Fleeing from Hurricane Irma: Empirical Analysis of Evacuation Behavior Using Discrete Choice Theory

Extended Abstract

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Abstract
In 2017, the United States (U.S.) was severely impacted by a number of devastating natural disasters that required mass evacuations. Of these disasters, Hurricane Irma in September 2017 led to one of the largest evacuations in U.S. history, involving over six million people. This research analyzes the behavior of a survey sample of evacuees and non-evacuees (n= 645) from Hurricane Irma (September 2017) by developing advanced modeling techniques in discrete choice theory. Given recent increases in size and scope of natural disasters and evacuations around the world, this work is a timely contribution to the evacuation and emergency management literature. We uncover and solve several key gaps in the literature related to evacuee behavior by 1) modeling the full multi-dimensional and interdependent nature of evacuee choices; 2) developing a portfolio choice model for evacuation behavior; and 3) advancing a latent class choice model using revealed-preference hurricane evacuation behavioral data. We use these models to infer new behavioral insights from our data, which can be leveraged by practitioners to improve preparedness and response strategies for large-scale evacuations.

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1. Introduction

In September 2017, Hurricane Irma prompted one of the largest evacuations in U.S. history involving over six million people. This paper analyzes the observed decision-making behavior of a sample of individuals impacted by Hurricane Irma (n = 645) by developing advanced methods based in discrete choice theory. Our first contribution is the collection and analysis of a new empirical dataset of revealed evacuation behavior. Second, we use these data to identify population segments with distinct behavior by developing a latent class choice model for the choice whether to evacuate or not. We find two latent segments distinguished by demographics and risk perception that tend to be either evacuation-keen or evacuation-reluctant and respond differently to mandatory evacuation orders.

Evacuees subsequently face a multi-dimensional choice composed of concurrent decisions of their departure day, departure time of day, destination, shelter type, transportation mode, and route. While in previous studies these concurrent decisions are analyzed in isolation, our third contribution is the development of a portfolio choice model, which captures decision-dimensional dependency without resorting to restrictive assumptions on hierarchy. Estimated models reveal subtle yet intuitive relations and allow us to derive new policy implications based on the statistical significance of a wide range of dimensional variables, secondary interactions, demographics and risk-perception variables. For example, we find joint preferences for early-nighttime evacuation and early-highway evacuation, indicating that transportation agencies must have the capabilities and resources to manage significant nighttime traffic along highways well before hurricane landfall.

2. Data

To address the research objectives, we developed an online survey to collect information on the individual choices of those impacted by Hurricane Irma in Florida. We distributed a 146-question online survey from October to December 2017 with the assistance of local emergency management, transportation, public transit, planning, and non-governmental agencies. The survey elicited 921 completed surveys from 1,263 respondents (74% completion rate). We retained 645 cleaned surveys for modeling. Additional details on this underlying data can be found in (*1*).

3. To Evacuate or Not: Development and Application of a Latent Class Choice Model (LCCM)

Latent classes capture population segmentation into specific classes that are not directly observed or measured, but they show distinct behaviors. LCCM applications in transportation and travel behavior have found the influence of latent differences in lifestyles on behavior (*2-4*). Here, we develop and estimate a LCCM for the decision to evacuate, which is the most widely studied evacuation choice.

For the decision to evacuate or not, we identified two distinct classes of individuals. The first class contained individuals who were inherently evacuation-reluctant (reflected by a negative intercept), but they were positively influenced by receiving a mandatory evacuation order. Approximately 45% of the sample was estimated to belong to this class, of which about 15% did eventually

evacuated. The second class contained individuals who were inherently evacuation-keen (reflected by a positive intercept) and were not influenced by the mandatory evacuation order. Of the 55% of the sample estimated to belong to this class about 92% evacuated.

For the class membership model, positive values indicate a higher likelihood to be part of the evacuation-keen class. Risk variables including "worry of Irma severity," "belief of major structural damage," and "belief of injury or death" were all positive and significant. This indicates that individuals with higher risk perceptions have a stronger tendency to evacuate, but they are minimally impacted by receiving a mandatory order. However, those who perceived logistical challenges such as: "worry in finding housing," "finding gas," "housing costs," and "work requirements" were more likely to be evacuation-reluctant, but they may be persuaded by an evacuation order. In general, females, people with pets, previous evacuees, and long-time residents were more likely to be evacuation-reluctant, while families with children and those living in Southwest Florida (where Irma made landfall) were more likely to be evacuation-keen.

