

A Theory of Evacuation as a Coordination Problem

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Abstract:

On August 29th, 2005, New Orleans was hit with one of the most damaging hurricanes in the history of the United States. Even before the storm, the Federal Emergency Management Agency (FEMA) listed a hurricane strike in New Orleans as one of the most ruinous threats to the nation. Despite these warnings and the mandatory evacuation orders, more than 70,000 citizens chose not to evacuate the city prior to the storm. Previous literature focuses on income, frequency of exposure to hurricanes and credibility issues to explain the unwillingness of individuals to evacuate (Baker, 1991; Gladwin & Peacock, 1997; Lindell and Perry, 1992). In this paper, I propose a theory of evacuation based on individuals' property related concerns. During a hurricane strike, it is especially difficult to maintain law and order. Thus an individual might decide to put his life at risk in order to protect his property; causing coordination problems. I model evacuation decisions as a noncooperative game and examine its Nash equilibrium. I find that as property-related concerns increase, probability of evacuation decreases. I further find that as the number of residents increase in the city, probability of evacuation decreases. This paper provides the policy makers with the tools to determine welfare associated with mandatory vs. voluntary evacuation orders and the groundwork to lay out guidelines to follow prior to making any type of evacuation decision.

I. Introduction

Hurricane Katrina was the costliest and one of the deadliest hurricanes in the history of the United States. The estimated cost to the economy was around \$ 81.2 billion dollars and at least 1,836 people lost their lives (National Hurricane Center [NHC], 2006).¹ When New Orleans mayor Ray Nagin ordered a mandatory evacuation 19 hours before landfall, he emphasized that there may be extensive flooding which could ultimately lead to the deaths of many citizens. Unfortunately, despite aggressive warnings, 70,000 Louisianans decided not to evacuate the city following the announcement of the mandatory evacuation (United States House of Representative [USHR], 2005). As a consequence, there has been a lot of discussion among policymakers about why people put their lives at stake by choosing not to evacuate.

Previous research that is unique to Hurricane Katrina is very limited in scope. Most of the work comes from the public policy domain supported by governmental investigations and surveys (USHR, 2005; Harvard School of Public Health [HSPH], 2005). The most recent research has been carried out by the Select Committee appointed by U.S. Congress (USHR, 2005). Their analysis, which dealt with issues such as evacuation, communication, law enforcement, command and control, was a detailed overview of Katrina. This research was not academic and could not draw any conclusions about households' evacuation decisions during the hurricane. Another attempt to understand the motivations of the residents of Alabama, Louisiana and Mississippi was made by the Harvard School of Public Health (HSPH, 2005). Harvard School of Public Health (2005) conducted a survey among 100 randomly selected adult evacuees residing

¹ The estimated cost to the economy for Hurricane Andrew (1992) was \$44.8 billion, for Hurricane Wilma (2005) was \$20.6 billion and for Hurricane Charley (2004) was \$15.4 billion.

in Houston shelters to determine why evacuees chose not to leave New Orleans despite mandatory evacuation orders. The answers of the evacuees were quite varied, ranging from not having access to a car, to not wanting to leave a pet behind. Needless to say, the small sample size of this survey makes it difficult to draw from it any confident conclusions.

There have been scholarly studies of hurricane evacuation behavior more generally, but they are also small in number. Most research in the academic field has been conducted by economists, sociologists and geologists (Gladwin & Peacock, 1997; Dynes, 2002; Dow & Cutter, 1997). The research was mainly empirical, based on phone surveys of people living in high-risk areas and sometimes backed up with theoretical models. Previous literature has concentrated mostly on three reasons that may explain the decisions of people to comply (or not) with a mandatory evacuation order: government credibility issues due to false alarms; previous and/or recent exposure to hurricanes; and income (Baker, 1991; Whitehead, 2004; Gladwin & Peacock, 1997; Lindell and Perry, 1992). Contrary to the popular belief that false alarms significantly affect a household's decision to not evacuate during future natural disasters, Lindell and Perry (1992) find that people living in areas that are frequently threatened by natural disasters may be more likely to comprehend the significance of the threat and to comply with warnings. As long as the rationale for evacuation orders is understood, false alarms are unlikely to reduce willingness to evacuate in the future (Dow & Cutter, 2000). Prior studies which concentrate on previous and/or recent hurricane exposure indicate that experiencing multiple natural disasters is not uncommon. At least one-third of natural disaster survivors may have experienced another disaster (Freedy et al., 1994). An

additional analysis by Sattler (2000) reveal how there is a high, positive correlation between previous and future evacuation behavior. People who are likely to evacuate during future hurricane threats are the same people who evacuated during a previous hurricane experience. Finally, studies which investigate the relationship between income and evacuation behavior have found that income is not a good predictor of future household behavior. According to these studies, having more income, and thus more means to evacuate, did not increase the likelihood of evacuation.

Focusing as it does on credibility, frequency of exposure, and income, none of the research just discussed can help us understand why people did not evacuate for Hurricane Katrina, for there is reason to believe that neither credibility, frequency, nor income were important factors with respect to Katrina. For households in New Orleans, credibility could not have been an important factor that influenced their decisions to leave the city since the mandatory evacuation ordered by Mayor Nagin on August 29th, 2005 was the first ever mandatory evacuation in the city's history (Fox News/Associated Press, 2005). Considering the fact that the last two major hurricanes that struck New Orleans were Hurricane Betsy and Hurricane Camille (which took place in 1965 and 1969 respectively), we can assume that the frequency of exposure to hurricanes would not be a sufficient explanation of behavior during Katrina either. Furthermore, the evidence that the victims of Hurricane Katrina were roughly proportionate to the pre-landfall population (based on census data) in terms of wealth, shows how income was also not an underlying factor for Hurricane Katrina (USHR, 2005). In other words, lack of sufficient means to evacuate was not the main determinant for individuals who decided not to evacuate the city prior to Hurricane Katrina.

So what might explain the decisions of New Orleans residents to stay in the city and not evacuate, despite the mandatory evacuation order? In this paper, I propose a theory of evacuation based on individuals' property related concerns, which I define as any valuables they leave behind.² An individual's property faces two threats during a hurricane strike. The first threat to his property is caused by the severity of the hurricane. The second threat arises from potential criminals who decide to not evacuate. Recall that during a hurricane strike, it becomes especially difficult to maintain law and order in the city. This state of anarchy gives potential criminals an opportunity to harm others' properties. Hence, an individual might put his life at stake to stay behind and protect his property.

