

Time To Leave: An Analysis of Travel Times During the Approach and Landfall of Hurricane Irma

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Abstract

Hurricane Irma caused widespread evacuation activity across Florida and some of its neighboring states in September of 2017. The researchers gathered estimated travel times from the Google Distance Matrix API over about a month to identify and analyze evacuation periods on roads in Florida, Georgia, and South Carolina during this time. Travel time data was mathematically adjusted to show more realistic estimations. Both sets of travel times were then graphed, with the assumption that elevated travel times prior to and during hurricane landfall were indicative of evacuation activity. The study generally corroborated the well-established daytime evacuation preference. However, not all evacuation periods followed the daytime travel preference, and at least one nighttime evacuation may have been caused by flooding. In another case, later elevated travel coincided with significant power loss. Finally, the Florida data suggest that most of the evacuation traffic departed before local jurisdictions' recommended evacuation start times.

Keywords

evacuation, Florida, Hurricane Irma, travel time

1 Introduction

Hurricane Irma's approach in September 2017 led to a variety of evacuation announcements in the southeastern United States. Florida Governor Rick Scott urged residents to prepare for rapid evacuation on September 5 (Mitchell 2017), and, two days later, he issued another public statement to emphasize the danger the storm posed (WFLA staff 2017). These warnings were accompanied by local advisories around Florida. Also on September 5, Florida Keys emergency management officials issued a mandatory evacuation order for both tourists (beginning the next morning) and residents (beginning the evening of Sept. 6th) (NWS Key West 2017a,b). Irma made landfall near Cudjoe Key as a category 4 hurricane around 9:00 a.m. on September 10 and a subsequent landfall near Marco Island, FL around 3:35 pm local time (Stein et al. 2017; Weather Underground 2018). As Irma approached the Florida coast, some communities received advisories while others received mandatory evacuation notices (e.g., the differences between areas in the Florida panhandle, as shown by Etters (2017) and Payne (2017)). The announcements, initial concern, and uncertainty surrounding the storm's path resulted in evacuation traffic across Florida. The traffic continued into Georgia and South Carolina, as those states were both evacuation destinations and possible secondary targets for Irma (Stein et al. 2017).

This study uses travel time estimates from the Google Distance Matrix API (Google Maps' data source) recorded from September 5 to October 2, 2017 to gain more insight into aggregate evacuation behavior. Google Maps uses historical data and real-time data from sensors and cell phones to produce travel time estimates and route recommendations (Brindle 2020 and references therein). In this study, travel time estimate data is considered along with power outage information where available (recorded at UM-Ann Arbor from Florida Power and Light, Gulf Power, and Duke Energy) to provide more context. These datasets were used to address five research questions:

1. How do the estimated travel times at departure compare with travel times that have been adjusted to better reflect driver experiences?
2. When did evacuation noticeably begin and end in different areas, based on the travel time data indicating high travel times?
3. How do the evacuations align with official evacuation notices?
4. Do power outages have a discernible association with evacuation activity?
5. What were the best times (i.e., the moments with shortest travel times) for evacuees to leave their respective areas prior to Irma?

This paper is divided into four sections. First, a literature review covers some key points related to the choices to evacuate and when. Then, the methodology and results are presented. The paper concludes with a discussion of the findings and suggestions for further investigation.

2 Literature Review

There has been substantial research into the factors associated with the decision of whether or not to evacuate. Since this paper is based on aggregate data, the following discussion is focused on broader factors, rather than individual or household level characteristics.

Based on survey responses, Baker (1991) found that safety during an event is a primary concern and perceptions of safety are influenced by public announcements and advice from others. Similarly, Sorensen (2000) indicated moderate levels of empirical support for perceived risk being associated with warnings and response to the warnings increasing with higher risk perception. Murray-Tuite and Wolshon (2013) and Thompson, Garfin, and Silver (2017) also reported consistency in the literature of higher risk perception and receiving warnings as factors associated with evacuating across hazard types.

Areas that are geographically vulnerable during hurricanes often have evacuation rates over 80 percent; areas with lower perceived risk have much lower evacuation rates. However, low-risk areas also tend to produce evacuees that are not necessarily accounted for in the overall calculus, because they are not seen as likely candidates to join the evacuation stream (Baker 1991). This secondary group creates a “shadow” evacuation (Zeigler et al. 1981), which may contribute a non-trivial traffic volume.

Evidence also suggests that personal risk perception tends to encourage evacuation decision making. In focusing on the Florida Keys and Hurricane Georges, Dash and Morrow (2001) found that residents made their decisions to evacuate based on their awareness of their precarious situation and their monitoring of the storm. Even though there was a mandatory evacuation in the Keys, only around 53% of residents evacuated, with a much higher percentage evacuating in the region that actually experienced landfall. This suggests that Keys residents had a good feel for how their respective communities would be affected by Georges, and also that the mandatory evacuation order was a secondary consideration for them (Dash and Morrow 2001). It is possible that because of the unique circumstances in the Keys (one route of evacuation; isolated and exposed to hurricanes on the south side of

Florida; limited shelter availability) (Chen et al. 2005), the residents have developed a heightened awareness of hurricane impacts.

To properly manage hurricane evacuations, it is necessary to understand not only the factors involved in making the decision to evacuate, but also the timing of the evacuation trips. In Urbanik et al.'s (1980) function of the time it takes a household to evacuate are three terms not including travel time and thus associated with departure time: the time it takes for authorities to decide to issue an evacuation notice, the time it takes a household to receive the warning, and the time it takes a household to prepare to evacuate. These terms are not necessarily additive in the hurricane context since a household may begin preparing to evacuate based on weather forecasts and other information and may even leave before an evacuation notice. However, announcements from authorities can affect evacuation urgency, as was believed to have been the case in Hurricane Floyd in 1999. Voluntary and mandatory evacuation announcements spaced just five hours apart appeared to contribute to the ensuing severe traffic congestion on the interstates heading inland. Though the announcements probably did not give people the initial idea to leave, the rapidity with which the bulk of the evacuation ensued thereafter (61% left the same day) suggests that the decision of *when* to leave was affected by the announcements (Dow and Cutter 2002). Lindell, et al. (2005) found that during Hurricane Lili in 2002, the evacuation on the U.S. Gulf Coast began on the same morning that the National Hurricane Center (NHC) issued a hurricane warning, indicating that some evacuees in this region had also decided to leave prior to an official announcement. This may have been due in part to the fact that the NHC had also declared a hurricane watch the previous night, and also because authorities in the affected areas issued their own warnings (Lindell et al. 2005).

Fu and Wilmot's (2004) logit model for household evacuation decision-making was created from data from Hurricane Andrew in 1992. Consistent with the above discussion, they found that increased risk levels (for example, living in a flood-prone area versus not) raise the likelihood of evacuation, and that warning announcements tend to hasten evacuation. The model also showed a strong preference for evacuation during daylight hours, consistent with many other studies, e.g., Baker (1991), Dow and Cutter (2002), and Lindell et al. (2005).

Hurricane Irma provides an opportunity to evaluate how travel time estimates fluctuated during different time periods. The travel times are examined in the context of available announcement information, hurricane arrival times, and power outages to see if associations can be discerned.

3 Method

3.1 Data Acquisition and Selection of Origin-Destination Pairs

Evacuations are often characterized by higher than usual traffic volumes and related travel times. Evacuation periods therefore may be able to be inferred by examining travel times and finding increased travel time intervals that correspond to the onset of an evacuation-causing event. The likelihood of an identified period being attributable to evacuation behavior increases when the period features travel times that are significantly higher than those during normal peak hours.

The researchers used Google's Distance Matrix API to record travel time estimates along routes in Florida, Georgia, and South Carolina that lead inland and north, away from the threatened coastal areas. Florida was anticipated to be the primary impact area for the hurricane, and the Carolinas would potentially be subject to at least storm surge. Georgia can be an evacuation destination for Florida residents.

Data recording began at 11:06 p.m. on September 5, 2017, and estimates were gathered at roughly fifteen-minute intervals. When researchers recognized the potential scope and force of Irma, more origin-destination pairs were added to the list. This expanded collection effort began at approximately 11:45 p.m. on September 6th. Each data group contains a set of routes that were assigned to the same collection routine in the same general area; all routes within a given group therefore have the same times assigned to their readings.

In assessing the data, researchers examined longer journeys in different parts of the study area (Figure 1) to obtain a broad picture of the evacuation across the impacted region, and particularly in Florida. The travel time estimates for the selected pairs of locations were then plotted against time of day. The graphs illustrate how traffic patterns evolved during Irma's approach and landfall, and for a few weeks thereafter (data collection stopped on October 2). Evacuation windows were approximated based on the knowledge that statewide warnings were issued as early as September 5. As discussed above, previous studies demonstrate that people in hurricane-prone areas may respond to official announcements fairly quickly, and also that they are often prepared to take action based on their own assessments beforehand.

INSERT FIGURE 1 APPROXIMATELY HERE

The routes shown in Figure 1 are represented as straight lines because the exact routes taken by drivers cannot be determined from the data sets. The only

information is the origin-destination pair. Numbers in the pairs refer to major roads; as shown in Figure 1, N75-275 is close to Tampa-St. Petersburg, 10_19 is just east of Tallahassee, and 95_4 is beside Daytona.

3.2 Adjusting Travel Time Estimates

Because evacuations are not typical events, it is possible that the time estimated for a longer trip at a given departure time is not what was experienced during the evacuation. Some refinement of the data may yield a better picture of travel times that were experienced by Irma evacuees.

A preliminary review of the raw data revealed situations where the travel times reported for two or three adjacent time entries varied tremendously. For example, if a vehicle departed from Orlando for Columbus on September 8 at 15:49, its estimated travel time was 410 minutes. If the vehicle left 15 minutes later, the journey was estimated to take 367 minutes. This 43-minute fluctuation suggests that the raw data may not be an accurate reflection of experienced travel times, especially on the longer routes. Thus, adjusted travel time estimates were developed based on the strong, simplifying assumption that each vehicle on a route experienced the travel time that applied to each 15-minute interval during which it was on the roadway. Using the previous example to demonstrate, a vehicle that started from Orlando at 15:49 on September 8 would initially travel at a speed based on 410.05 minutes of estimated road time for the first interval of its journey to Columbus. Then, at the next reading at 16:04, the vehicle's speed would increase based on an overall travel time of 366.53 minutes. The speed changes would continue at each interval until the vehicle finished its journey. For this particular case, the adjusted estimated travel times were 373.91 minutes for vehicles that started at 15:49, and 371.92 minutes for vehicles that started 15 minutes later. This is a much smaller fluctuation.

Determination of these adjusted travel time estimates began with estimating the distance traveled during each interval. The total distance traveled was not known with certainty for each pair of locations, since the actual route corresponding to the estimate was not recorded. Distances between pairs were selected based on recommended routes shown on Google Maps (determined in December 2017). The selected total distance (D , in miles) was used to calculate the distance traveled during each interval based on each raw total travel time (equation 1):

$$d_{j,j+1} = \frac{D}{R_j} * t_{j,j+1} \quad (1)$$

where

$d_{j,j+1}$ is the distance traveled during an interval between two readings j and $j+1$ in miles,
 R_j is the raw travel time corresponding to reading j ,
 $t_{j,j+1}$ is the duration of an interval between readings j and $j+1$ in minutes, and
 j is the record number of the observation.

At this point in the calculations, the sums of the interval distances were checked for completed journeys. The minimum number of intervals that had one or more results that sum to at least the total mileage for the journey was chosen as the starting point for deriving adjusted travel time estimates, since this was the threshold within the dataset at which vehicles began completing the journey. The summed travel times were not accurate though, because a given vehicle finished its journey at some point during the final interval that it was on the road. It was therefore necessary to adjust the summed times based on the rate of travel during the last interval (equation 2):

$$m_j = \left(\sum_{i=j}^{j+x-1} d_{i,i+1} \right) - D \quad (2)$$

where

m_j is the amount of extra distance in a completed trip distance sum assigned to record j (miles),
 x is the number of intervals in a completed trip set, and
 all other terms are as previously defined.

