Empirical Evacuation Response Curve during Hurricane Irene in Cape May County, New Jersey

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ABSTRACT

Understanding evacuation response behavior is critical for public officials in deciding when to issue emergency evacuation orders during an impending hurricane. Such behavior is typically measured by an evacuation response curve that represents the proportion of total evacuation demand over time during evacuation. This study analyzes evacuation behavior and constructs an evacuation response curve based on traffic data collected during Hurricane Irene (2011) in Cape May County, New Jersey. The evacuation response curve follows a general S-shape with sharp upward changes in slope following the issuance of mandatory evacuation notices. The sharp upward changes in slope represent quick response behavior, which may be in part caused by an easily mobilized tourist population, lack of hurricane evacuation experience, and/or the nature of the location, which in this case is a rural area with limited evacuation routes. Moreover, the widely used S-curves with different mathematical functions and the state-of-art behavior models are calibrated and compared with empirical data. The results show that the calibrated S-curves with Logit and Rayleigh functions fit empirical data better. The evacuation behavior analysis and calibrated evacuation response models based on this recent Hurricane evacuation event may benefit evacuation planning in similar areas. In addition, traffic data used in this study may also be valuable for the comparative analysis of traffic patterns between the evacuation periods and regular weekdays/weekends.
INTRODUCTION

Hurricane Irene crossed and affected much of the east coast of the United States in August 2011. In New Jersey, flood waters covered roadways and transit lines, high-speed wind took down trees and power lines, and caused significant damages and disruptions during the post-hurricane days. Fortunately, thanks to the proactive hurricane evacuation plans by state and local emergency authorities (1-3), as well as early evacuation order declarations (4), the evacuation process in New Jersey was relatively smooth with little traffic disturbance. More than one million people, including at least 90 percent of the residents in the most-impacted counties, left the New Jersey shore over 36 hours after the declaration of mandatory evacuation order (5).

This study investigates the time-dependent evacuation demand during Hurricane Irene in Cape May County, the southernmost county of New Jersey, using empirical data. Evacuation demand rate is typically estimated by using a so-called response or mobilization curve, which estimates the proportion of total demand beginning to evacuate within defined time intervals. These curves have been established either by expert judgment (6-9), or by using mathematical models based on empirical evacuation behavior data (10-13). Because of the environmental, social, and geographic factors (14), evacuation response curves typically vary between different hurricane scenarios.

The objectives of this study are to construct the evacuation response curve in Cape May County, NJ using observed data collected during Hurricane Irene, and assess the state-of-art mathematical models with the constructed empirical response curve. Several features distinguish this study from the previous ones.

First, New Jersey is not a hurricane prone state such as Southeastern Atlantic or Gulf Coast states; Hurricane Irene was the first hurricane to directly hit the state since 1903. While a great deal of research focuses on hurricane prone states (16), northern states along the Atlantic Coast receive insufficient attention. In addition, there is a high seasonal tourist population visiting and living along the New Jersey coast during the summer months. The total population of Cape May County can increase up to 850,000 in summer from 107,000 in winter (3). The behavioral patterns of residents have been well discussed in the literature (14-17); however, much less is known about the empirical evacuation behavior of tourists (18). The data in this study may contribute to this emerging research area (19-20).

Second, when modeling evacuation response behavior, the available models (6-13) are based on empirical data from hurricane prone states. However, whether such models are applicable to states with little hurricane experience is still unknown. In this study, the transferability of the models from hurricane prone states is also discussed by calibrating and comparing a number of mathematical functions presented in the literature (7-9, 12) with empirical data. The results may be valuable for evacuation modeling in similar areas.

Finally, the data used in this study come from automatic traffic counters, rather than from traditional post-hurricane surveys. Compared with post-hurricane surveys, traffic data yield more realistic results and avoid the general “problem of recall” in social science (17). While much attention has been paid to hurricane evacuation behavior analysis, relatively few studies make use of real-world traffic data (21). With the increasing number of sensors being deployed on our roadways, this study also illustrates how to introduce empirical data sources as a useful feedback to evacuation planning.
LITERATURE REVIEW

Research interest in evacuation response behavior started from empirical evidence of population response to emergency warnings. Baker (22) reviewed four post-hurricane sample surveys and identified variables for predicting evacuation behavior. These variables were later summarized in five categories: risk level of the area, action by public authorities, housing, prior perception of personal risk, and storm-specific threat factors (14). More post-hurricane surveys were conducted in late 1980s (23). However, these post-hurricane surveys were criticized as being not statistically reliable due to limited sample size or limited range of emergency situations. Relatively few studies provided concrete evidence on evacuation behavior during a particular type of emergency situation (24).