Coordination problems in the face of an evacuation occurs when an individual chooses to stay behind to protect his property from other residents who he assumes are not evacuating when, in fact, they have already evacuated. Coordination problems might explain why a need for mandatory evacuation evolved. By forcing all individuals out of the city, the governments try to solve the coordination problem. However, a mandatory evacuation order might be socially inefficient since it forces each individual to incur a cost of evacuation. This paper expands the existing literature by modeling evacuation behavior as a coordination problem which arises from property-related concerns.³

To investigate the potential coordination problem, I have a constructed a theoretical model in which a city with two citizens, is about to be struck by a hurricane.

² Such valuables include houses, cars, pets, elderly and sick relatives at stake or any tangible property left behind in the house

³ The coordination problem is similar to the Battle of the Sexes game where a husband and wife might fail to coordinate due to miscommunication problems

While the severity of the hurricane, the cost of evacuation, and value of surviving are commonly known by all residents, the property value of each individual is privately known, though others have some knowledge over its distribution. Under voluntary evacuation, each individual decides whether or not to evacuate independent of others. I model these decisions as a non-cooperative game and examine their Nash equilibria. In equilibrium, I find that each individual follows a cut-off strategy: evacuate if the property value is less than a threshold, and stay behind otherwise.

In my model, I will first analyze evacuation patterns for two people, living in a city where the wealth has a uniform distribution. I will further extend my model to all cumulative distribution functions and to all population sizes and analyze how property concerns and number of residents affect probability of evacuation. My first finding is that as property-related concerns increase, probability of evacuation decreases. My second finding is that as the number of residents increase in the city, probability of evacuation decreases.

The abovementioned conclusions have essential policy implications. Mandatory evacuation is important in the face of a natural disaster such as a hurricane because the majority of individuals would not voluntarily evacuate. Unfortunately, mandatory evacuation orders are ordered arbitrarily; they are inefficient. They create a sense of urgency, yet fail to be enforced at a legislative level. This paper provides the policy makers with the tools to revise the current evacuation legislation, to determine welfare associated with both types of evacuation decisions and to precisely define the parameters under which a mandatory vs. voluntary evacuation should be called.

This paper is organized into six main sections. Section II reviews the relevant literature on hurricane evacuation. Section III presents a theoretical model to help explain how two individuals decide to evacuate or stay during a hurricane strike and analyzes welfare implications in a uniform distribution of wealth. Section IV extends the model to more than two individuals and analyzes the changes in evacuation behavior and welfare implications. Section V broadens the scope of the paper from a uniform distribution to all cumulative distribution function. Section VI concludes with the results, policy implications of the model and avenues for future research.

II. Literature Review

Hurricane evacuation literature is scant, partly because there is no clear definition of mandatory and voluntary evacuation (USHR, 2005). There are widely accepted facts that people who hear mandatory evacuation orders are the most likely to evacuate, while recommended evacuation orders are met with less urgency (LSU Hurricane Center [LSU], 2001). It is also known that individuals who receive a voluntary evacuation order are twice as likely to evacuate than those who did not receive an order at all, while those who received a mandatory evacuation order are almost five times more likely to evacuate (Smith, 1999). Unfortunately, the lack of a precise definition of mandatory versus voluntary evacuation is likely to have discouraged further research by academics, especially economists.

The previous literature focused on credibility issues, frequency of exposure to hurricanes and lack of income to investigate evacuation patterns. The existing literature on hurricane evacuation behavior is divided into three strands. One strand consists of

face-to-face interviews or surveys conducted mostly by universities in evacuation shelters among randomly selected adults (HSPH, 2005; HSPH, 2006; Southeast Louisiana Hurricane Taskforce [SLHT], 2005; LSU, 2001). Another is research prepared by government agencies, which has started contributing to the literature significantly over the past decade (USHR, 2005; Congressional Research Center [CRS], 2005). Finally, academic studies from economics and environmental science constitute the third strand of the prior literature (Dow & Cutter, 2000, Sattler, 2000, Whitehead, 2000). Academic research has given more emphasis to empirical analyses, even though theoretical models explaining evacuation behavior can be found. Theoretical models relating to hurricane evacuation have mainly used revealed preferences. Revealed preference data has a limited scope, since it can only be used to predict evacuation rates during similar hurricanes. Stated preference data can assess behavior and response to different hurricane situations through hypothetical questions. Unfortunately it is prone to hypothetical bias⁴ (Whitehead, 2003) which makes it harder for the findings to be extended to future hurricane situations.

The previous literature mainly investigated factors that influence a household's decision to evacuate: the credibility issues due to false alarms, previous and/or recent exposure to hurricanes and income. The popular belief that the credibility of emergency managers and government officials is the major determinant of future evacuation behavior has been analyzed by Dow and Cutter (2000). Dow and Cutter performed a

⁴ Hypothetical bias refers to the tendency for participants of surveys or field studies to overestimate their willingness to pay, their willingness to engage in an activity since the respondents do not incur real costs and are passive decisions-makers. For example, participants of evacuation surveys might overestimate their probability of evacuation since they are not engaged in the active costly process of evacuation, but passive cost-free process of decision making.

survey of residents of Hilton Head and Myrtle Beach, S.C., and Wilmington, N.C., after Hurricanes Bertha (July, 1996) and Fran (August, 1996). Of the respondents 39% evacuated for both hurricanes, 37% stayed home for both and 21% did not evacuate for Bertha but evacuated for Fran. Dow and Cutter found a significant reduction in the credibility of government officials and emergency managers from Bertha to Fran; however, credibility issues were irrelevant in households' decisions. Furthermore, since the mandatory evacuation ordered by Mayor Nagin was the first ever, in the history of the city, false alarms have no significance in the case of Hurricane Katrina.

Exposure to recent and/or previous hurricanes was studied by Baker (1991). He found that in Hurricane Carla, which struck Texas, one of the better predictors of evacuation behavior was whether people had evacuated for past hurricane threats; those who had left in the past were also more likely to evacuate in Hurricane Carla. However, this research does not help clarify why 70,000 Louisianans did not evacuate since New Orleans did not have very recent hurricane activity prior to Katrina. Hurricane Betsy from 1965 and Hurricane Camille from 1969 were the most recent storms that severely affected the area.