The travel times for the extra distances are based on equation (3), and these values can then be subtracted from their associated interval sums to yield the desired adjusted travel time estimates (equation 4):

$$c_j = m_j * \frac{t_{j+x-1,j+x}}{d_{j+x-1,j+x}} \quad (3)$$

where

c_j is the number of minutes to be subtracted from a sum of intervals for a completed trip as in equation (4) and other terms are as previously defined.

$$T_j = \left(\sum_{i=j}^{j+x-1} t_{i,i+1} \right) - c_j \quad (4)$$

where

T_j is the adjusted travel time estimate in minutes for record j .

This computational approach assumes that the conditions on any particular route were uniform along the length of the route for each time interval, based on the raw travel times given.

After the adjusted travel time estimates were calculated and graphs were produced, basic comparative calculations were carried out. These results include ranges and range differences; differences between low-end/high-end raw travel times and their respective corresponding adjusted travel time estimates; and differences between the highest and lowest adjusted travel time estimates. These figures are accompanied by estimated start and end times for each location pair (where possible) and the shortest adjusted travel time estimates for daylight departures.

4 Travel Times and Events

Because there were major announcements that predated the data collection start times, the timings and potential effect(s) of those announcements cannot be analyzed directly in this paper. The residents of the Florida Keys in particular were likely sensitive to the approach of Irma, given what Dash and Morrow (2001) found for that group over a decade ago. Based on the findings of Lindell et al. (2005) and Dow and Cutter (2002), there is a chance that the largest part of the Keys evacuation happened early on September 5, the day after the first major hurricane watch notice was posted (NWS Key West 2017c). Similar evacuation peaks were observed the day after the NHC issued a Hurricane Watch for Hurricanes Rita (Huang et al, 2016) and Ike (Huang et al., 2012). This part of the evacuation would have taken place almost a full day prior to the earliest data reading in this study, and thus it is not reflected in the data. However, it was possible that some of the Keys traffic appeared later in other states and/or the northern part of Florida during the sampling windows of this study.

For each origin-destination pair, two graphs were developed: a graph showing travel times for the recording period from September 6 to September 30 (only a few of these are depicted here to save space, but the others are available from the authors upon request) and an annotated graph showing travel times proximate to Irma (September 6-13 where possible; September 7- 13 otherwise). The annotations give the times of various hurricane warning and evacuation announcements and the first and second landfall times. The first landfall refers to the one at Cudjoe Key, and the second landfall refers to the one at Marco Island (Stein et al. 2017).

4.1 Key Largo to Belle Glade

The Key Largo-Belle Glade pair represents a primary evacuation corridor out of the Keys. Due to limited connectivity between the Keys and the mainland, the Keys should be evacuated well in advance of the arrival of tropical storm force wind and hurricane landfall. Both Figure 2A and Figure 2B show how the adjusted travel time estimates differ from the recorded ones: the adjusted times have a smaller range (lower high values and higher low values). The adjusted travel time estimate curve is shifted slightly to the left of the original because of the way the adjusted estimates are calculated (as described in section 3.2). This general relationship between the adjusted and recorded travel times is consistent for all of the data sets due to the calculation method employed.

Figure 2B shows an interval (September 6) that appears to have extended travel times, approximately coinciding with the recommended evacuation start times for visitors (morning) and residents (evening), but this may not be indicative of the main evacuation period because Figure 2A demonstrates that these travel times also occur on the route during non-hurricane conditions. Using detector data from the Florida Department of Transportation (FDOT), Parr and Acevedo (2019) identified the evacuation start time for the Keys as 120 hours (5 days) before landfall at Cudjoe Key at 9am on September 10. They indicated the peak of the evacuation demand occurred about 89 hours before landfall, which corresponds to the higher travel times in the afternoon of September 6 shown in Figure 2B. The figure shows a sustained period of slightly elevated travel times lasting from the evening of the 9th to the evening of the 12th. FDOT's detector near Key Largo indicated low traffic counts (less than 100 vehicles) from noon on September 9 until 10 am on September 12, suggesting that the travel time estimates were more based on historical data for that time of day rather than real time data from travelers (Brindle, 2020; Palmer, 2014) unless significant travel speed decreases occurred (e.g., because of debris).

Somewhat uniquely for the set of O-D pairs in this study, the Key Largo to Belle Glade travel times increased close to landfall and afterwards compared to September 8 and 9. Tropical storm force winds arrived between 2 and 8 pm on September 9 (Varinsky, 2017). The islands were closed to tourism in the immediate aftermath of Irma, and massive amounts of roadway debris impacted traffic flows for weeks (Contorno 2017).

Gov. Scott said shortly after Irma passed that he wanted the Keys reopened by October 1st. Although some Keys residents felt this goal was too ambitious, they were aware that without a formal barrier, tourists would still start returning as soon

as they had the opportunity. As of September 30th, this was indeed the case (Contorno 2017), and the increased traffic heading out of the Keys could indicate heightened activity on the roadways in general later in the month (Figure 2A).

INSERT FIGURE 2 APPROXIMATELY HERE

4.2 Port St. Lucie to Sebring

Port St. Lucie is located to the north of Miami on the east coast of Florida. As shown in Figure 2C, there is a period at the beginning of the analysis that has inflated travel times that do not occur again during the month. The higher travel times last for a little more than two days from the morning of September 6 to the afternoon of the 8th. The bulk of the evacuation period appears to have immediately preceded the recommended evacuation start time of 3 pm on September 8 and preceded the arrival of tropical storm force winds by at least 42 hours. Port St. Lucie is two counties north of what Parr and Acevedo (2019) grouped into Southeast Florida in their study based on detector data, but Southeast Florida was their closest analyzed area. Parr and Acevedo (2019) indicated an evacuation start time of 95 hours before landfall at Cudjoe Key and peak demand at 66 hours before landfall. Despite being in different counties, these timings well correspond to the higher travel times on September 6 and 7 shown in Figure 2D.

As shown in Figure 2D, even though the evacuation appears to have begun in the early morning on the 6th, noticeably high travel times are present in the evening and even close to midnight on the 7th. Within the main evacuation period (September 6 and 7), the difference between the longest and shortest travel time is nearly 12 minutes (see Table 2). Although travel speeds at night tend to be lower than during the day, the values for September 6 and 7 exceed those of corresponding hours on other days in September, as shown in Figure 2C (e.g., travel time at 12:00am on September 7 is approximately 7% higher than that of September 14). This suggests the presence of an evacuation wave that chose to travel on roads in the area during the night, something that goes against the general daylight evacuation preference highlighted by Baker (1991) and many others. The nighttime travel may have been somewhat attributable to school closures on the 7th and 8th that were announced on the 5th (Atterbury 2017). The elevated travel times that persisted the following night might have had the first mandatory evacuation notice as a contributing factor. Although night is not the preferred time to travel, Lindell et al. (2019) note that people will do so if necessary, such as for Hurricanes Eloise (Baker et al. 1976), Elena (Baker 1986), and Opal (USACE Philadelphia District 1996).

4.3 Fort Pierce to Turnpike Orlando

Fort Pierce is just north of Port St. Lucie on the east coast, and Orlando is inland to the northwest. Like Port St. Lucie to Sebring, this route had elevated travel times at the beginning of the analysis window (September 7 and 8) that did not appear for the rest of the month. This pattern suggests this is a probable evacuation route, and a heavily impacted one. The raw travel times during the evacuation window approach 160 minutes (see Table 1), and even the adjusted values exceed 150 minutes (see Tables 1 and 2) (approximately 80% higher than the typical travel times for the route post-evacuation - between 80 and 90 minutes). These highest travel times were observed close to the evacuation announcement at 5:30pm on September 7 that indicated the evacuation orders would be in effect at 3:00pm on the 8th. The main evacuation period appeared to end more than 40 hours prior to the arrival of tropical storm force winds at Fort Pierce. Like Port St. Lucie, Fort Pierce's evacuation may have been affected by the regional school closure announcement (Atterbury 2017), leading to departures that preceded the mandatory evacuation announcements. The timing of the official evacuation the next day coincided with what appears to be the tail end of the evacuation period (Figure 3A). While there was evacuation-type behavior throughout the 7th, it is not possible to tell if the evacuation began earlier.

4.4 Orlando to Columbus

Orlando to Columbus is a long trip that has Interstate 75 as a prominent possible component. I-75 is an interstate highway that connects Atlanta with major cities in central Florida. As with Fort Pierce to Turnpike Orlando, the travel time estimates suggest an evacuation period that may have begun before the 7th. The peak points on the evacuation days (around mid-day) show a strong preference for daylight travel, as travel times increased into the evening before declining to a local minimum around midnight (Figure 3B). The peak adjusted travel time estimate occurred at approximately 2:30pm on the 7th and was 16% greater than the corresponding adjusted travel time estimate on the 14th. The evacuation period ended on the 8th, nearly two full days before the arrival of tropical storm force wind in Orlando. Notably, much of the evacuation traffic preceded the timing of the local jurisdiction's notice for mobile home evacuation. Because this pair includes a major roadway in central Florida, the evacuation travel times may have been primarily attributable to through traffic from locations to the south and the east.

INSERT FIGURE 3 APPROXIMATELY HERE

4.5 Daytona to Columbus

As with Orlando-Columbus, Daytona-Columbus had at least two days of elevated travel times, indicating probable evacuation traffic (Figure 3C). The highest adjusted travel time estimate occurred near noon on September 7 and was approximately 7% greater than the corresponding time on September 21 (the 14th was not used for comparison due to power outages remaining). The pattern of the evacuation is also similar to Orlando-Columbus, with the evacuation possibly starting before the 7th and ceasing on the 8th, a preference for daylight travel, much of the evacuation appearing to occur before the local jurisdiction's notice for mobile home evacuation (and beachside areas), and most of the evacuation appearing to end two days before the arrival of tropical storm force winds.

Just after tropical storm winds arrived in Daytona on the evening of the tenth, power outages began to manifest and escalate. On the 11th and 12th, 80% of the customers in the area were without power (Figure 3C). The heavy loss of power coincided with another period of slightly elevated travel times, perhaps indicating another evacuation wave that was catalyzed by the lack of power. People traveling from Daytona to Columbus during the evacuation had the typical preference for daylight travel, even during the possible second evacuation period.

4.6 95-4 to S95-Jacksonville

This journey originates in the Daytona area as well. The data shows the same basic evacuation pattern as the two preceding origin-destination pairs (Figure 3D). The evacuation period covers the 7th and the 8th, with much of the evacuation appearing to precede the official evacuation order effective period by 1-33 hours and the arrival of tropical storm force winds by approximately 48-81 hours. The data suggest a preference for daylight travel with the highest adjusted travel time estimate occurring near noon on September 7 (approximately 57% longer than the corresponding time on September 14). The flat period before the travel times started to rise on the 7th makes it difficult to determine if the evacuation carried over from the previous day.

4.7 N75-275 to 10-19

N75-275 to 10-19 starts in the greater Tampa area and goes into the panhandle of Florida, east of Tallahassee. This pair shows three days of evacuations, approximately centered around the evacuation order that was issued for Zone A in

Tampa (comprised of coastline areas; Office of Emergency Management 2017) in the middle of September 8 (Figure 4A). The end of the third day of this evacuation appeared to precede the arrival of high winds by about 24 hours. The data follows the overall trend of featuring a pattern that implies a preference for daylight travel (all three days, as in Figure 4A). While there is no way to know from the data if the evacuation began on the 6th or earlier, it would be notable if it did because that would extend the evacuation period to around four days.

Parr and Acevedo (2019) indicated that, based on detector data, the Tampa region experienced an initial gain in the number of vehicles (potentially due to being an evacuation destination before Hurricane Irma changed paths). However, an evacuation of the Tampa area appeared to start approximately two days before the first landfall (Parr and Acevedo 2019). This corresponds to the second peak in travel times seen in Figure 4A. The highest adjusted evacuation time estimate on September 8 occurred near noon and was approximately 28% higher than the corresponding time on September 22 (the 15th was not used for comparison due to the power outage).