Besides post-hurricane surveys, the stated preference surveys of potential evacuees were also commonly used in evacuation planning for areas with little prior evacuation experience. However, these surveys suffer from the usual problems associated with discrepancies between what people say they will do during hypothetical situations and what they actually do when confronted with the reality of the situation. “Those expected to evacuate may not, and those who do not need to evacuate often do” (17).

Given the problems associated with using either the revealed or stated preference survey data, some evacuation studies used subjective judgment based on expert experience. The sigmoid curves, also called S-curves, which were introduced by Lewis (6) were generally used to represent the evacuation process. The evacuation rate (number of evacuees choosing to leave over time) starts slowly, then accelerates steeply, and finally slows down again (18). Depending on the speed, S-curves were classified as rapid, medium, and slow response, as shown in FIGURE 1. A number of mathematical functions were used to exemplify the S-curves. Radwan et al. (7) suggested the use of Logistic distribution based on behavioral research. Tweedie et al. (8) used Rayleigh distribution by consulting with experts in the state Civil Defense Office. Cova and Johnson (9) recommended the use of Poisson distribution based on queuing theory.

![FIGURE 1 Evacuation behavior response curves (6)
Although widely adopted in hurricane evacuation plans of different states (23), there are some disadvantages of using S-curves (25). One issue is that S-curves may not be able to model multi-day evacuation with time-of-day variations in evacuation demand. The other issue is their subjectivity by reflecting the analyst’s perception, but not including hurricane characteristics and evacuation behavior. In order to remedy these drawbacks, a Sequential Logit model based on empirical data gathered during Hurricane Floyd (1999) was proposed first by Fu and Wilmot (10) and later updated by Fu et al. (11-12). The data included post-hurricane evacuation response behavior surveys and hurricane-specific characteristics such as wind speed, evacuation order, etc. Recently, a random-parameter hazard-based model was also proposed to understand household evacuation time behavior (13). While these models with behavioral variables contribute to a better explanation of the evacuation process, they are difficult to apply in evacuation planning because such variables cannot be accurately measured and predicted in future hurricane scenarios. A detailed review and comparison of S-curves and behavior models is presented in Yazici and Ozbay (26).

DATA

Recently, a number of studies attempted to use traffic data to analyze evacuation behavior. For example, Wolshon (27) used volume data from automatic traffic counters in Louisiana to investigate empirical maximum evacuation traffic flow during Hurricane Katrina (2005) evacuation. Traffic data is generally preferable to data derived from post-hurricane evacuation surveys in terms of evacuation response curve modeling since the data provide more samples than post hurricane surveys, and since post hurricane surveys are expensive to conduct, and therefore have limited sample size (24). Also, traffic volume data such as electronic toll collection (ETC) data or sensor data do not have the general “problem of recall” in social science, where people may have difficulty in remembering their exactly hour by hour decisions during a hurricane (17).

The data used in this study include hourly toll plaza volume counts on the Garden State Parkway (GSP). GSP is a statewide corridor in New Jersey, and is also the only major (limited access) northbound evacuation route from the shore area of Cape May County. The Cape May toll plaza is a one-way northbound (outbound) mainline barrier tollbooth located at mile marker 19.4 on GSP. In addition, the traffic data from southbound (inbound) Great Egg toll plaza were also collected to check the possible “background traffic” (non-evacuating traffic. Please see a detailed definition in next section). The Great Egg toll plaza is also a one-way mainline barrier tollbooth located at mile maker 28.8 on GSP.