The Select Committee appointed by the U.S. Congress identified income to be an imperative factor in households' reluctance to evacuate (USHR, 2005). According to the Select Committee, many people in New Orleans lived on a fixed income such as a Social Security check or a retirement check. These households have exhausted their limited income by the end of the month and did not have the financial means to evacuate. On the contrary, prior studies show that income is related to the distance traveled during

evacuation, but not to the decision to evacuate prior to the storm (SLHT, 2005). Furthermore, the victims of Hurricane Katrina were roughly proportionate to the pre-landfall population (based on census data) in terms of wealth (USHR, 2005). The statements of Louisiana First Assistant Attorney General Nicholas Gashassian who stated that there were approximately 250,000 vehicles left in New Orleans further verifies the findings about wealthier individuals. Many people with the financial means to leave the city chose not to. A major drawback of these income-related studies is the way they define income. Income has been too narrowly defined to mainly include liquid assets such as annual earnings, salaries or wages before taxes (USHR, 2005). However, in this paper, I will extend the definition of income to wealth to include all the tangible and intangible possessions an individual highly values.⁵

As I have just outlined, most literature has analyzed evacuation behavior in the context of credibility issues, recent and/or previous exposure to hurricanes and income. In this paper, I will consider another factor, property-related concerns, which I suggest had a significant affect on the evacuation behavior of New Orleanians during Hurricane Katrina. Despite the fact that no empirical or theoretical research exists on how property-related concerns specifically affected Louisianans during Hurricane Katrina, there is evidence to suggest that these concerns are especially relevant for New Orleans due to the inadequacy of law enforcement institutions. According to the Uniform Crime Reports of the Federal Bureau of Investigation (2004), the property crime rate and the violent crime

⁵ In this paper, an individual's wealth could include pets, extended family members, elderly and sick relatives at stake, tangible property left behind in the house etc... In fact, on May, 22,, 2006, the House passed a bill which requires states consider pets future emergency preparedness plans to qualify for grants from the Federal Emergency Management Agency (FEMA) – supporting the importance of extending the definition of income to wealth. This assumption further clarifies why tourists who had no tangible or intangible wealth at stake in New Orleans were the first ones to evacuate regardless of their income ('A Failure of Initiative', 2005)

rate per 100,000 habitants for New Orleans have always been above the national average.⁶ In addition, Louisiana was the state with the highest murder rate in 2004. The presence of high levels of crime and violence causes Louisianans to have concerns over the safety of their properties and their lives. This is further confirmed by a survey conducted by the Committee for a Better New Orleans (CNBO) in 2000 where 73% of residents living in New Orleans stated that they were worried about their personal safety.

Despite the prevalence of violence and crime in the city, the law enforcement institutions are relatively inefficient and small in size. Even though New Orleans has a homicide rate 10 times that of the American average (Tarrant, 2005), the number of police officers per capita is lower than many other cities- especially cities with comparable murder and crime rates (CNBO, 2000). Only 25% of the people arrested in the city for serious murder are eventually convicted. Due to the inefficiencies, the residents of New Orleans do not trust their police officers to protect and serve them. In addition, they are reluctant to come forward as witnesses, fearing retaliation- further diminishing command and control in the city. Lack of confidence in the law enforcement capabilities of the city were demonstrated in 2004 during a university experiment. During this experiment, the police fired 700 blank rounds in a New Orleans neighborhood in a single afternoon, yet no one called to report gunfire (Tarrant, 2005). I claim that the inadequacy of the police force and the lack of an efficient law enforcement mechanism might have caused individuals, even those with the means to evacuate, to stay behind to ensure the safety of their property. In fact, a report prepared by CNBO in 2000

⁶ In 2004, the property crime rate and the violent crime rate per 100,000 habitants in New Orleans were 4,425.3 and 673.4 respectively compared with the national average of 3,517.1 and 465.5 respectively.

acknowledges these property-related concerns by emphasizing the importance of better communication with the public in the face of a Category 4 or 5 storm, as many individuals have indicated they would stay home to protect their property.

This paper employs these property related concerns to construct a general theoretical framework for evacuation literature. My first hypothesis is that as property concerns increase, probability of evacuation decreases. My second hypothesis is that as the number of residents in a city increase, coordination problems lead to a lower probability of evacuation. This paper further provides the policy makers with the tools to evaluate expected welfare associated with voluntary and mandatory evacuation orders.

III. Theoretical Framework

One of the basic assumptions of neoclassical economics is that decisions-makers are utility-maximizing rational individuals. Consequently, an individual who is trying to determine whether he should evacuate the city or stay prior to a hurricane goes through a cost-benefit analysis. He has two different payoff functions regarding his evacuation behavior. If he decides to evacuate the city, he will face a completely different payoff function than if he decides to stay. He compares these payoff functions to determine his voluntary evacuation behavior.

The variables in our model are as follows⁷:

w_i = the wealth of an individual determined from a random distribution of wealth $F(w)$ where $w_i \in [0, \bar{w}]$. The information about w_i is not publicly known. An individual has information only about his own wealth.⁸

⁷ In real life, the value of life is not equal for all and the probability that someone is a criminal is not fixed, however I make these assumptions about v and γ for tractability and simplicity reasons.

- v = value of life (equal for all and known)
- c = cost of evacuation
- α = severity of hurricane where $\alpha \in [0,1]$
- γ = fixed probability that an individual is a criminal
- N = population size
- ϕ = probability that someone breaks into your house

I start my model with $N=2$. Furthermore, for the sake of simplicity, I assume in this model that the hurricane strikes the city with a definite probability of 1.

Let U_0 , the payoff function for individual i who decides not to evacuate the city, be defined as follows:

$$U_0^i = (1 - \alpha)(w_i + v) \tag{1}$$

If the hurricane were to definitely hit the city, an individual's life would be subject to harm and his property would be subject to damage. Thus, I assume that individual i is going to lose a proportion of his wealth and his life, α , when the hurricane strikes.

Therefore, the remaining of his wealth and life will be $(1 - \alpha)(w_i + v)$. Our variable α is between 0 and 1. If α is equal to 1, individual i loses all his property and dies, however if α is equal to 0, he receives no damage to his life or his wealth. Any number in between 0 and 1 indicates the severity of the damage after the hurricane strikes.

⁸ Wealth includes all the tangible and intangible possessions an individual highly values. These possessions could include pets, extended family members, sick or elderly relatives at stake, annual earnings, cars etc.

When considering the payoff function for an individual who decides to evacuate the city, I introduce a new variable ϕ_j . When a person evacuates the city, and leaves his property unprotected, his property has a risk of being looted. In this model where $N=2$, the only risk of looting could stem from the neighbor j who may or may not break into the house of the individual i .