Through this latent class construction, we learned whether a socio-demographic characteristic or risk perception was associated with receipt of a mandatory evacuation order. For example, previous evacuees who are evacuation-reluctant may be persuaded to evacuate through a mandatory evacuation order. This signals to agencies that they should target outreach to recently evacuated areas to increase future evacuation rates. This additional behavioral insight and associated policy implication can be extended to other evacuation-reluctant individuals to increase compliance.

4. Evacuations as a Multi-Dimensional Choice: Development and Application of a Portfolio Choice Model (PCM)

After deciding to evacuate, an individual is faced with a multi-dimensional choice composed of the concurrent decisions regarding departure day, departure time of day, destination, shelter type, mode, and route. The core idea behind a PCM is that a choice is made between all possible combinations (called portfolios) of dimensions: each portfolio being a bundle of values, one per dimension (*5-8*). We recognize that we need to determine a suitable level of granularity for the dimensions. High granularity (more categories per dimension) leads to very large choice sets (up to a maximum of 5*2*4*4*3*5=2,400 portfolios per choice set in our case) and risks offering a false sense of precision in light of possible measurement errors present in the data. Based on pre-testing, we split each dimension into a policy-driven and suitable number of categories to offer a rich overview of behavior. This approach offers insightful categorization that is policy applicable. Subsequently, we constructed 144 portfolios by categorizing the different dimensions as follows:
- Departure Day: Early, Regular, Late
- Departure Time of Day: Night, Day
- Destination: Within County, Out of County but Within Florida, Outside Florida
- Shelter: Private, Public
- Mode: Two or More Vehicles, One Vehicle or Other
- Route: Highway, Non-Highway

4.1 PCM: Model Results

As seen in Table 1, results indicated that evacuees have a joint preference for evacuating early, at night, and on highways. This should be interpreted as follows: the probability that a randomly sampled individual will, for example, evacuate early and at night is higher than what would be predicted based on the two direct effects of these variables. The same holds for early departure and choosing highways. During early days of the evacuation, evacuees did not face visibility risks at night due to the hurricane, and the highways were largely clear of congestion. We found the same joint preferences for regular time evacuees when interacted with both night and highway variable. We found, however, that there is a joint disutility for evacuating early and within Florida and within county, largely because these destinations were physically closer than out-of-county and out-of-state destinations. We found a joint preference against evacuating at night and evacuating within Florida and within the county. Given the shorter travel distances, evacuees did not need to evacuate at night to avoid congestion. However, night evacuations and private shelter types had a positive interaction. This may be because friends and family were flexible in accepting evacuees during all hours of the day. Several additional interactions were found to be significant for within county evacuations including a joint preference for two or more vehicles but a joint preference against highways. Evacuees only traveling short distances may have felt more comfortable taking multiple vehicles and would be less likely to use highways given their knowledge of local roads. We found a similar result for individuals who evacuated to a different county in Florida. Within Florida but out-of-county evacuations also negatively interacted with private shelters. This may be indicative of the predominance of public shelters throughout Florida.

Table 1 Portfolio Choice Model Results

	Primary + Interactions			Primary + Interactions + Demographics		
	Estm. Coef.	p-value		Estm. Coef.	p-value	
Primary Variables						
Early Evacuee (More than Three Days Before Landfall)	-0.71	0.050	*	-1.86	<0.001	***
Regular Time Evacuee (Between 2-3 Days Before Landfall)	-0.29	0.153		-0.40	0.155	
Night Evacuee (Between 6:00 pm and 5:59 am)	-1.14	0.002	**	-1.89	<0.001	***
Within County Evacuee (Destination Within County)	1.59	<0.001	***	-0.73	0.547	
Within Florida Evacuee (Destination to Other County)	2.02	<0.001	***	0.76	0.297	
Private Shelter Evacuee (Friend's or Family's Residence)	0.84	<0.001	***	0.20	0.536	
2+ Vehicle Evacuee (Used Two or More Vehicles)	-1.50	<0.001	***	-2.29	<0.001	***
Highway Evacuee (Used Highway for Majority of Route)	0.33	0.250		0.61	0.052	
Interactions						
Early x Night	0.96	0.012	*	0.92	0.016	*
Early x Within Florida	-0.80	0.013	*	-0.95	0.004	**
Early x Highway	1.03	0.007	**	1.07	0.005	**
Regular x Night	0.51	0.107		0.53	0.098	
Regular x Highway	1.39	<0.001	***	1.38	<0.001	***
Night x Within Florida	-0.65	0.015		-0.57	0.035	*
Night x Private Shelter	0.51	0.050	*	0.45	0.088	
Within County x Early	-1.10	0.158		-1.12	0.154	
Within County x Night	-0.73	0.055		-0.66	0.084	
Within County x 2+ Vehicles	1.06	0.002	**	1.12	0.001	***
Within County x Highway	-2.29	<0.001	***	-2.29	<0.001	***