The analyses included in this study are based on hourly traffic volumes from the Cape May toll plaza on GSP during August 24-28, 2011. This traffic primarily comes from Cape May peninsula and coastal barrier islands inside Cape May County, NJ. Thus, the traffic data can also be interpreted as samples of evacuees from all cross Cape May County, NJ. The location and photos of both tollbooths and detailed evacuation process are shown in FIGURE 2.
Sat, Aug 20. Tropical Storm Irene forms in east of Leeward Islands.

Fri, Aug 26.
• 8:00 AM EDT. Mandatory evacuation for the whole of Cape May County becomes effective.

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

Mon, Aug 22. Irene becomes a Category 2 hurricane, and affect significantly in Puerto Rico.

Thu, Aug 25.
• 12:00 PM EDT. New Jersey Governor Chris Christie declares a state of emergency
• 3:00 PM EDT. Mandatory evacuation for the barrier islands Cape May County becomes effective.

Sat, Aug 27.
• 2:00 PM EDT. New Jersey Governor Chris Christie states that one million residents have evacuated their homes, including 90 percent of Cape May County.

Sun, Aug 28.
• 5:35 AM EDT. Irene makes initial landfall in Little Egg Harbor Inlet, just north of Cape May County.

FIGURE 2 Toll plazas on GSP and Hurricane Irene evacuation process (Sources: 3, 5, 28)
EVACUATION TRAFFIC AND DEMAND RESPONSE CURVE

The temporal progression of Irene evacuation traffic is illustrated in FIGURE 3(a): the hourly traffic volume at Cape May toll plaza on GSP Northbound from Wednesday, August 24, through Sunday, August 28. The time stamps of mandatory evacuation orders and Hurricane Irene landfall time are shown as dashed vertical lines. As a reference, traffic flows for the same days during the prior week are also included in FIGURE 3(a), to illustrate typical traffic conditions.

In order to construct evacuation response curve, background traffic is needed to be eliminated by following the suggestions of Urbanik (29). "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" (29). Note that the mandatory evacuation order of barrier islands issued in the afternoon of Thursday, August 25. FIGURE 3(b) shows the inbound traffic volumes at Great Egg toll plaza on GSP. It can be observed that there are no significant differences in traffic patterns between Thursday, August 25 and the same day of the prior week. Such traffic pattern shows that people still commuted to Cape May County in the morning, and possibly went back home as usual in the afternoon. Thus, when constructing the evacuation response curve, the regular commuting trips are eliminated from the traffic volume counts on Thursday, August 25. Such time-dependent commuting demand is assumed to have the same values as the same day of the prior week (Thursday, August 18). The significant reduction in traffic volume on Friday, August 25 in FIGURE 3(b) was caused by the restriction at the entrance. We assume that all of the traffic volume on Friday is due to the evacuation demand.

FIGURE 3(c) shows the evacuation response curve without background traffic derived from the Cape May toll plaza hourly traffic volumes during the evacuation. FIGURE 3(c) also includes the evacuation response curve with background traffic, and the cumulative demand curve based on the same day of the prior week. The demand curves from the literature are shown in FIGURE 1 are also added for comparison purposes.

The volume trend lines in FIGURE 3(a) show the Irene evacuation process in Cape May County. The process started around 9:00am on Thursday, August 25, when traffic volumes start to become significantly higher than the prior week’s volumes. This increase in traffic volumes starts six hours before the mandatory evacuation order for the barrier islands. 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. The so-called evacuation tail (30), less than 8 percent of the evacuees, chose to evacuate on Saturday, August 27. In total, the duration of Irene evacuation in Cape May County was approximately 36 hours, and half of the total number of evacuees evacuated within 23 hours.

It can be observed in FIGURE 3(a) that the evacuees in Cape May County responded very quickly to the mandatory evacuation order. Traffic volumes increased significantly when the official mandatory evacuation order was issued. Two peak evacuation demand periods were observed around the start times of the mandatory evacuation for the shore areas (3:00pm, Thursday, August 25) and the whole county (8:00am, Friday, August 26), respectively. The quick evacuation response behavior is also illustrated graphically in FIGURE 3(c). Sharp upward changes in the slope of the curve represent increases in the evacuation rate following the mandatory evacuation notices. Moreover, it should be noted that because the evacuation order was well before landfall of Hurricane Irene (approximately 72 hours ahead of the storm), the empirical curve is much more spread out than the theoretical ones in FIGURE 3(c).
(a) Outbound traffic counts from Cape May toll plaza on GSP