Let U_1 , the payoff function when individual i decides to evacuate, be defined as follows:

$$U_1^i = \underbrace{(1 - \phi_j)[(1 - \alpha)w_i + v]}_1 + \underbrace{\phi_j v}_2 - \underbrace{c}_3 \quad (2)$$

If individual i decides to evacuate the city, he is faced with two different scenarios. In the first scenario, the neighbor j does not break into his house and his wealth is safe. The first term in equation (2) represents the scenario in which neighbor j does not break into individual i 's house with a probability $(1 - \phi_j)$. In this case, the only danger on his wealth stems from the severity of the hurricane. After the hurricane strikes with a probability of 1, $(1 - \alpha)$ proportion of his wealth, w_i , will remain undamaged.

Furthermore, since he evacuated the city, his life, v , will not be harmed. In the second scenario, the neighbor breaks into his house and robs all his property. The second term in equation (2) represents the scenario in which the neighbor j breaks into the house of individual i with a probability of ϕ_j . In this case, individual i is only able to save his life, v and none of his wealth, w . Therefore, the final payoff in the second scenario is $\phi_j v$.

Finally, a person who evacuates the city incurs a cost, c .

A utility-maximizing decision-maker evacuates the city if $U_1^i \geq U_0^i$. By plugging

the payoff functions in equation (1) and (2) into this inequality, I find that this individual evacuates if the following inequality holds true.

$$(1 - \phi_j)[(1 - \alpha)w_i + v] + \phi_j v - c \geq (1 - \alpha)(w_i + v) \quad (3)$$

I can further simplify the equation above as follows:⁹

$$w_i \leq \frac{\alpha v - c}{\phi_j(1 - \alpha)} \quad (4)$$

$$\text{Let } w_i^* = \frac{\alpha v - c}{\phi_j(1 - \alpha)} \quad (5)$$

Note that if $\alpha v - c \leq 0$, $w_i^* \leq 0$. Since an individual's wealth is always greater than 0, the inequality $w_i \leq w_i^*$ will never be true; leading to no evacuation. The inequality $\alpha v - c \leq 0$ holds if either cost of evacuation, c , is very large or the severity of the hurricane, α , is really small. This makes intuitive sense, because if the cost of evacuation is really large or if the hurricane does not pose a significant threat, or if individuals have a low value of life, they would not be willing to evacuate the city. Thus, given that

$$\begin{aligned} (1 - \phi_j)(1 - \alpha)w_i + (1 - \phi_j)v + \phi_j v - c &\geq (1 - \alpha)(w_i + v) \\ (1 - \phi_j)(1 - \alpha)w_i + v - \phi_j v + \phi_j v - c &\geq (1 - \alpha)(w_i + v) \\ (1 - \phi_j)(1 - \alpha)w_i + v - c &\geq (1 - \alpha)(w_i + v) \\ (1 - \alpha)(w_i + v) &\leq (1 - \phi_j)(1 - \alpha)w_i + v - c \\ {}^9 (1 - \alpha)(w_i + v) - (1 - \phi_j)(1 - \alpha)w_i &\leq v - c \\ (1 - \alpha)w_i + (1 - \alpha)v - (1 - \alpha)w_i + \phi_j(1 - \alpha)w_i &\leq v - c \\ (1 - \alpha)v + \phi_j(1 - \alpha)w_i &\leq v - c \\ \phi_j(1 - \alpha)w_i &\leq \alpha v - c \\ w_i &\leq \frac{\alpha v - c}{\phi_j(1 - \alpha)} \end{aligned}$$

$\alpha v - c \leq 0$, a household i will always choose to stay regardless of ϕ_j , the probability that someone breaks into his house. However, in my model I am specifically analyzing the effect of property concerns on the probability of evacuation, so I will rule out the cases where $\alpha v - c \leq 0$. For the rest of the analysis, I will assume that $\alpha v - c > 0$.

I define w_i^* to be the cut-off point which helps us determine our evacuation behavior. If w_i^* increases, probability of evacuation increases since evacuation takes place when $w_i \leq w_i^*$. Under which circumstances does w_i^* increase? When v or α increases or when c or ϕ_j decreases, w_i^* increases. In other words, as a hurricane becomes more damaging or as individuals start valuing their lives more, their cut-off points increase, which makes evacuation more likely. On the other hand, as cost of evacuation increases or as the probability of someone else breaking into your house increases, cut-off points decrease, which makes evacuation less likely.

Defining the probability of evacuation e_i

I have outlined how individuals decide whether they should evacuate or not. The next step is to show how to determine the probability of evacuation for an individual i . Let e_i = the probability that an individual i evacuates the city. Given that an individual i determines his evacuation behavior from the inequality $w_i \leq w_i^*$, I state that $e_i = \Pr(w_i \leq w_i^*)$. Furthermore, we also know that w_i^* is determined from a random distribution, $F(w)$ of wealth. The cumulative distribution function, $F(w)$ is equal to the probability of the random variable W taking on values less than w . Thus, $F(w) = \Pr(W \leq w)$. Consequently, $F(w_i^*) = \Pr(w_i \leq w_i^*)$. In conclusion, I state that:

$$e_i^* = F(w_i^*) \tag{6}$$

Since I defined w_i^* to be equal to $\frac{\alpha v - c}{\phi_j(1 - \alpha)}$, I can rewrite the formula above as follows:

$$F(w_i^*) = F\left(\frac{\alpha v - c}{\phi_j(1 - \alpha)}\right) = e_i \quad (7)$$

This equality can be further modified since the probability that someone breaks into your house, ϕ_j and the probability of evacuation, e_i are closely linked. A person can only break into your house with a probability of ϕ_j , if he has not evacuated the city with a probability of $(1 - e_j)$. In addition, even if he stays behind, he will break into your house with a probability of ϕ_j , if he is a criminal with a probability of γ . Consequently, ϕ_j can be defined as follows:

$$\phi_j = (1 - e_j)\gamma \quad (8)$$

Equation (7) can be rewritten in the following form:

$$F(w_i^*) = F\left(\frac{\alpha v - c}{(1 - e_j)\gamma(1 - \alpha)}\right) = e_i \quad (9)$$

To make my model simple and tractable, I assume that w_i is derived from a uniform distribution of wealth $(w_i^*) \in [0, \bar{w}]$. In probability and statistics theory, the continuous uniform distribution is a probability density function whereby any $(w_i^*) \in [0, \bar{w}]$ has an equal, $\frac{1}{w}$, probability of occurring. Since I assume the probability density function of wealth to be uniformly distributed, the cumulative distribution function takes the following form.

$$F(w_i) = \frac{w_i}{w}. \quad (10)$$

I defined $w_i = \frac{\alpha v - c}{(1 - e_j)\gamma(1 - \alpha)}$, so I can revise equation (9) as follows:

$$F(w_i^*) = \frac{\alpha v - c}{w(1 - e_j)\gamma(1 - \alpha)} = e_i \quad (11)$$

Determining the symmetric Nash equilibrium e_i :

Let S be a game and e_i be the strategy individual i chooses. A strategy e^* is a Nash equilibrium if no deviation in strategy by any single player is profitable. Thus a symmetric Nash equilibrium takes place when the best response for all players is e^* .