The outage data (Figure 4A) shows a similar scenario to the one in Figure 3C, where the onset of tropical storm-force winds portended power loss. In the N75-275 area, power loss was as high as 61% before recovering to about 40% on the 13th. Note that there is not a discernable secondary evacuation that could be ascribed to the power problems, possibly because this is a road location and not a specific municipality.

INSERT FIGURE 4 APPROXIMATELY HERE

4.8 Jacksonville Beach to Lake City

Jacksonville Beach-Lake City does not appear to have had a typical evacuation, since the travel times in the hurricane period were very similar to the ones that were reported for the post-hurricane period later in the month (e.g., September 18-23; 26-30 not shown here). Some variation in travel time exists throughout the day on September 6-8 that drops on September 9 and 10. However, this area did experience elevated travel times beginning just before the arrival of tropical storm force winds late on September 10 and becoming more prominent on the 11th (Figure 4B). Similar to Figures 3B and 3C, 4B shows increased travel times after Irma's arrival. While three FDOT detectors in Duval county indicated obviously lower traffic counts in the Jacksonville area on the 11th compared to the 12th, these counts were in the multiple hundreds around 2pm. The elevated travel time period on the 11th followed

the arrival of tropical storm winds the previous night. This could have been partially due to flooding in the Jacksonville area (News4Jax staff 2017).

4.9 Jacksonville to 95-Savannah

Figure 4C for Jacksonville-Savannah shows probable evacuation traffic, again on the 7th and 8th with some evidence of preference for daylight travel. Though the travel times are not drastically elevated, they are still consistently above the norm shown in the post-hurricane weeks. The 8th, in particular, has a couple of recorded travel times that are outliers; these were “smoothed” by the adjusted travel time estimate calculation process. The highest adjusted travel time estimate occurred near noon (more than 48 hours before the arrival of tropical storm force winds) and was 18% greater than that for the corresponding time on the 15th. These highest travel times on the 8th occurred after the evacuation announcement, while the peak on the 7th preceded the announcement.

4.10 10-19 to Montgomery

10-19 to Montgomery, which starts outside of Tallahassee in the Florida panhandle, had the peak of its evacuation on the 8th, more than 24 hours before the voluntary evacuation notice and more than two days before power losses (see Figure 4D). Evacuees may know well in advance of official evacuation orders that they are going to do so. The highest adjusted travel time estimate occurred near 6pm on the 8th and was 19% greater than that of the 22nd. The travel times between this pair of locations could also be due to other evacuation traffic coming from the south of Florida, but the absence of elevated travel times after the announcements suggests either there were few evacuations in response, or that the roads were able to easily accommodate the volume that was generated.

This location did not have powerful enough sustained wind speed to make it easy to identify the arrival of tropical storm force wind (Weather Underground 2018). However, it is likely that strong winds are associated with power losses (see the power outage ratio line in Figure 4D). This area started to lose power around midnight on the 11th, and this outage continued to expand until, by the evening of the 11th, approximately 90% of customers were without power. Since 10-19 refers to a road location rather than a municipality, the outage severity probably did not trigger another discernible evacuation; people could have been driving through on the way to other destinations.

Though this path follows on directly from the terminus of the N75-275-to-10-19 route, it does not have a similar evacuation profile. Like the N75-275 route, there

is evacuation activity on the 8th; however, unlike N75-275, there is comparatively little travel time inflation on the 7th and 9th (Figures 4A and 4D).

4.11 Charleston city center to Florence, SC

Unlike Florida, South Carolina employed contraflow in select locations to expand evacuation capacity. It is possible that drivers traveling from Charleston to Florence were able to benefit from contraflow, as it was implemented on Interstate 26 leading out of Charleston (Haire 2017). The somewhat balanced travel times throughout the month shown in Figure 5A suggest that contraflow was a success or, possibly, that contraflow was unnecessary. However, as is visible in Figure 5B, there were still discernible higher travel times during the evacuation period on September 7 and 8, approximately 16 and 30 hours before implementation of the official evacuation notice and 66 and 90 hours before the arrival of tropical storm force wind. The highest adjusted travel time estimate occurred at approximately 6pm on the 8th and was approximately 22% greater than that for the corresponding time on the 15th. The evacuation appeared to begin right after the announcement that there would be an official evacuation start time and contraflow measures on the interstate. The data implies that a late-day evacuation took place, perhaps partially in response to the announcement, and then a larger one transpired the next day for the population segment that either had to wait or had a strong daytime evacuation preference.

The Charleston situation stands out because evacuations in Florida largely seem to have commenced well before official evacuation start times. In contrast, the evacuation in Charleston appears to have been at least in part in response to the official announcement on September 7, approximately four days before the arrival of tropical storm force winds. Florida notices tended to be issued closer to the arrival of tropical storm force winds.

INSERT FIGURE 5 APPROXIMATELY HERE

4.12 Calculated Differences Between Recorded and Adjusted Travel Times

In Table 1, the adjusted values provide travel times over a smaller range in all cases. The differences between the recorded and adjusted travel time estimate ranges are often substantial. Adjusted travel time estimates are important because people may choose to evacuate based on a lower travel time estimate, only to be confronted by a much more daunting figure 15 minutes later while enroute. The reality of their travel situation would more likely lie somewhere in the middle, and this would be shown by adjusted travel time estimates.

For every high and low value in the recorded set, the corresponding adjusted travel time estimate (the value in the same record slot, not the overall high/low experienced time) is a more conservative travel time estimate (Table 1). The major differences are shown with the recorded high-end values. The recorded high-end values tend to be more extreme than the low-end values. As a result, the differences between the highest values and their associated adjusted travel time estimates tend to be larger by comparison. (Note: The calculations for the differences between the recorded and adjusted travel time estimates were carried out using only data from the evacuation windows defined in Table 2.) As can be seen in Table 2, the majority of the evacuations started after midnight and before 6 a.m. While the early morning hours are devoid of sunlight, evacuations likely started at these times because drivers knew they would be on the road during daylight in the event of a large delay. The notable exception in terms of timing was Jacksonville Beach, a coastline community in the northeastern part of Florida. These increased travel times are possibly a reaction to flooding and/or power outages which are post-impact environmental cues (Lindell 2018; Lindell and Perry 2012).

4.13 High and Low Adjusted Evacuation Travel Time Estimates

The most common theme amongst the estimated departure times (Table 2) is that the best time to leave was usually between midnight and dawn. This is logical considering the well-established preference for daytime evacuation: on a given day, there are simply fewer cars on the road during the early hours of the morning, and thus lower travel times. The question for anyone evacuating in a personal vehicle would be whether he/she values time saved over evacuating at a preferred hour. In Table 2, time savings between the longest and shortest evacuation travel times range from 11.72 minutes to 60.49 minutes (although these routes do not necessarily constitute the entirety of an individual's evacuation route). Only one difference exceeds an hour (N275-75 to 10_19), and the longest routes by travel time only have a difference of a little more than half an hour (Orlando to Columbus and Daytona to Columbus). If a person were determined to evacuate during a peak travel time hour, it would not seem that the extra time spent on the road would be a huge deterrent in these cases. Unsurprisingly, the best post-sunrise time to leave was usually right after the sun rose, because evacuations tend to build from the lowest travel times early in the morning through the day.

591 **Table 1:** Travel time ranges and comparisons between recorded and adjusted estimates

Route*	Recorded			Adjusted			Range difference	Recorded low	Corresponding adjusted estimate	Difference (recorded – adjusted low)	Recorded high	Corresponding adjusted estimate	Difference (recorded – adjusted high)
	Low	High	Range	Low	High	Range							
Port St. Lucie to Sebring	93.45	109.65	16.20	94.35	106.07	11.72	4.48	93.45	94.72	-1.27	109.65	105.74	3.91
Fort Pierce to Turnpike Orlando	101.30	159.47	58.17	102.08	154.08	52.00	6.17	101.30	106.79	-5.49	159.47	148.04	11.43
N75-275 to 10_19	192.22	261.12	68.90	193.21	253.69	60.48	8.42	192.22	194.23	-2.02	261.12	250.04	11.07
95-4 to S95-Jacksonville	63.32	107.52	44.20	63.59	97.73	34.14	10.06	63.32	64.08	-0.76	107.52	92.06	15.46
Jacksonville Beach to Lake City	81.32	131.53	50.22	82.37	131.34	48.97	1.25	81.32	82.37	-1.05	131.53	131.27	0.26
Orlando to Columbus	350.52	420.17	69.65	365.18	402.20	37.02	32.63	350.52	371.81	-21.29	420.17	376.77	43.40
Daytona to Columbus	349.07	400.58	51.52	351.86	382.75	30.89	20.63	349.07	368.15	-19.09	400.58	374.03	26.56
Daytona to Columbus (2)	339.25	373.65	34.40	346.27	366.34	20.07	14.33	339.25	349.94	-10.69	373.65	363.25	10.40
Jacksonville to Savannah	110.78	163.77	52.98	111.71	129.72	18.02	34.97	110.78	113.49	-2.71	163.77	126.61	37.16
10_19 to Montgomery	228.32	331.77	103.45	230.59	283.36	52.77	50.68	228.32	233.51	-5.20	331.77	282.61	49.16
Charleston to Florence	121.18	153.58	32.40	121.65	147.45	25.80	6.60	121.18	122.19	-1.00	153.58	137.54	16.05

592 * Key Largo to Belle Glade is not shown here since the evacuation appeared to start earlier than the data collection.

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595 **Table 2:** Evacuation start and end times; longest and shortest travel times during evacuation

Route*	Main Evacuation		Shortest Evacuation Travel Time (Irma Approach)		Longest Evacuation Travel Time (Irma Approach)	Longest Minus Shortest Time
	Start	End	Overall	After Sunrise		
Port St. Lucie to Sebring	9/6 at 2:00 a.m.	9/7 at 9:33 p.m.	94.35 min at 2:00 a.m. on 9/6	97.80 min at 8:15 a.m. on 9/6	106.07 min at 11:15 p.m. on 9/6	11.72 min
Fort Pierce to Turnpike Orlando	9/7 at 1:15 a.m.	9/8 at 11:00 a.m.	102.08 min at 9:00 a.m. on 9/8	102.08 min at 9:00 a.m. on 9/8	154.08 min at 6:45 p.m. on 9/7	52.00 min
N75-275 to 10_19	9/7 at 2:32 a.m.	9/9 at 11:47 a.m.	193.20 min at 5:02 a.m. on 9/9	202.15 min at 7:17 a.m. on 9/9	253.69 min at 11:32 a.m. on 9/8	60.49 min
95-4 to S95-Jacksonville	9/7 at 5:15 a.m.	9/8 at 1:30 p.m.	63.59 min at 5:15 a.m. on 9/7	74.37 min at 12:15 p.m. on 9/8	97.73 min at 11:45 a.m. on 9/7	34.14 min
Jacksonville Beach to Lake City	9/10 at 4:48 p.m.	9/11 at 2:34 p.m.	NA	NA	NA	NA
Orlando to Columbus	9/7 at 2:33 a.m.	9/8 at 9:33 a.m.	365.18 min at 11:48 p.m. on 9/7	383.22 min at 7:18 a.m. on 9/7	402.20 min at 2:34 p.m. on 9/7	37.02 min
Daytona to Columbus	9/7 at 12:33 a.m.	9/8 at 9:18 a.m.	351.86 min at 12:33 a.m. on 9/7	365.73 min at 7:34 a.m. on 9/8	382.75 min at 12:04 p.m. on 9/7	30.89 min
Daytona to Columbus (2)	9/11 at 6:03 a.m.	9/11 at 2:34 p.m.	NA	NA	NA	NA
Jacksonville to Savannah	9/7 at 7:45 a.m.	9/8 at 2:30 p.m.	111.36 min at 7:45 a.m. on 9/7	111.36 min at 7:45 a.m. on 9/7	129.72 min at 1:00 p.m. on 9/8	18.36 min
10_19 to Montgomery	9/8 at 1:02 a.m.	9/9 at 8:32 a.m.	230.59 min at 2:47 a.m. on 9/9	247.83 min at 7:17 a.m. on 9/9	283.36 min at 6:17 p.m. on 9/8	52.77 min
Charleston to Florence	9/7 at 9:01 a.m.	9/8 at 8:02 p.m.	121.65 min at 5:16 a.m. on 9/8	122.19 min at 7:01 a.m. on 9/8	147.45 min at 6:01 p.m. on 9/8	25.80 min

596 * Key Largo to Belle Glade is not shown here since the evacuation appeared to start earlier than the data collection.