(b) Inbound traffic counts from Great Egg toll plaza on GSP

(c) Irene evacuation response curves and theoretical curves

FIGURE 3  Irene evacuation traffic and demand response curves in Cape May County, NJ
The quick evacuation response behavior in Cape May County may have been due to the high tourist population. During the summer/hurricane season, more than 85 percent of the people in Cape May County are non-residents. As stated in Drabek (19), tourists exhibited a faster response rate than that of permanent residents. One of the reasons is that tourists, especially day-trippers, do not have the responsibility of protecting their residences. Moreover, tourists usually stay together, thus it is quick for them to gather and evacuate, while residents may be scattered, as discussed in Murray-Tuite and Mahmassani (31-32). Tourists would instead first meet in a single location and then evacuate as a unit. This so-called household trip-chain sequencing may delay residents’ evacuation departure times.

Several other factors may also affect the evacuation response behavior in Cape May County. One critical factor in evacuation behavior is evacuation experience. Residents of New Jersey, unlike Southeastern Atlantic Coast or Gulf Coast states, have relatively little or no hurricane evacuation experience. Prior literature (14-15) found that people with no prior storm experience were more likely to evacuate than those with storm experience. For example, it was observed that without recent major hurricane history, 97 percent of people living in Pensacola and Pensacola Beach, Florida evacuated before Hurricane Frederic in 1979 (14). Another factor that affects the evacuation response behavior is the location type (14). The people who live in rural areas, especially along the shore, are more prone to evacuate than those who live in urban areas. For example, prior to Hurricane Andrew (1992) making landfall in South Florida, people in the Florida Keys decided to leave earlier than necessary. However many in urban areas in and around Miami decided not to leave at all, in part because of a perception of greater building safety in those areas (19).

COMPARATIVE ASSESSMENT OF EVACUATION RESPONSE MODELS

The hourly volume data at the Cape May toll plaza of GSP during Hurricane Irene are extremely valuable for modeling evacuation behavior and comparing with other estimates and responses. As seen in FIGURE 3(c), significant differences are observed between the theoretical evacuation response curves (6) and the empirical evacuation response curve from Hurricane Irene evacuation. In this section, four evacuation response models in the literature (Logit, Rayleigh, Poisson, and Sequential Logit) are reviewed and compared with the empirical evacuation response curve from Hurricane Irene.

Evacuation Response Models

Logit Function

The Logit function suggested by Radwan et al. (7) is the most common approach to model the hurricane evacuation response curve. It is used in some of the developed evacuation modeling software tools such as TEDSS (33) and MASSVAC (34). The Logit function is shown in equation (1):

\[ P_t = \frac{1}{1 + \exp[-\alpha (t - H)^2]} \]  

Where \( P_t \) is the percentage of the evacuees departed by time \( t \), and \( \alpha \) and \( H \) are model parameters to be calibrated. \( \alpha \) gives the slope of the cumulative traffic loading curve, and \( H \) is
half loading time: the time when half of the vehicles in the system are loaded onto the highway network.

Rayleigh distribution

The Rayleigh distribution was suggested by local civil defense officials to describe evacuation departure time (8). The Rayleigh distribution is shown in equation (2):

\[ P_i = 1 - \exp[-0.5(t / \beta)^2] \]  

(2)

Where \( P_i \) is the percentage of the evacuees departed by time \( t \), and \( \beta \) is a parameter controlling the slope of the traffic loading curve.

Poisson distribution

The Poisson distribution is commonly used in queuing theory to describe the probability of \( n \) events occurring within a given time period. The distribution was proposed in Cova and Johnson (9) to model a random evacuation departure process. Poisson distribution is shown in equation (3):

\[ P_i = \exp(-\gamma) \sum_{i=0}^{\lfloor t \rfloor} \frac{\gamma^i}{i!} \]  

(3)

Where \( P_i \) is the percentage of the evacuees that have departed by time \( t \), and \( \gamma \) is a parameter controlling the slope of the traffic loading curve.