Thus at equilibrium $e_i = e_j = e^*$. I rewrite equation (11) as follows:

$$F(w_i^*) = \frac{\alpha v - c}{w(1 - e^*)\gamma(1 - \alpha)} = e^* \quad (12)$$

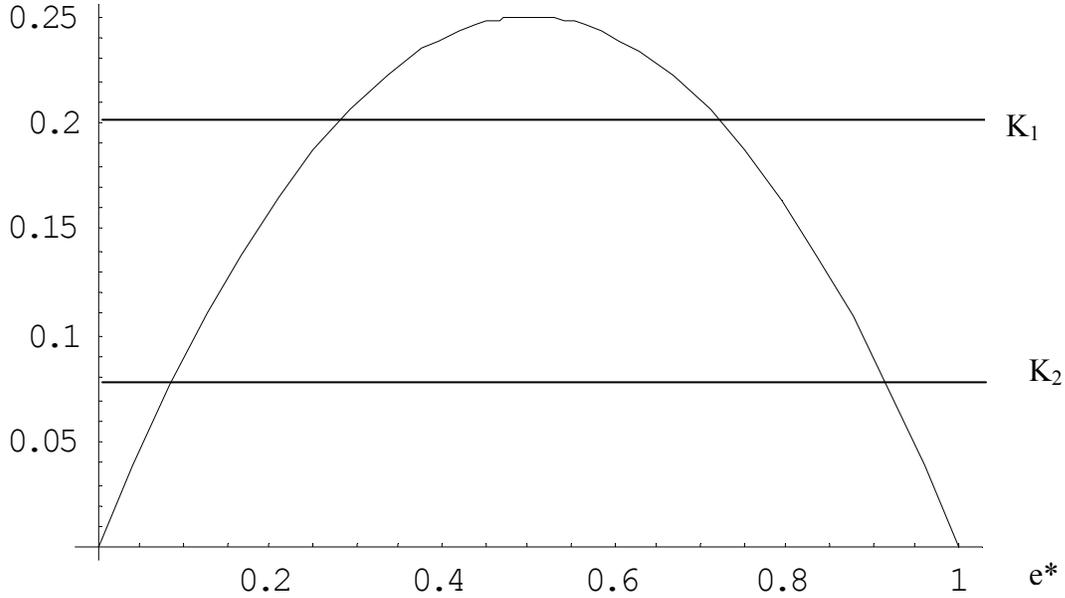
$$\frac{\alpha v - c}{w\gamma(1 - \alpha)} = (1 - e^*)e^* \quad (13)$$

$$\text{Let } K = \frac{\alpha v - c}{w\gamma(1 - \alpha)} \quad (14)$$

$$K = (1 - e^*)e^* \quad (15)$$

The graph of equation $y_1(e) = (1 - e^*)e^*$ is an inverted parabola which crosses the x-axis at $e^* = 1$ and $e^* = 0$.

Figure 1: Nash equilibria for a Uniform Distribution



Notice that the maximum of $y_1(e)$ occurs at $(0.5, 0.25)$. In other words, when $K=0.25$, there is only one intersection; however as K decreases, $y_1(e) = (1 - e^*)e^*$ and $y_2(e) = K$ intersect at two distinct points. As K decreases, the intersection points move farther away from each other, however as K increases, the intersection points move closer towards each other.

Equation (15) can be rewritten as $(e^*)^2 - e^* + K = 0$. By using the quadratic formula, we can find the values of e^* which satisfy equation (15).

$$e^* = \frac{1}{2} \pm \frac{\sqrt{1-4k}}{2} \tag{16}$$

In summary, there are two symmetric Nash equilibria in my model, both of which are symmetrical around the point $e^* = \frac{1}{2}$. Notice that this formula gives real solutions if and only if $1 - 4K \geq 0$. Thus, if $K \leq \frac{1}{4}$, the probability of evacuation can be determined from equation (16).

Consider the following case :¹⁰

$v = 1000;$
 $c = 100;$
 $\alpha = 0.5;$
 $\bar{w} = 95000;$
 $\gamma = 0.05;$
 $N = 2$

These values lead to two different probabilities of evacuation, whereby $e_i = 0.21$ or $e_i = 0.79$. Since $F(w_i^*) = e_i = \frac{w_i^*}{\bar{w}}$, $w_i^* = 0.21 * \bar{w}$ or $w_i^* = 0.79 * \bar{w}$. Given the fact that \bar{w} is assumed to be 95,000, $w_i^* = 19,950$ or $w_i^* = 75,050$.

What do these results indicate to us? Individual i has no knowledge about the wealth of his neighbor j , thus he does not know which cut-off point w_j^* individual j uses to determine whether he should evacuate or not. If individual i believes that individual j will use the cut-off point $w_j^* = 19,950$, it is in his best interest to use the inequality $w_i \leq w_i^* = 19,950$ to determine whether he should evacuate or not. On the other hand, if

¹⁰ I chose $\gamma = 0.05$ to be the probability that someone is a criminal since 0.05 is the property crime rate for New Orleans in 2004 according to the FBI Crime Report. The mean of a uniform distribution is equal to $\frac{\bar{w}}{2}$ so I used the mean income for New Orleans in 2004 which was approximately 47,000 to determine \bar{w} to be approximately 95,000. The variables v , c and α are arbitrary.

individual i believes that individual j will use the cut-off point $w_j = 75,050$, it is in his best interest to use the inequality $w_i \leq w_i^* = 75,050$ to determine whether he should evacuate or not. If individual i communicates with individual j to learn his exact level of wealth, he could determine whether individual j will evacuate or not and respond accordingly. However due to lack of communication between them, these households fail to coordinate their evacuation behavior. In fact, the best individual i can do is to make inferences about the cut-off point, w_j^* , individual j will use to determine his evacuation behavior.