597 (Note on Tables 1 and 2: The specific evacuation end times were taken from the peak region of the last perceivable evacuation wave on each graph, since there is
 598 no good way to define a moment for the “end” of a given evacuation on the downside of its last interval. By choosing the last peak instead of a point later in time,
 599 the most and least favorable leaving times are kept within a window in which evacuation traffic can be safely assumed to have still been entering the road segments.)

5 Discussion of Results and Conclusions

5.1 Summary of Observations

The Irma evacuation origin-destination pairs in this analysis conformed to some of the commonly observed features of hurricane evacuations. Consistent with Baker (1991), Dow and Cutter (2002), and Lindell et al. (2005), evacuees often demonstrated a preference for daylight travel. This preference was less pronounced in at least one case (Port St. Lucie to Sebring), but the overall trend in the data reinforces this preference.

Many evacuations in this analysis seemed to *finish* before official start times were announced. This appears to support the finding by Lindell et al. (2005) that people start to prepare and make their decisions to evacuate when they have significant information about the probable approach of a hurricane (through news services, friends, online forums, etc.); official evacuation announcements then only serve as confirmations. Because of the time period of the data recording, the early Irma statements issued by Florida Governor Scott could not be matched with travel times in this paper. However, Governor Scott did make a statewide announcement about school closure in Florida on the evening of September 7 (Postal 2017), which overlaps with the evacuation activity apparent in the southern part of Florida on the same day. Based on what Dash and Morrow (2001) found for residents of the Keys specifically, it is likely that many people knew well in advance of even Governor Scott's notices that they were going to evacuate inland for at least a few days.

In this study, it is not possible to definitively state the starting times of all of the evacuations. However, due to the preference for daylight travel, it is likely that any evacuation traffic that preceded the data collection would have followed a similar pattern (high travel times in the middle of the day, with the lowest times generally occurring just before and just after midnight). Considering this finding, someone who wants to avoid delays could leave well before dawn on the chosen departure day. On the planning side, finding a way to better distribute traffic over a 24-hour period would perhaps help even out travel times in future events, and reduce the travel time for those who have to evacuate during daylight hours exclusively (such as people with poor night vision).

In Figures 3C and 4A, a significant power outage seems to coincide with late evacuation behavior. Power outages leading to later evacuation surges is an issue that should be more thoroughly investigated, if only so officials can prepare for sudden evacuations under compromised circumstances. While the preference for daytime evacuation seems to hold under power outage circumstances, it does not

seem to be as reliable (Figure 3C has a local travel time peak close to midnight on the 11th). This may make sense, because if one already has no light or cooling, the preference for staying at night might be diminished. This implies that evacuations stemming from power loss may happen suddenly regardless of hour, so disaster officials have to be prepared for egress roads to be accessible and navigable for large volumes of traffic at any time of day.

5.2 Conclusions

This study investigated the evacuation travel time patterns for selected locations for Hurricane Irma. Five questions were central to the research:

1. How do the estimated travel times in the data match up with travel times that have been adjusted to better reflect driver experiences?

The adjusted travel times have smaller estimate ranges than those recorded from the Google API, and this is a function of their more moderate overall values. This is to be expected. Since the adjusted values “look ahead” in the recorded data to arrive at their results, they shift the overall travel time curves marginally to the left on the graphs.

The recorded travel time estimates may have reduced accuracy for longer routes because unexpected conditions can arise (as acknowledged when Google Maps provides a travel time). Using the travel time adjustment method in this paper thus provides a way to create a more reasonable picture of the long-route experienced travel times. This can be helpful to residents and officials alike during evacuations.

2. When did evacuation noticeably begin and end in different areas, based on the travel time data?

In most cases, evacuations began in the early morning before dawn. The only evacuations appearing to start after dawn were on the Jacksonville-Savannah (Figure 4C) and Charleston-Florence (Figure 5B) routes. The Jacksonville Beach-Lake City evacuation began in the late afternoon (Figure 4B), and that was perhaps due to flooding and/or power outages. This general pattern somewhat reinforces the daytime travel preference that has been observed in many previous evacuation studies. The occurrence of an evacuation that started well into the afternoon implies that there are other events that can cause more spontaneous evacuations.

3. How do the evacuations match up with official evacuation notices?

Evacuations were typically already underway by the time official evacuation notices were issued or the evacuations were officially supposed to begin; in addition, most evacuations had already largely ended by the time evacuation announcements were officially made. Figures 4A (N75-275 to 10-19), 4C (Jacksonville to Savannah), and 5B (Charleston to Florence) might be considered exceptions, as they show notices being issued right before or during a potential evacuation wave. All of these locations are either in northern Florida or another state. It is possible that since Hurricane Irma approached from the south, evacuees in these locations had a greater opportunity to monitor the conditions before making a decision. In all three locations, strong winds did not arrive until at least 12 hours after the first landfall. In the case of Charleston, SC, people largely did not evacuate until official confirmation was issued. After declaring a state of emergency for South Carolina on September 6 (Waters 2017), Governor McMaster announced a contraflow plan for I-26 into Charleston on the 7th (for implementation on the 9th; Haire 2017) – four days before the arrival of tropical storm force winds, preceding a NHC Watch and logically preceding most household departures. He then issued mandatory evacuation notices for the barrier islands in the Charleston area on the 8th (Shain and Lovegrove 2017). Though Charleston residents had sufficient warning, they waited until later to leave.

4. Do power outages have any discernible association with possible evacuation activity?

There is some potential evidence of power outages being associated with evacuations; hence, they *might* be a causative factor. The circumstances surrounding these kinds of quasi-spontaneous evacuations and the means of safely facilitating them is an area for further exploration. In particular, is there heightened risk during an evacuation attributable to a power outage? And if so, how can this risk be mitigated efficiently?

5. What were the best and worst times for evacuees to leave their respective areas prior to Irma?

The best times to leave were early in the morning before dawn, on a given day, in all but one pre-Irma case featured in this analysis. Only Jacksonville-Savannah and Fort Pierce-Turnpike Orlando featured advantageous departure times that occurred after sunrise in the morning. The worst time to leave before Irma was often between 11am and 1pm; in three cases, it was after 6pm (Table 2). This timing is problematic for people who have strict 9-to-5 work schedules or have other

responsibilities prior to a hurricane, because unless they can alter their usual schedules, they will experience heavier afternoon/evening evacuation traffic.

5.3 Limitations

This study used a dataset not typically used to identify evacuation periods. More traditional data types are based on surveys and traffic counts/speeds available from detectors. This initial study faced several limitations that can be addressed in future studies. First, the data collection for this study began potentially after some early evacuees departed, particularly from the Florida Keys. Starting the collection earlier will capture the whole evacuation period. Second, the travel time adjustment process used a distance based on recommended routes, which may not match with the travel times. Future studies should collect both the route distance and the travel time simultaneously. Third, the travel times were based on the shortest travel times, which may not align with evacuee route preferences. Evacuees tend to use Interstates regardless of whether an alternate route's travel time is shorter (Dow and Cutter 2002; Lindell et al. 2019). Future data collection efforts should obtain data for multiple routes. Fourth, the adjustment process used a strong assumption that each vehicle on a route experienced the travel time that applied to each 15-minute interval during which it was on the roadway. This assumption could be relaxed in the future by creating smaller route segments as well as alternative data generation systems (e.g., individual vehicle tracking).

5.4 Future Directions

In this study, adjusting the instantaneous travel times smooths very high and low travel time values (especially high ones). This narrows the range of estimated travel times for a given route, and it shifts the travel time curve slightly to the left as a byproduct of the method. The next logical step is to try to verify the adjusted travel times by obtaining travel time data *recorded* during a pre-event evacuation on specific routes. These recorded times could also be used to compare travel speeds after dark with those during daylight for corresponding traffic counts to determine how much travel speed is affected by lighting conditions during an evacuation.

This study also revealed limited information about the phenomenon of an evacuation caused by flooding and/or power loss. An approach to predicting the occurrence of one of these comparatively spontaneous evacuations might include information about how much experience a given community has with hurricanes, as well as its likelihood of being hit with a strong storm and susceptibility to water inundation. The duration of tropical storm force wind in an area could also be

explored for a relationship with travel, particularly travel occurring after the wind's arrival with and without associated power losses. Hurricane Irma was significantly weakened and well inland by the time it affected communities like Jacksonville and Charleston with heavy rains and storm surge. The degree to which the Jacksonville area in particular could have mitigated roadway congestion after the storm by effecting a preemptive evacuation would make for interesting further inquiry.

The research findings have reinforced two of the established notions about evacuation behavior: daytime preference and living in risk-prone areas leading to advanced evacuation planning. Other features of this study that require further investigation are power outage evacuations and the question of why some households begin their evacuations before state and local officials issue evacuation notices. The relationship between inferred evacuation travel and evacuation notices in this study seem to contradict Baker's (2000) conclusion that typically less than 15% of evacuees depart before evacuation notices are issued. These conflicting results could be due to changes in evacuation behavior over two decades or the difference in research methods. The difference in results warrants additional exploration and the study of evacuation departure times, in general, still has room for additional research (Lindell et al. 2019).

Data Availability

The travel times and calculations are available from the authors upon request.

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Figure Captions

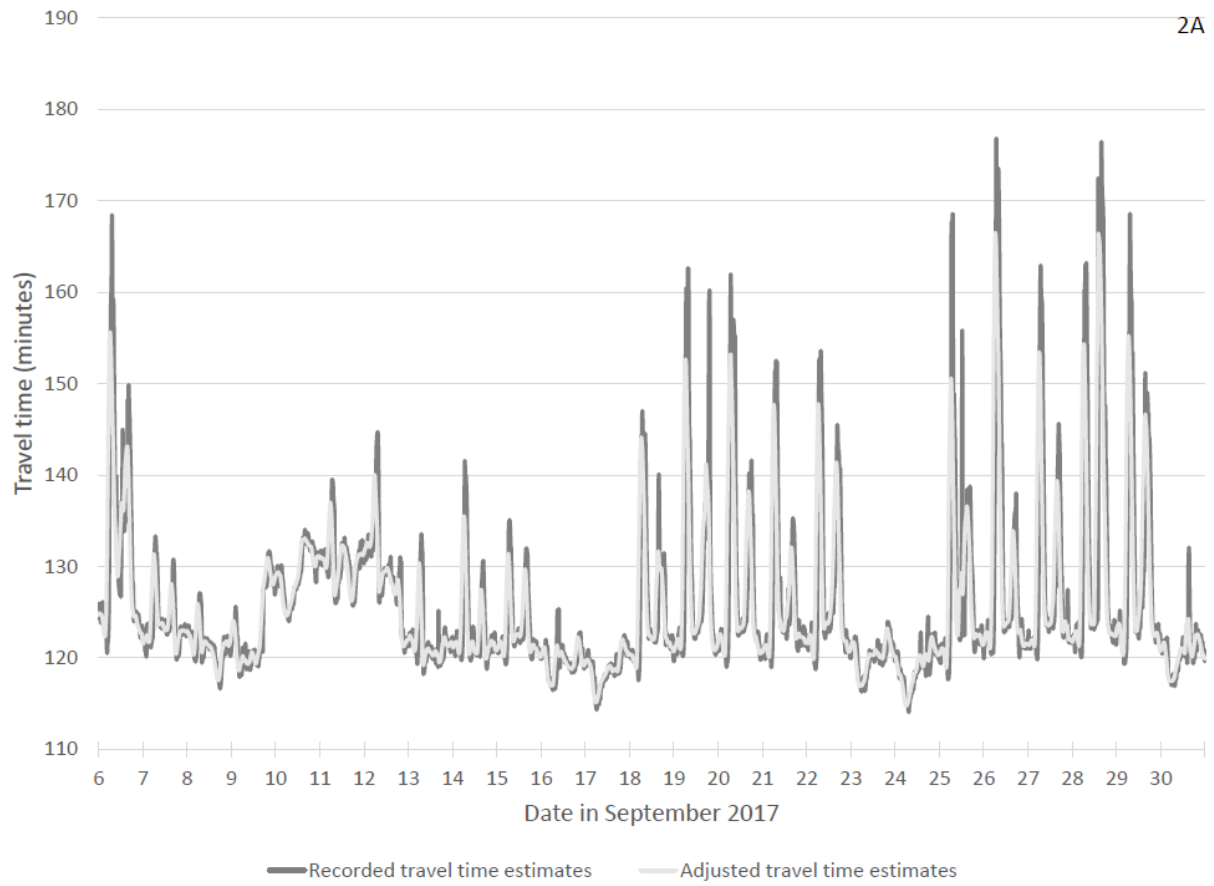
Fig. 1: Routes in this study represented by Euclidian paths with Hurricane Irma's track and strengths; base layer credit to Esri, HERE, DeLorme, MapmyIndia, OpenStreetMap contributors, and the GIS user community; Irma data from Weather Underground (2018)