Within Florida x Private Shelter	-0.86	<0.001	***	-0.86	<0.001	***
Within Florida x 2+ Vehicles	0.88	0.002	**	0.89	0.002	**
Within Florida x Highway	-0.95	0.001	***	-0.95	0.001	***
Variables for Early (Base: Late)						
Living in Southeast Region of Florida	------	--------	-----	3.87	<0.001	***
Less than One Year in Current Residence	------	--------	-----	1.48	0.001	***
Children Present in Household	------	--------	-----	0.88	0.010	**
Living in Southwest Region of Florida	------	--------	-----	0.63	0.084	
Received a Mandatory Order	------	--------	-----	-0.54	0.078	
Variables for Regular (Base: Late)						
Living in Southeast Region of Florida	------	--------	-----	2.27	0.030	*
Less than One Year in Current Residence	------	--------	-----	0.92	0.017	*
Children Present in Household	------	--------	-----	0.48	0.073	
Living in Southwest Region of Florida	------	--------	-----	-0.84	0.002	**
Variables for Night (Base: Day)						
Extreme Worry of Traffic	------	--------	-----	0.72	0.006	**
More than 10 Years in Residence	------	--------	-----	0.65	0.049	*
Received a Voluntary Order	------	--------	-----	0.64	0.008	**
Previous Evacuee	------	--------	-----	0.42	0.086	
Young Adult: Under 35	------	--------	-----	0.36	0.164	
Extreme Worry of Finding Gas	------	--------	-----	-0.54	0.047	
Variables for Within County (Base: Out of Florida)						
Living in the Southeast Region of Florida	------	--------	-----	2.12	0.005	**
Experienced a Hurricane Before	------	--------	-----	1.87	0.099	
Received a Mandatory Order	------	--------	-----	1.07	0.001	***
Living in the Central West Region of Florida	------	--------	-----	0.83	0.196	
Household Income $100,000 and Over	------	--------	-----	-1.02	0.010	**
Variables for Within Florida (Base: Out of Florida)						
Received a Mandatory Order	------	--------	-----	1.33	<0.001	***
Living in the Southeast Region of Florida	------	--------	-----	1.28	0.003	**
Living in the Central West Region of Florida	------	--------	-----	1.13	0.151	
Experienced a Hurricane Before	------	--------	-----	0.77	0.198	
Extreme or Some Likelihood Belief of Injury/Death	------	--------	-----	-0.67	0.006	**
Household Income Under $40,000	------	--------	-----	-0.70	0.052	
Variables for Private Shelter (Base: Public Shelter)						
Extreme Worry of Severity of Irma	------	--------	-----	0.71	0.004	**
Pet(s) Present in Household	------	--------	-----	0.68	0.013	*
Young Adult: Under 35	------	--------	-----	0.59	0.033	*
Extreme or Some Worry of Finding Housing	------	--------	-----	-0.71	0.008	**
Extreme Worry of Housing Cost	------	--------	-----	-1.01	0.002	**
Variables for 2+ Vehicles (Base: One Vehicle/Other)						
Own Two or More Vehicles	------	--------	-----	1.40	0.001	***
One and Two Person Households	------	--------	-----	-0.53	0.058	
Less than One Year in Current Residence	------	--------	-----	-0.90	0.021	*
Variables for Highway (Base: Non-Highway)						
Extreme Worry of Finding Gas	------	--------	-----	-0.54	0.016	*
Number of Observations	368			368		
ρ^2	0.093			0.166		
$\bar{\rho}^2$	0.079			0.131		
Final Log-Likelihood	-1,506.1			-1385.9		