Determining the stable equilibrium points:

Even though my model predicts two Nash equilibria, only of them is stable. In order to determine which of the two Nash equilibria is stable, I slightly change the cost of evacuation, c , to determine how it affects the probability of evacuation for individual i . Assume that the cost of evacuation increased from 100 to 150. This increase in c is going to decrease K , therefore the two equilibrium points will get farther away from each other. I hypothesize that *ceteris paribus*, as the cost of evacuation increases, probability of evacuation decreases. The new two Nash equilibria we find are $e_i^* = 0.18$ and $e_i^* = 0.82$. Even though the decrease in probability from 0.21 to 0.18 as the cost of evacuation increases makes sense, the increase in probability from 0.79 to 0.82 does not make intuitive sense. Everything else equal, why should an increase in the cost of evacuation make an individual more likely to evacuate? Consequently, in my model, the equilibrium

points smaller than $\frac{1}{2}$ are stable, whereas equilibrium points greater than $\frac{1}{2}$ are unstable.

These equilibrium points are determined using equation $\frac{1}{2}[1 - \sqrt{1 - 4K}]$.

Determining the corner solutions:

I have determined that when $K \leq \frac{1}{4}$, the probability of evacuation can be derived from Equation (16). However, equation (16) suggests that the maximum probability of evacuation for a household is $\frac{1}{2}$. What happens when $K > \frac{1}{4}$? I will start out by looking at the case when $K \geq 1$.

$$\text{Let } k = \frac{\alpha v - c}{\gamma(1 - \alpha)}. \quad (17)$$

Then,

$$K = \frac{k}{w} \quad (18)$$

By plugging equation (17) into equation (9), we find that

$$F(w_i^*) = F\left(\frac{k}{(1 - e_j)}\right) = e_i \quad (19)$$

If $K \geq 1$, then by equation (18), $k \geq \bar{w}$. Since $1 - e_j$ is always less than 1,

$\frac{k}{(1 - e_j)} \geq \bar{w}$ should be true. By definition, the cumulative distribution function

$F\left(\frac{k}{(1 - e_j)}\right) = \Pr\left(w_i \leq \frac{k}{(1 - e_j)}\right)$. This cumulative distribution function measures the

probability that the wealth of individual i is less than $w_i \leq \frac{k}{(1 - e_j)}$. By equation (19),

this probability is equal to e_i , the probability of evacuation for individual i . Since

$\frac{k}{(1-e_j)} \geq \bar{w}$ and \bar{w} is defined as the maximum level of wealth in the society, the

$\Pr\left(w_i \leq \bar{w} \leq \frac{k}{(1-e_j)}\right)$ will always be true, thus by equation (19), $e_i=1$.

This finding makes intuitive sense, because $K \geq 1$, for really small values of γ or really high values of α . If the damage of the hurricane is severe, individuals would be concerned about the safety of their lives and evacuate. Furthermore, if the probability that someone is a criminal is low, individuals would not be as concerned about the safety of their belongings and so would evacuate. In other words, for situations where $K \geq 1$, there is no need for mandatory evacuation as households would voluntarily leave the city.

Now, I will consider the case when $\frac{1}{2} \leq K \leq 1$. Equation (14) shows that K increases when the cost of evacuation decreases or when value of life increases. Everything else equal, a decrease in the cost of evacuation or an increase in the value of life would make individuals more likely to evacuate. Consequently, for the case when $\frac{1}{2} \leq K \leq 1$, I would expect the probability of evacuation to be greater than the case when $K \leq \frac{1}{4}$. Recall that when $K \leq \frac{1}{4}$, the largest value the probability of evacuation, e , could take on is $e = \frac{1}{2}$. Thus when $K \geq \frac{1}{4}$, the probability of evacuation has to be $e^* \geq \frac{1}{2}$.

As defined in Equation (18), $K = \frac{k}{w}$. Hence I am considering the case when

$\frac{1}{2} \leq \frac{k}{w}$. In other words, I am trying to solve for the case when $\bar{w} \leq 2k$. Due to the

restriction on e^* , I deduce that $\frac{1}{1-e^*} \geq 2$. Since $k > 0$, $\frac{k}{1-e^*} \geq 2k$. Using equation (19),

$$F(w_i^*) = F\left(\frac{k}{(1-e^*)}\right) = \Pr\left(w_i^* \leq \frac{k}{(1-e^*)}\right) = e_i \quad (20)$$

Since $\frac{k}{(1-e_j)} \geq 2k$ and $\bar{w} \leq 2k$, $\frac{k}{(1-e_j)} \geq \bar{w}$. I defined \bar{w} to be the maximum level of

wealth in the society; such that for all i , $w_i \leq \bar{w}$. Consequently, $\Pr\left(w_i^* \leq \frac{k}{(1-e^*)}\right)$ will

always be true, thus by equation (20) $e_i = 1$.

Finally I will consider the case where $\frac{1}{4} < K < \frac{1}{2}$. For this scenario, I will explore the possibility of an asymmetric Nash equilibrium to find out how player i responds to player j 's strategy. By combining equations (11) and (14), I conclude that

$$\frac{K}{1-e_j} = e_i \quad (21)$$

Equation (21) enables us to determine how player i reacts to player j 's decisions. Since the probability of evacuation for player i , $e_i \leq 1$, it must be true that the probability of evacuation for player j is determined as follows:

$$e_i = \min\left\{\frac{K}{1-e_j}, 1\right\} \quad (22)$$

Since values i and j are arbitrary, the following expression holds true as well.