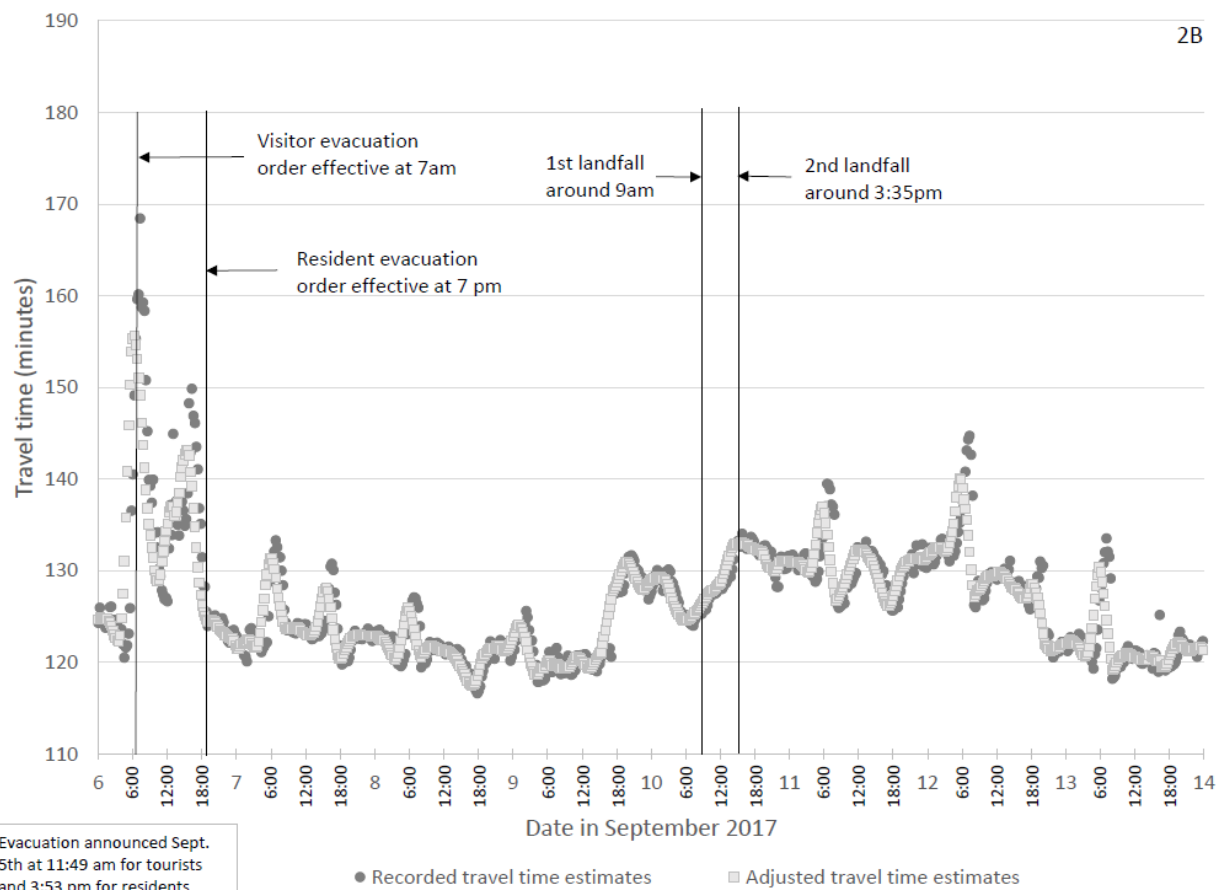
Fig. 2: Key Largo to Belle Glade travel times, 9/6 through 9/30 of 2017 (2A); Key Largo to Belle Glade travel times with announcements and events, 9/6 through 9/13 of 2017 (2B); Port St. Lucie to Sebring travel times, 9/6 through 9/30 of 2017 (2C); Port St. Lucie to Sebring travel times with announcements and events, 9/6 through 9/13 of 2017 (2D)

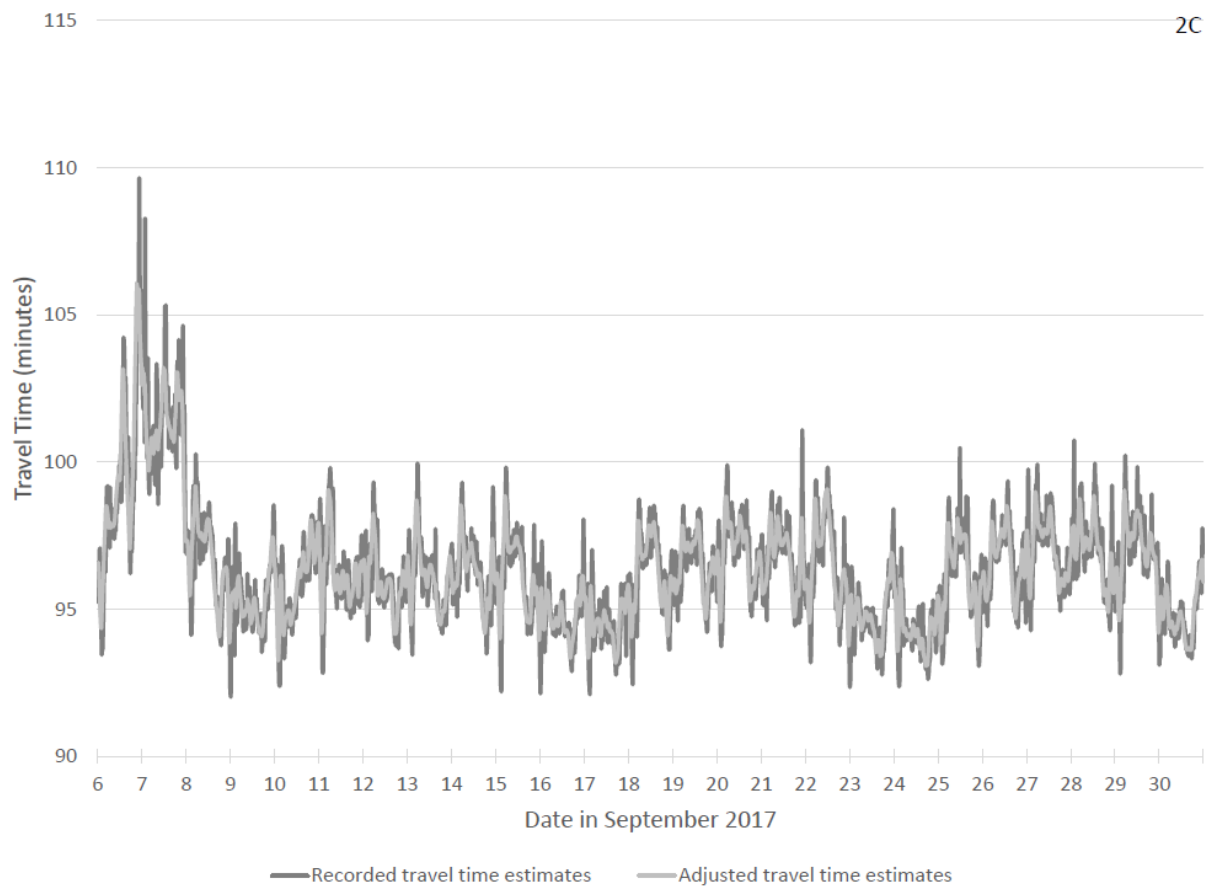
Fig. 3: Fort Pierce to Turnpike Orlando travel times with announcements and events, 9/7 through 9/13 of 2017 (3A); Orlando to Columbus travel times with announcements and events, 9/7 through 9/13 of 2017 (3B); Daytona to Columbus travel times with announcements, events, and portion of power out, 9/7 through 9/13 of 2017 (3C); 95-4 to S95-Jacksonville travel times with announcements and events, 9/7 through 9/13 (3D)

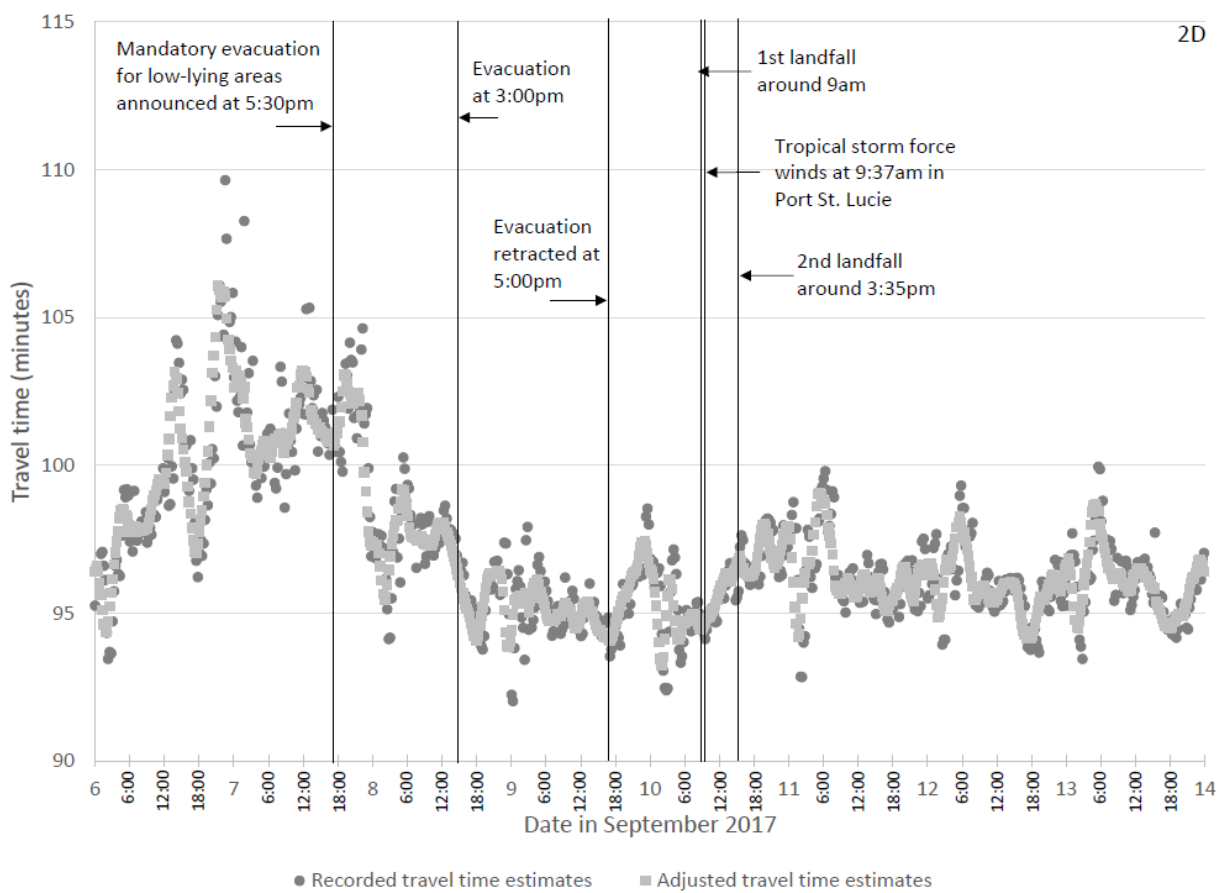
Fig. 4: N75-275 to 10-19 travel times with announcements, events, and portion of power out, 9/7 through 9/13 of 2017 (4A); Jacksonville Beach to Lake City travel times with announcements and events, 9/7 through 9/13 of 2017 (4B); Jacksonville to 95-Savannah travel times with announcements and events, 9/7 through 9/13 of 2017 (4C); 10-19 to Montgomery travel times with announcements, events, and portion of power out, 9/7 to 9/13 of 2017 (4D)

