand in the case of Sandy was much less compared with the demand observed in the case of Irene. The total number of evacuees in Sandy is less than 30 percent of the number of evacuees in Irene.

(b) The observed reduced evacuation demand during Hurricane Sandy may have been partly due to the late-summer season and differences in background traffic. In addition, the so-called “crying wolf” effect may have also affected the total evacuation demand.

(c) Similar to Irene, people who evacuated in Sandy responded very quickly to mandatory evacuation order. Traffic volumes increased significantly when the official mandatory evacuation order was issued.

(d) The vast majority of the evacuation traffic during both Irene and Sandy moved westward, instead of traveling northbound along the major highways such as the GSP in shore area.

(e) The Irene and Sandy evacuation traffic patterns were similar to typical outbound traffic from the shore areas at the end of a typical summer weekend but with departure times that were 3-4 hours earlier than usual.

(f) The bottlenecks during Hurricane Irene evacuation were generally found at merge locations around on/off ramps or interchanges. However, probably because of less evacuation demand, fewer bottlenecks were observed during Hurricane Sandy evacuation.

These empirical observations can be used to improve real-world emergency response operations. They can also be extremely useful for improving evacuation models by adjusting their demand and other assumptions. In this study, we offer several plausible explanations for this kind of observed evacuation traffic patterns in NJ. However, such hypotheses still need to be rigorously tested with post-hurricane data collected from a large sample of the evacuees since the current traffic data does not contain such data. There are numerous studies being conducted especially in the aftermath of Hurricane Sandy. We thus recommend a future study that will combine surveys of Irene and Sandy evacuees which consist of residents and tourists from across New Jersey with the more aggregate data employed in this paper to better understand the reasons for observed demands and traffic patterns.

ACKNOWLEDGE

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REFERENCES