$$e_j = \min\left\{\frac{K}{1-e_i}, 1\right\} \quad (23)$$

Figure 2: The Nash equilibria when $\frac{1}{4} < K < \frac{1}{2}$

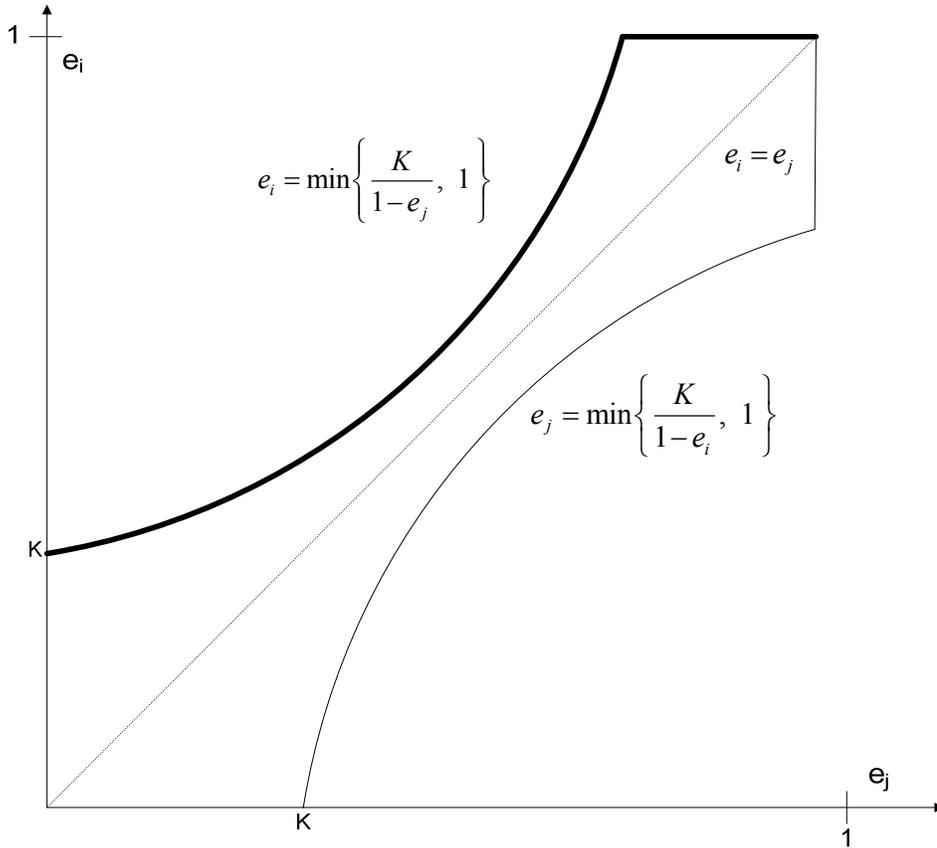
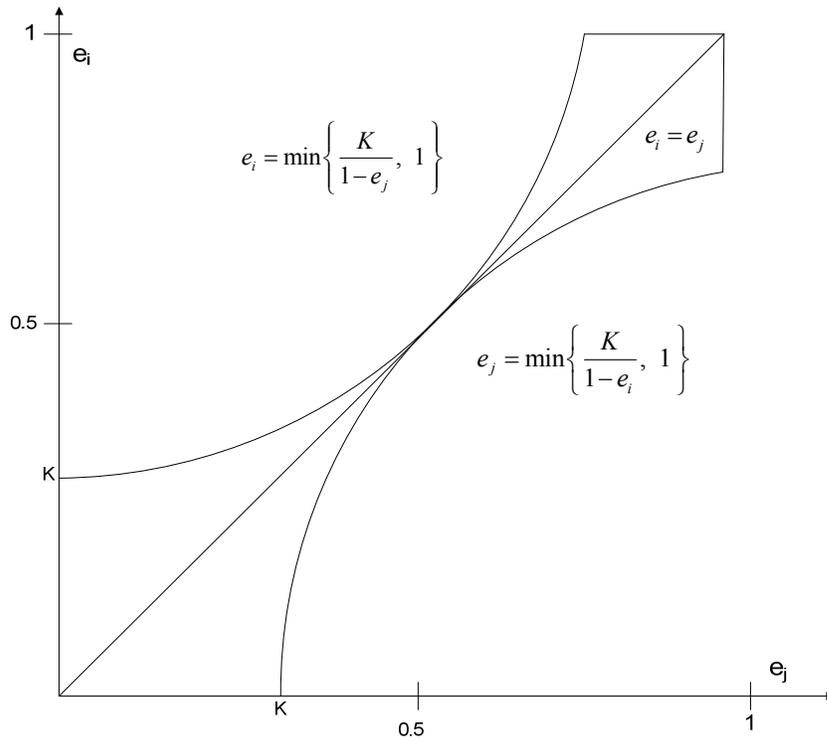


Figure 2 displays the reaction curves derived from equation (22) and (23) for both players i and j . Notice that the two graphs only intersect at $(1, 1)$. When $\frac{1}{4} < K < \frac{1}{2}$, the Nash equilibrium for both players occurs when $e_i = e_j = 1$. When $K = \frac{1}{4}$, according to Figure 3, there are two Nash equilibria, at $(0.5, 0.5)$ and $(1, 1)$. Finally when $K < \frac{1}{4}$, there are three Nash equilibria, one of which is $(1, 1)$. For all cases, probability of

evacuation $e_i = e_j = 1$ is a stable Nash equilibrium. If neighbor j definitely evacuates the city, there is no reason individual i to stay behind since he has no looting or property-related concerns. In fact, individual i can make decisions solely based on his own payoff functions. When I plug $e_j = 1$ into equation (3), I find that evacuation happens when $\alpha v - c > 0$, a constraint that is always true since it has been introduced to the model as a basic assumption at the beginning of this section.¹¹ In effect, probability of evacuation will always be equal to 1 for individual i . However, for cases with two stable equilibria, I will utilize the smallest value for the probability of evacuation since effective policies should take into consideration the worst possible outcomes.

Figure 3: The Nash equilibria when $K = 1/4$



¹¹ $(1 - \phi_j)[(1 - \alpha)w_i + v] + \phi_j v - c > (1 - \alpha)(w_i + v)$ where $\phi_j = 0$ leads to the inequality $\alpha v - c > 0$.