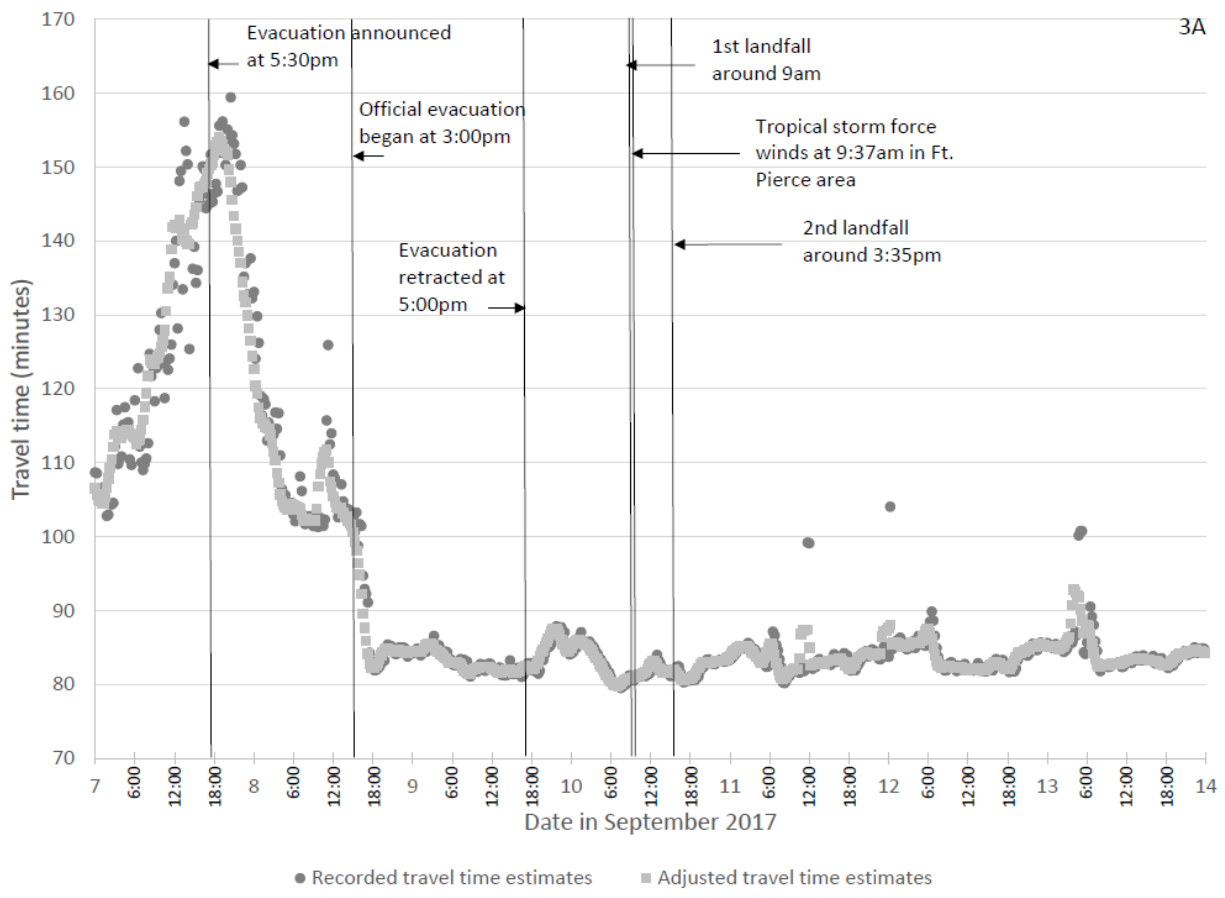
Fig. 5: Charleston to Florence travel times, 9/7 through 9/30 of 2017 (5A); Charleston to Florence travel times with announcements and events, 9/7 through 9/13 of 2017 (5B)