Significance: * 95%, ** 99%, *** 99.9%

4.2 PCM: Adding Demographics

We add further insight and explanatory power by inserting demographics to determine the groups of people who prefer specific dimensions of the evacuation choice. Evacuees from Southeast and Southwest Florida and who have lived in their current residence for less than one year were more likely to be early evacuees. Those geographic areas of Florida received warnings and mandatory orders first. People with little experience in their current residence may be unsure if their structure would be able to withstand the hurricane and may not have implemented hurricane-specific home improvements. Households with children were more likely to be both early and regular time evacuees. Families may have a stronger risk aversion, leading them to evacuate early.

Individuals with extreme worry about traffic congestion were more likely to evacuate at night. This is unsurprising considering the majority of congestion occurs during the day. Long-time residents (i.e., over 10 years in residence) and previous evacuees were also more likely to evacuate at night. With prior hurricane experience and knowledge of local routes, these individuals may have felt comfortable evacuating at night. Young adults (under 35) were also more likely to evacuate at night, possibly because they have more comfort driving under low-visibility conditions. However, those who were extremely worried about finding gas were less likely to evacuate at night. Since gasoline resupplies occurred during the morning hours, evacuees may have worried about finding empty stations during their evacuation.

For destination choice, evacuees from the Southeast and Central-West regions of Florida were more likely to evacuate within county or out-of-county but within Florida. We found the same result for those who received a mandatory evacuation. One possibility is that these orders contained additional information about shelters nearby and encouraged evacuees to remain close. Another possibility is these residents may have wanted to remain close to inspect damage. Belief of injury/death was only significant for out-of-county, but within Florida, evacuees. Evacuees who stayed closer within county may have been willing to accept the risks in favor of other benefits (easier communication streams, quicker access back to residence), while long-distance evacuees had a stronger risk aversion. Wealthy households were less likely to evacuate within county, likely due to having access to more assets/resources to travel further distances.

For sheltering choice, individuals who had extreme worry regarding Irma severity were more likely to seek a private shelter, possibly to be closer to their social connections. Households with pets were more likely to evacuate to private shelters, which were more likely to accept pets in contrast to public shelters. Young adults (under 35) were also more likely to evacuate to a private shelter, which may be related to their stronger friend networks. Those worried about finding housing and housing costs were less likely to evacuate to a private shelter. These worries may have been related to a limited network to assist in sheltering, adding new evacuation logistic challenges that must be overcome.

Evacuees owning two or more vehicles were more likely to use two or more vehicles while evacuating. Alternatively, smaller households with less drivers and vehicles were less likely to use two or more vehicles. Regarding highway evacuations, those with extreme worry of finding gas

were less likely to use highways. Evacuees may have perceived congestion and gas shortages to be linked and were willing to use smaller roads to find stations. Overall, we did not find any other significant variable for highway evacuations, suggesting that the choice may be more related to the variables of the route and less on demographic variables.

5. Conclusions

Using revealed-preference data of individuals impacted by Hurricane Irma through a robust and extensive online survey, we addressed the first gap by developing a LCCM that adds behavioral insights through two distinct classes of individuals. We found two clear classes exist a: 1) class of keen evacuees who were driven to evacuate through risk perception and 2) class of reluctant evacuees who preferred to stay in part due to a perception of significant evacuation logistic barriers yet could be encouraged to leave by receiving a mandatory evacuation order. This additional information, connected to class membership, pinpoints who should be targeted with a mandatory evacuation order

To address the latter two gaps, we constructed a PCM that could jointly model the multi-dimensional choice for evacuees. We found that multiple individual and household variables, risk perception variables, and dimension variables were significant. We also discovered that evacuees have a joint preference or joint dislike for certain secondary interactions among the concurrent decisions, further indicating choice dependency. Most importantly, we showed the applicability of the PCM in the evacuation field by successfully modeling multiple dimensions jointly without an imposed hierarchical structure. While the PCM requires additional verification in an evacuation context using other revealed preference datasets, this research signifies a key step toward more accurately analyzing evacuation behavior using discrete choice theory.

6. References

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