Sequential Logit

A sensitivity analysis of evacuation probabilities was proposed in Fu and Wilmot (10) and later improved by Fu et al. (11-12). In the model, each random utility function \( U_i^n \) (utility of a household not evacuating at time \( t \)) and \( U_i^e \) (utility of a household evacuating at time \( t \)) are assumed to be composed of a systematic component \( V_i \), and an error term \( \varepsilon_i \) (i.e. \( U_i^n = V_i^n + \varepsilon_i \) and \( U_i^e = V_i^e + \varepsilon_i \)). Also the utility differences \( U_i^n - U_i^e \) are assumed to be independently, logistically, distributed. Then, the probability of a household evacuating at time \( t \) given that it has not evacuated earlier is shown in equation (4):

\[ P(t)_{e/n} = \frac{\exp(U_i^e)}{\exp(U_i^n) + \exp(U_i^e)} = \frac{\exp(V_i)}{1 + \exp(V_i)} \]

\[ V_i = U_i^e - U_i^n = -2.292 + 1.018*TOD1 + 2.123*TOD2 + 1.949*TOD3 + 2.111*Order1 + 2.356*Order2 + 0.019*Speed - 1.748*Ln(T) \]  

(4)

The linear formulation was calibrated and validated in Fu et al. (12). Where
**Model Comparison and Discussion**

In order to compare the capabilities of the described evacuation response models, in terms of fitting the empirical data from Hurricane Irene, the first challenge is the parameter settings of each model. The values of parameters of each model are not fixed for different hurricane scenarios due to environmental, geographical, and social factors \( (14) \). For example, as stated in Lindell and Pratel \( (35) \), \( \beta = 40 \) provided the best fit of Rayleigh distribution to the empirical data in \( (8) \), while the response curve in \( (34) \) and \( (36) \) was equivalent to a Rayleigh distribution with \( \beta = 45 \) and 74, respectively.

In this section, we first calibrate the parameter settings of each described model with empirical data from Hurricane Irene. Then the results of the calibrated models are compared to find the best fit model. Some recommendations and limitations of the evacuation response models are also discussed.

**Statistical Measure**

The Root Mean Square Error (RMSE) is used in this study to measure the difference between the model result and empirical data. RMSE is a frequently used measure of how close a fitted line is to data points. Specifically, in this study RMSE is the difference between the result of each model and empirical data. It can be mathematically represented as follows:

\[
RMSE(\hat{s}) = \sqrt{E((\hat{s} - s)^2)} = \sqrt{\frac{\sum_{i=1}^{n} (\hat{s}_i - s_i)^2}{n}}
\]

Where \( \hat{s} \) is the fitted result from each model, \( s \) is the empirical data from Hurricane Irene, and \( n \) is the number of time interval (hours) in each S-curve. RMSE is thus the average distance of the empirical evacuation response curve from the fitted result of each model. The smaller the RMSE, the better fit of the model to the empirical data.

**Model Calibration and Comparison**

In this study, in order to calibrate each evacuation response model with empirical data, first the results of the model are calculated with different parameter settings. Then, RMSE values are used to compare each model result with the empirical data, as shown in FIGURE 4. The parameter setting with minimum value of RMSE is chosen as the calibrated one. Because the Sequential Logit model was calibrated and validated with empirical data from Hurricane Floyd and Hurricane Andrew, the parameter settings given in \( (12) \) are directly used in this study.

FIGURE 4 shows that improperly calibrated evacuation response models can have significant prediction error. The average errors of all three models fluctuate from less than 10 percent to as
large as 60 percent in the Poisson distribution. The recommended parameter settings are \( \alpha \in [0.1,0.3] \) for the Logit function, \( \beta \in [15,20] \) for the Rayleigh distribution, and \( \gamma \in [15,20] \) for the Poisson distribution.