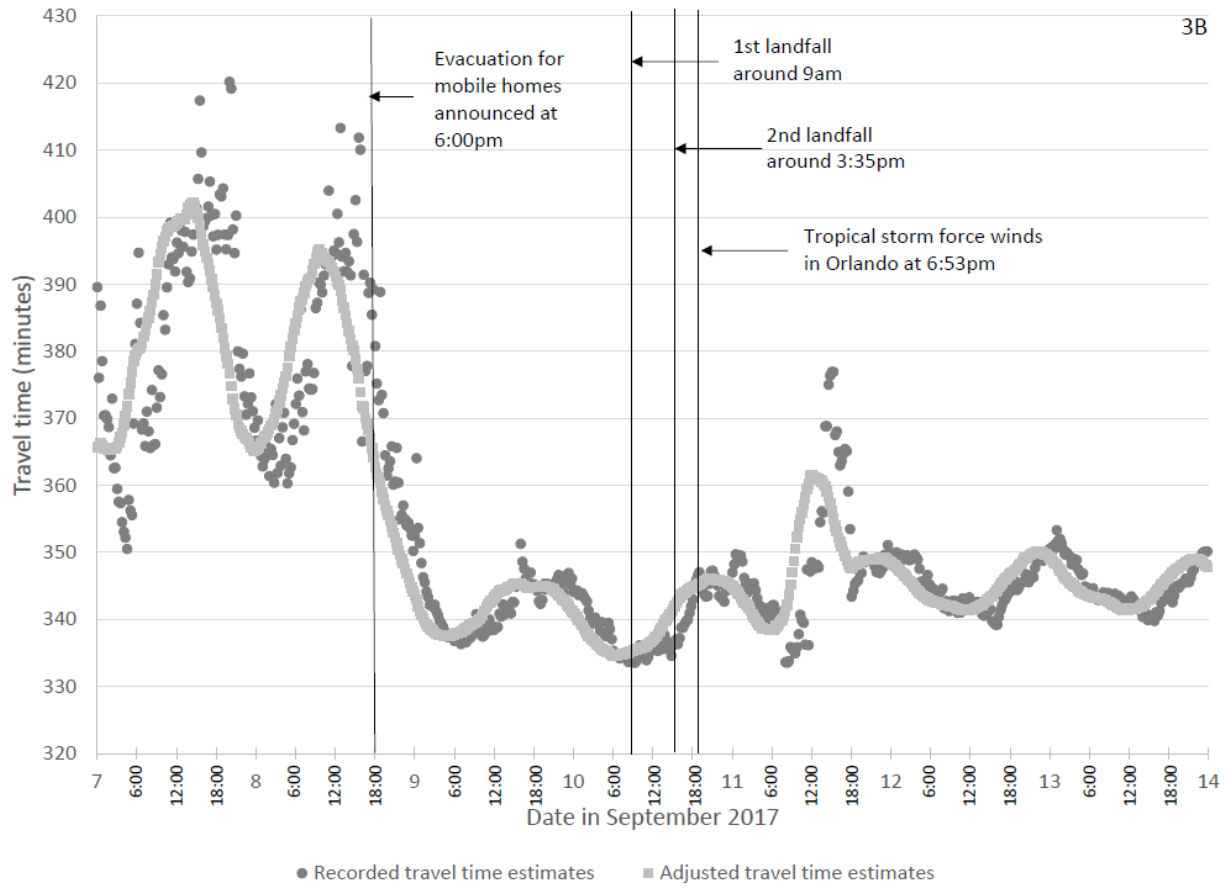


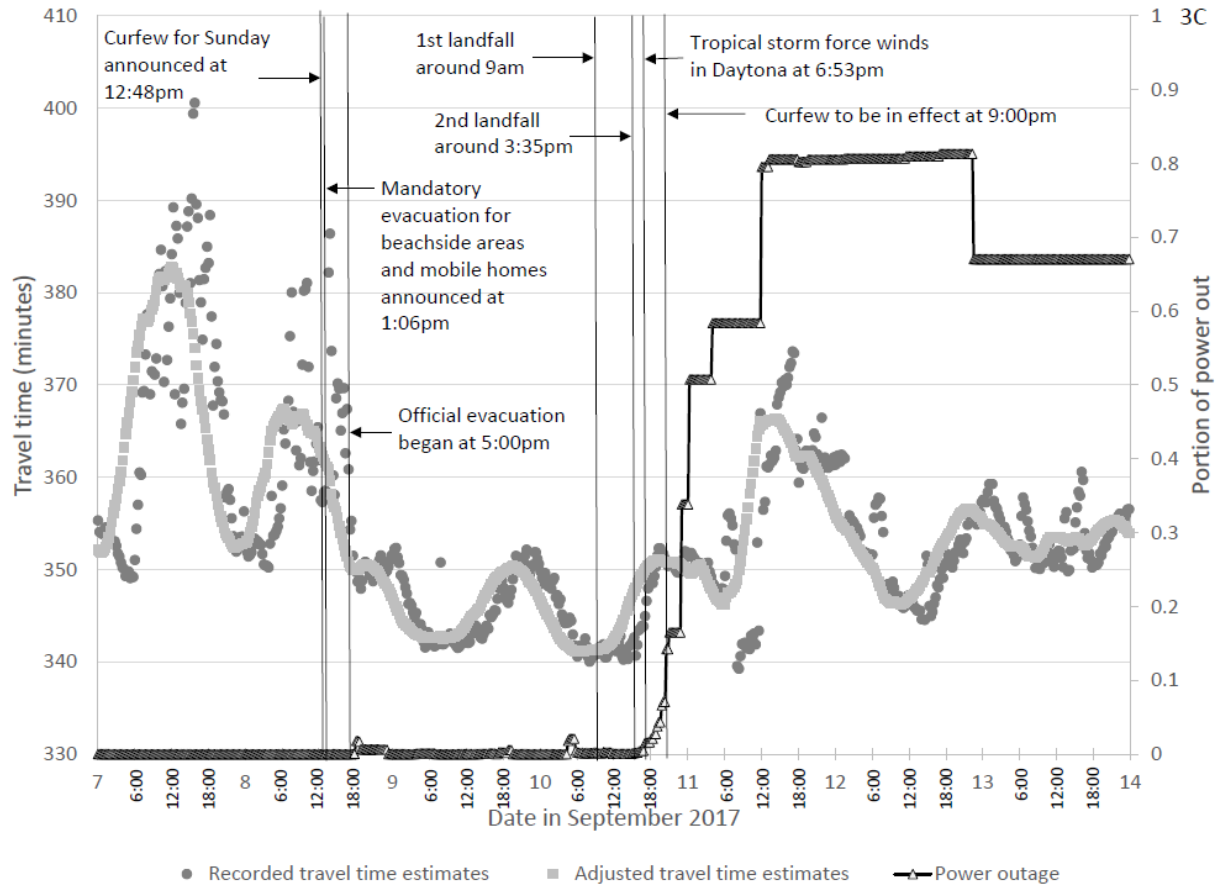






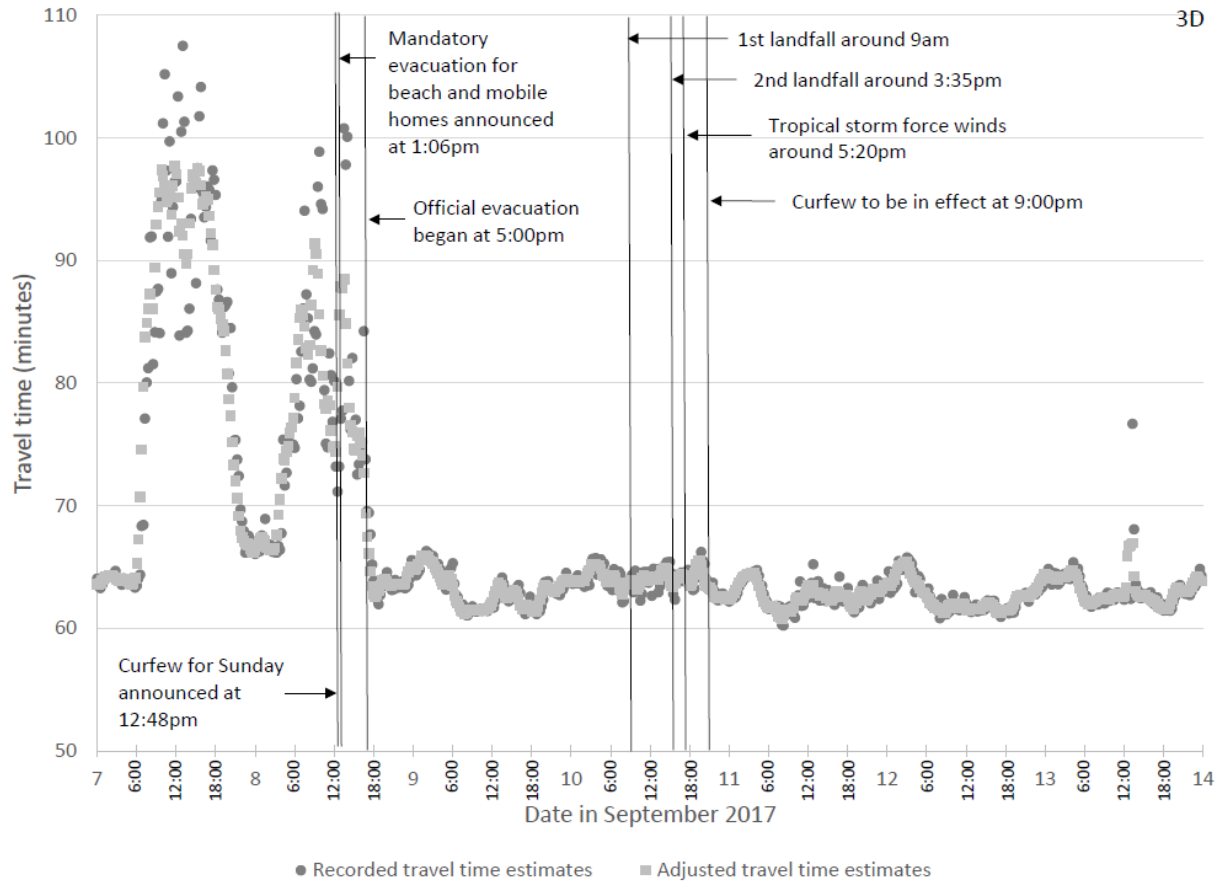
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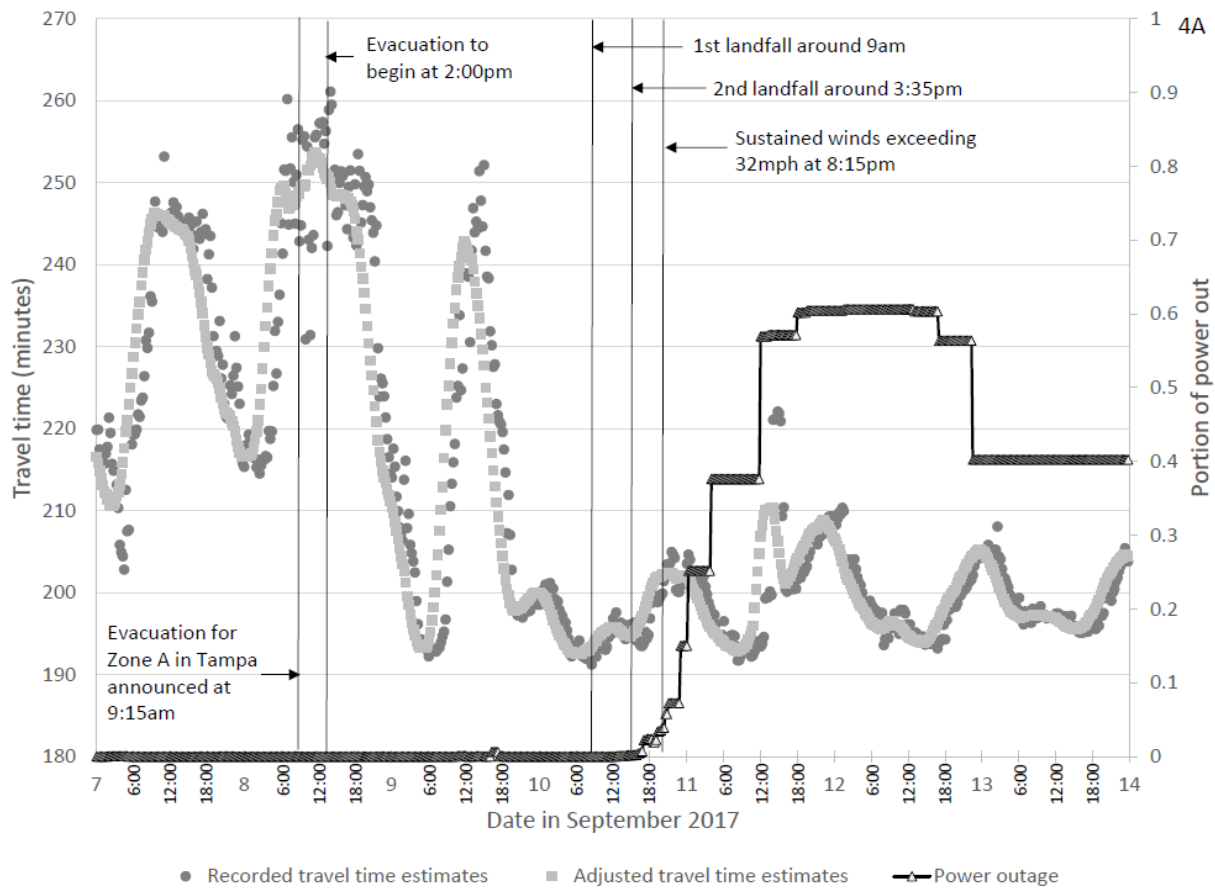
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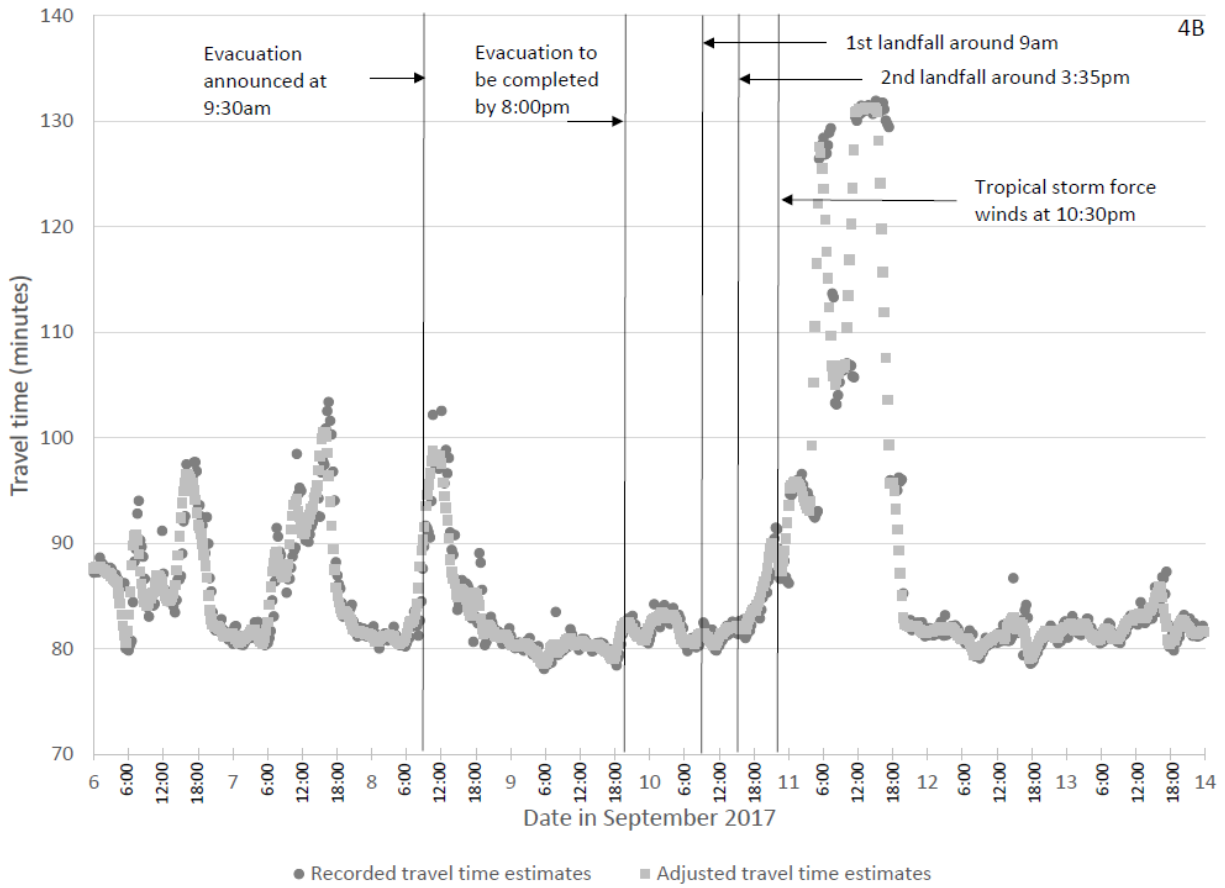
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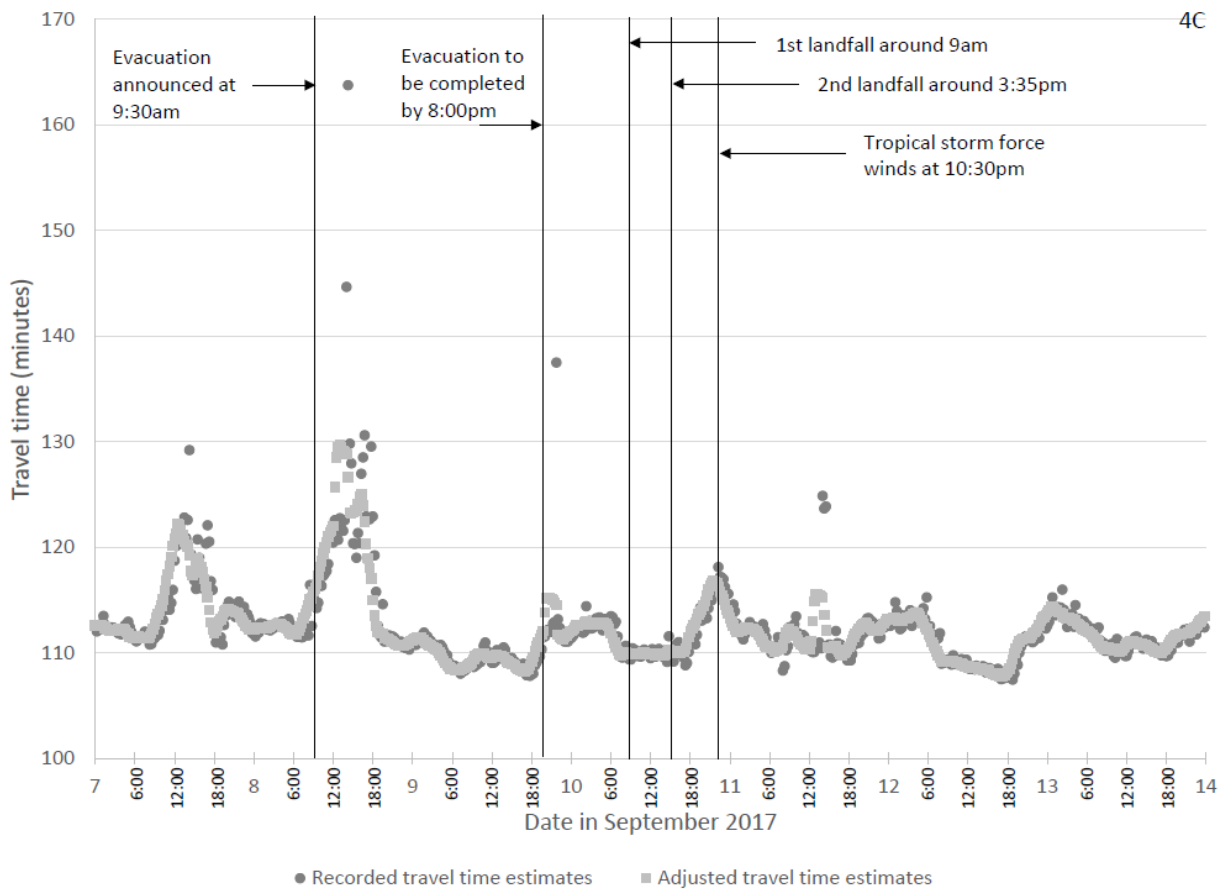
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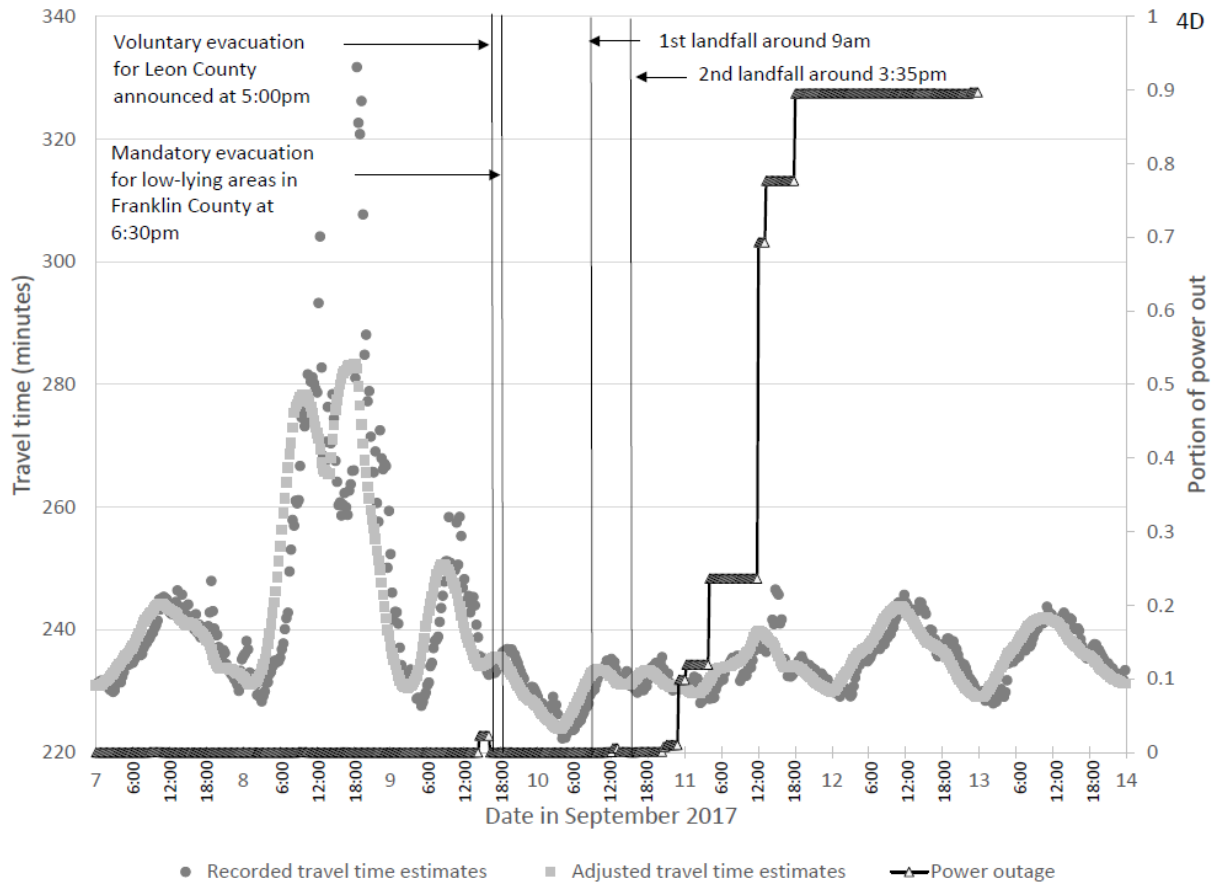
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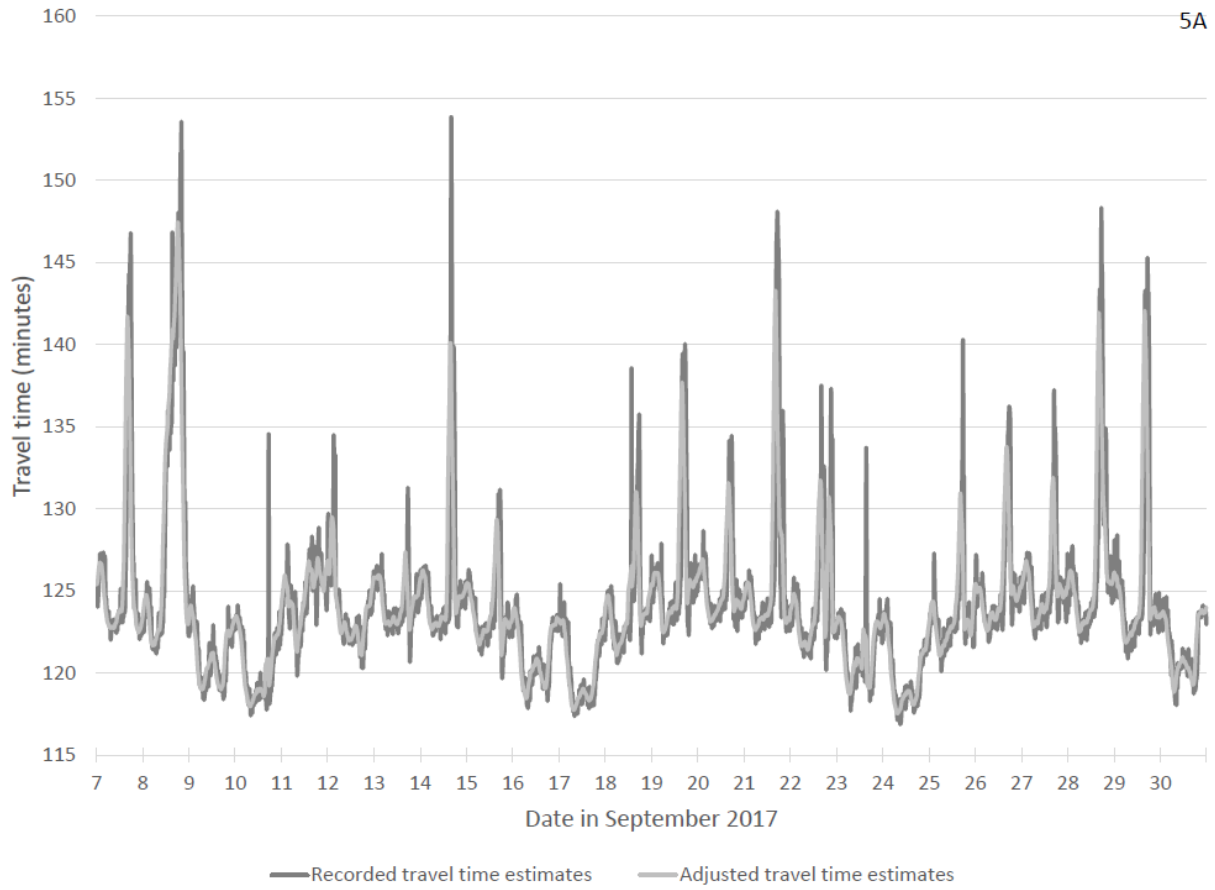
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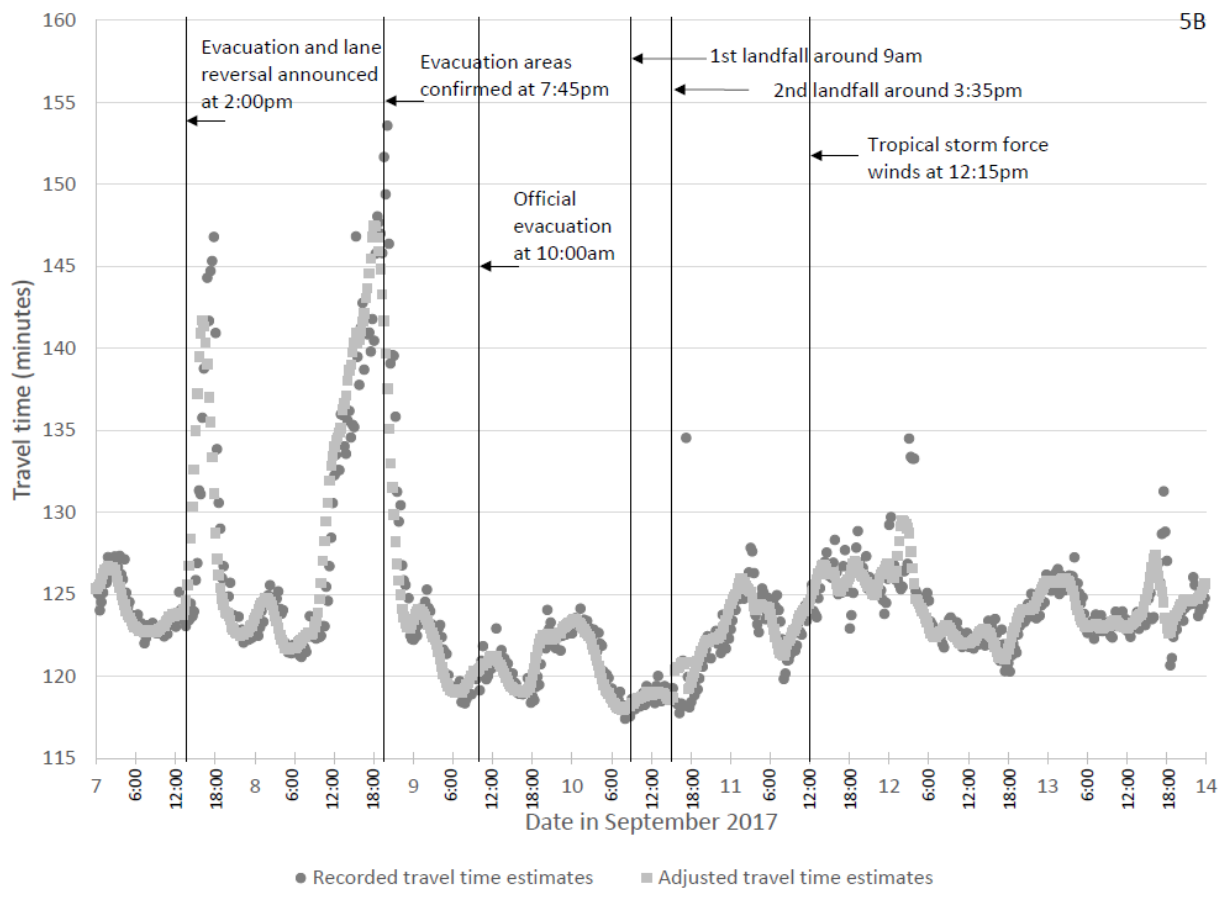
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