As seen in FIGURE 4, the Logit function yields a better fit compared with the other two distributions. As described above, the half loading time \( (H) \) of Hurricane Irene evacuation is 23 hours. When \( H = 23 \), it can be observed that the curve based on Logit function quickly converges and become stable. RMSE is between 15 percent and 20 percent on average, while less than five percent at its minimum. FIGURE 5 graphically shows the difference between each calibrated evacuation response model and the empirical response curve obtained from traffic data collected prior Hurricane Irene. The Logit and Rayleigh distributions fit empirical data better. RMSE of Logit and Rayleigh distribution are 3.21 percent and 4.77 percent, respectively. As a symmetric distribution, the Logit function fit the middle part of the empirical curve very well, as shown between hours 20 and 30, but underestimates the demand during the evacuation process following the mandatory evacuation order (between hours 10-20, and 30-40). While the Rayleigh distribution overestimates the demand during the early evacuation process (the first 24 hours), it generally underestimates the tail of the empirical curve.
However, the Logit function may increasingly misrepresent the empirical data with improper parameter settings of $H$, given the calibrated parameter $\alpha$. As described in Yazici and Ozbay (26), $\alpha$ can be interpreted as the parameter that controls the behavior of evacuees, while $H$ determines the half evacuation loading time or so-called clearance time ($2H$). The Logit density function is a symmetric distribution (35), and therefore given the value of parameter $\alpha$, different values of $H$ can shift the S-curve in the horizontal direction and affect the calibration result. It can be observed in FIGURE 4 that the Logit function with $H = 23$ fits better to the empirical data compared with the other two models (where it is known that the half loading time is 23 hours during Hurricane Irene evacuation). However, the half loading time is difficult to predict due to specific hazard conditions, geographical and social factors. A sensitivity analysis with different values of $H$ is suggested when applying the Logit function in the context of hurricane evacuation planning.

Results Discussion

In summary, in part because of the quick response behavior of evacuees, the response curve during the multi-day Hurricane Irene evacuation process can still be considered as a general S-shape, instead of multi S-shapes, for Cape May County, New Jersey. The widely used S-curve models with Logit and Rayleigh functions also fit the empirical data well.

Moreover, the recommended parameter settings of S-curves for the case of Irene evacuation are also compared with other empirical studies. As summarized in Lindell and Pratel (35), only a
modest amount of empirical data have been used for calibrating and comparing evacuation 
response curves recommended by Lewis (6) shown in FIGURE 1. A recent study by Koshute (40) 
evaluated Logit function vis-a-vis empirical evacuation response curves observed in six different 
hurricane scenarios. The results showed that Logit function with parameter $\alpha \in [0.4,0.5]$ fitted 
better in general for all hurricane scenarios. Such parameter values are slightly higher than the 
recommended setting ($\alpha \in [0.1,0.3]$) for Irene evacuation. However, the model parameter 
settings of empirical studies may also vary significantly, probably due to different environmental, 
geographical, and social factors. For example, $\beta = 117$ and $181$ provided best fit of Rayleigh 
distribution for empirical evacuation departure time distributions of Texas gulf coast residents 
leaving from home or work (35). The parameter settings are significantly different than our 
recommended range ($\beta \in [15,20]$).

The state-of-art Sequential Logit model may not be transferable to other areas with little 
hurricane evacuation experience. FIGURE 5 shows that the calibrated Sequential Logit model 
does not perform well compared with empirical data from Hurricane Irene in New Jersey. One 
possible explanation is that, as concluded by Hasan et al. (37), the parameters of the evacuation 
choice models are only transferable over different hurricane contexts in similar hurricane prone 
regions. The studies that modeled evacuation behavior, including the recent studies about the 
transferability of such models (37-39), are usually based on empirical data from hurricane prone 
regions including Florida and the Gulf Coast states. Obviously, such studies are not usually 
conducted due to insufficient data in northern states such as New Jersey that have little hurricane 
experience. It may also be argued that while regions such as New Jersey are not at high-risk for 
hurricanes, areas with medium or low risks are sometimes more critical and may have significant 
damage potential due to insufficient planning and experience. Sound behavior models will still 
be required to bridge the gap between hurricane prone states and other states with little hurricane 
experience.

Clearly, with the increasing number of traffic sensors being deployed throughout our 
transportation system, this study is also a demonstration of the possible use of empirical data 
sources as an important feedback to evacuation planning process. Compared with post-hurricane 
surveys, data from automatic sensors have several advantages, including large sample size, low 
cost, and wide spatial distribution. Such data may provide benefits for other applications, such as 
the comparison between evacuation traffic pattern and regular weekend traffic pattern, which 
studied by Archibald and McNeil (21). Interestingly, they used sensor data and found that the 
evacuation traffic during Hurricane Irene in Delaware was very similar to the regular weekend 
traffic. Such a finding is reasonable for areas with a high tourist population.

The question of the similarity of hurricane evacuation traffic and the usual weekend shore 
traffic can also be studied using the observed data in this study. In this case, we compared the 
traffic data from the weekends before (Sunday, August 21) and after (Labor Day, Monday, 
September 5) with the hurricane with evacuation data (Friday, August 26). FIGURE 6 shows 
that the evacuees tended to be more risk-averse with 3-4 hours earlier departure time than regular 
weekends and holidays. The comparison shows that evacuation traffic is not totally unpredictable, 
and may benefit from traffic management, especially for those without prior emergency 
evacuation experience. However, this analysis is beyond the scope of this study and may be a 
subject for future work.
CONCLUSION

This study analyzed the evacuation response curve during Hurricane Irene in Cape May County, New Jersey. The hourly toll plaza volume counts on the Garden State Parkway (GSP) were used for the analyses. Compared with traditional post-hurricane surveys, traffic volume data have several advantages, including large sample size, and avoiding the problem of recall in social science. The widely used so-called S-curves with different mathematical distributions (Logit, Rayleigh and Poisson) and state-of-art behavior model (Sequential Logit) are calibrated and compared with observed empirical data. The major conclusions of this study are as follows:

(a) The evacuees in Cape May County responded very quickly to the mandatory emergency order. Traffic volumes increased significantly when the official mandatory evacuation order was issued.
(b) The evacuation response curve is generally S-shaped with sharp upward changes in slope followed the issuance of mandatory evacuation notices. The sharp upward changes in the curve represent the quick evacuation response behavior observed during Hurricane Irene.
(c) The observed evacuation response behavior of the evacuees may have been partly caused by the high tourist population. Other factors such as little to no prior hurricane experience and limited evacuation routes may have also affected the observed evacuees’ behavior.
(d) When comparing different evacuation response models, the calibrated S-curves obtained using Logit and Rayleigh functions are observed to fit the empirical data better. The better fit of S-curves is partly due to the quick response behavior of evacuees.
(e) The Sequential Logit model has not performed well when compared with empirical data. This is possible due to the fact that state-of-art behavior models based on empirical data from hurricane prone regions may not be transferable to states such as NJ with little or no previous hurricane experience.
(f) The empirical data can also be used for comparative analysis of traffic patterns during evacuation periods and regular weekdays/weekends. Our preliminary results show that the evacuation traffic pattern is similar to typical outbound traffic from the shore areas at the end of a summer weekend but with 3-4 hours earlier departure times.
The observed data from Hurricane Irene and calibrated parameter settings of evacuation response models may benefit evacuation planning in areas with similar circumstances as Cape May County, NJ. However, it should be noted that the findings of this study cannot be generalized since they are based on the analysis of a single set of data of evacuation behavior from a specific hazard condition in a particular area. A sensitivity analysis is recommended in other areas based on the calibrated models. Moreover, in order to have a reliable evacuation response model, more empirical data from different hurricane scenarios is required. This data should be used to better calibrate and compare current state-of-practice and state-of-art evacuation response models. In addition, when using traffic data for evacuation response behavior analysis, one limitation of such data is that the traffic volume may come from different counties or regions, and cannot be easily differentiated. In other words, the data may be a mixture of all evacuees from different counties or regions with separate evacuation orders, geographic, and social circumstances. However, such data could still benefit local highway agencies for emergency traffic management in terms of understanding similar hazard conditions.

Moreover, besides evacuation modeling, the behavior analysis is a much more fundamental issue for better understanding of the evacuation decision making process. In this study, we offer several tentative explanations for quick response behavior, which may be in part caused by an easily mobilized tourist population, lack of previous hurricane evacuation experience, and/or the nature of the location, which in this case a rural area with limited evacuation routes. However, such hypotheses still need additional rigorous tests supplemented with the individual information from a large sample of evacuees. The current traffic data does not contain such data. A possible future work can be to conduct evacuation behavior surveys among residents and tourists in Cape May County, New Jersey.
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