Figure 4 : The Nash equilibria when $K < 1/4$

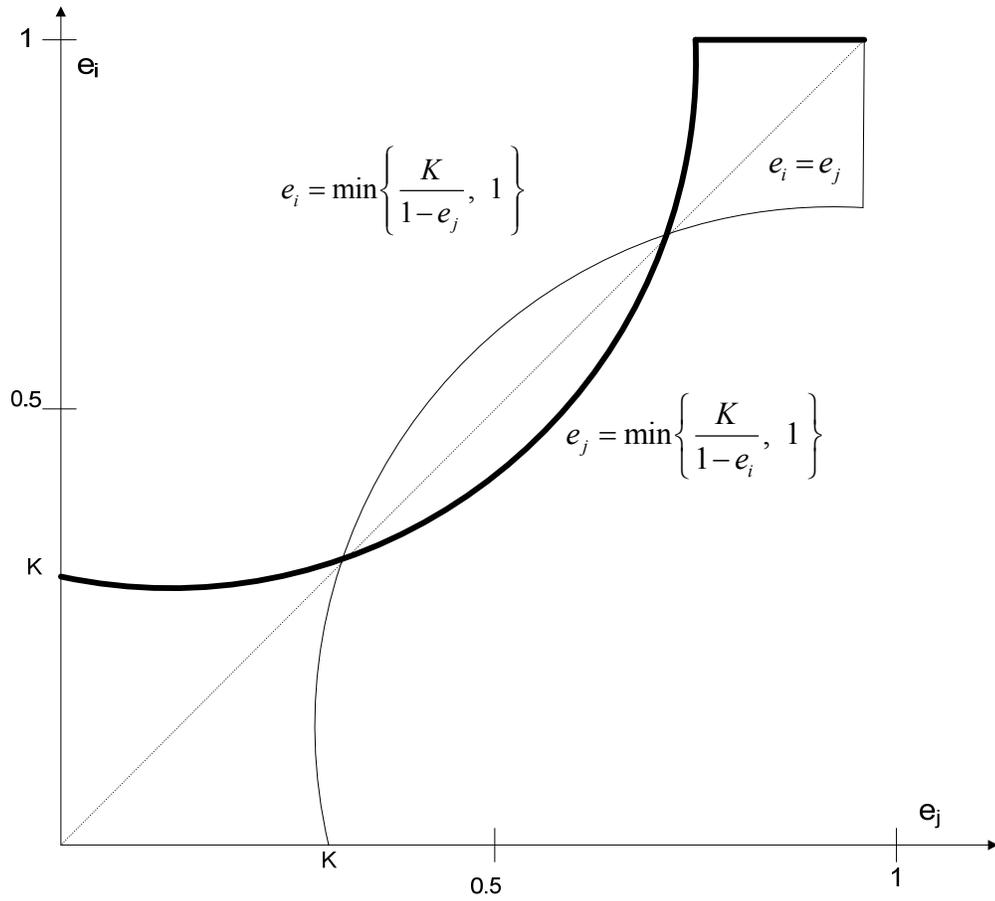
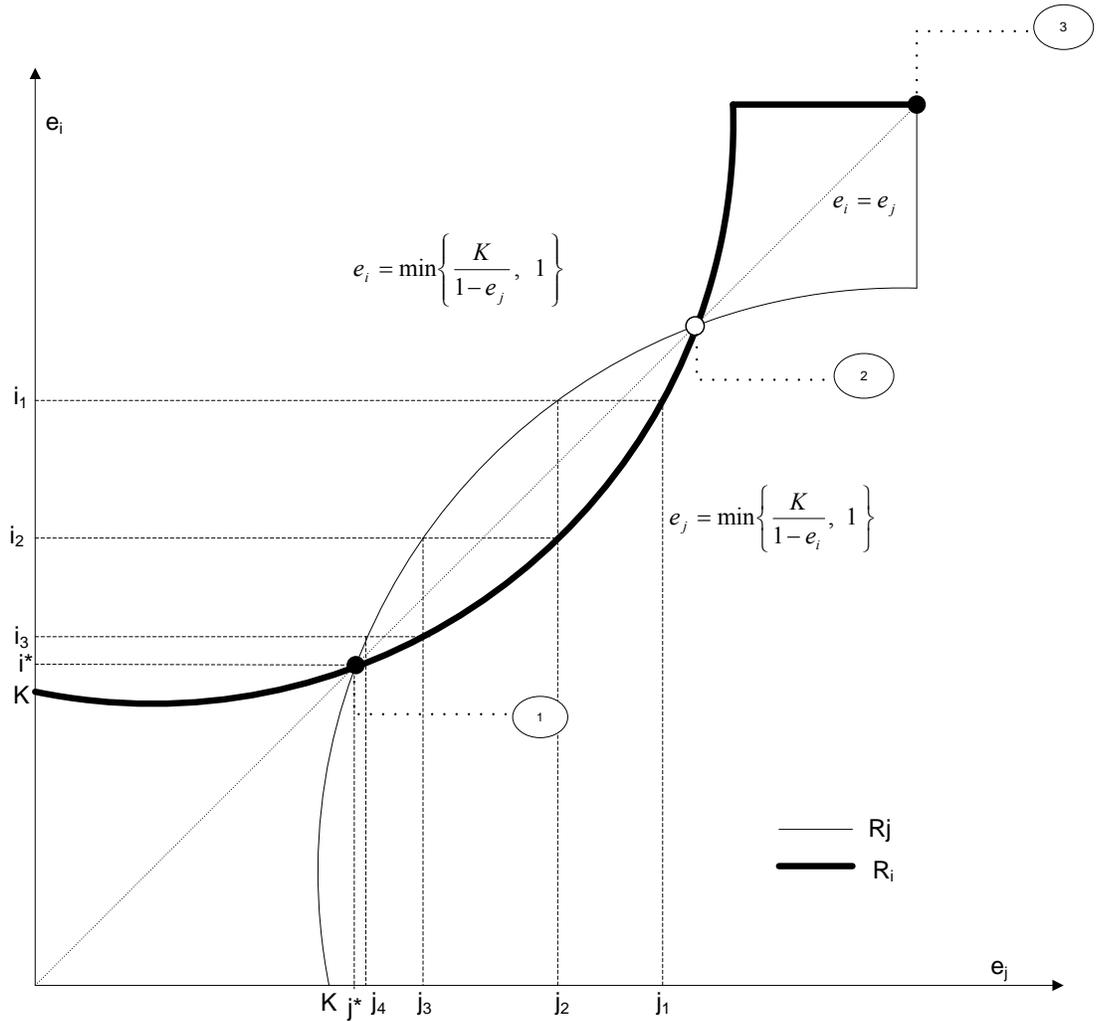


Figure 4(i) : The Nash equilibrium when $K < 1/4$



In Figure 4(i), there are three Nash equilibria; the first and the third Nash equilibria are stable, the second Nash equilibrium is unstable¹² I will start by proving the instability of the second Nash equilibrium. Suppose that player i conceives player j 's probability of evacuation to be j_1 . Player i will respond to player j 's decision by choosing i_1 on his reaction curve. Next, player j , will respond to this decision by

¹² The first equilibrium is $\frac{1}{2}[1 - \sqrt{1 - 4K}]$, the second equilibrium is $\frac{1}{2}[1 + \sqrt{1 - 4K}]$ and the third equilibrium is (1,1)

choosing j_2 on his reaction curve. As this game continues, the probabilities of evacuation for both players will decrease until they converge to the first Nash equilibrium, (j^*, i^*) . Stable equilibrium points are impervious to small perturbations in the system. If the second Nash equilibrium were stable, when I started at an off-point conjecture point, j_1 , j_1 would have eventually converged to the second Nash equilibrium.¹³ Instead, a small perturbation in the system impelled j_1 to converge to the first equilibrium point. Consequently, second Nash equilibrium in Figure 3(i) is unstable.

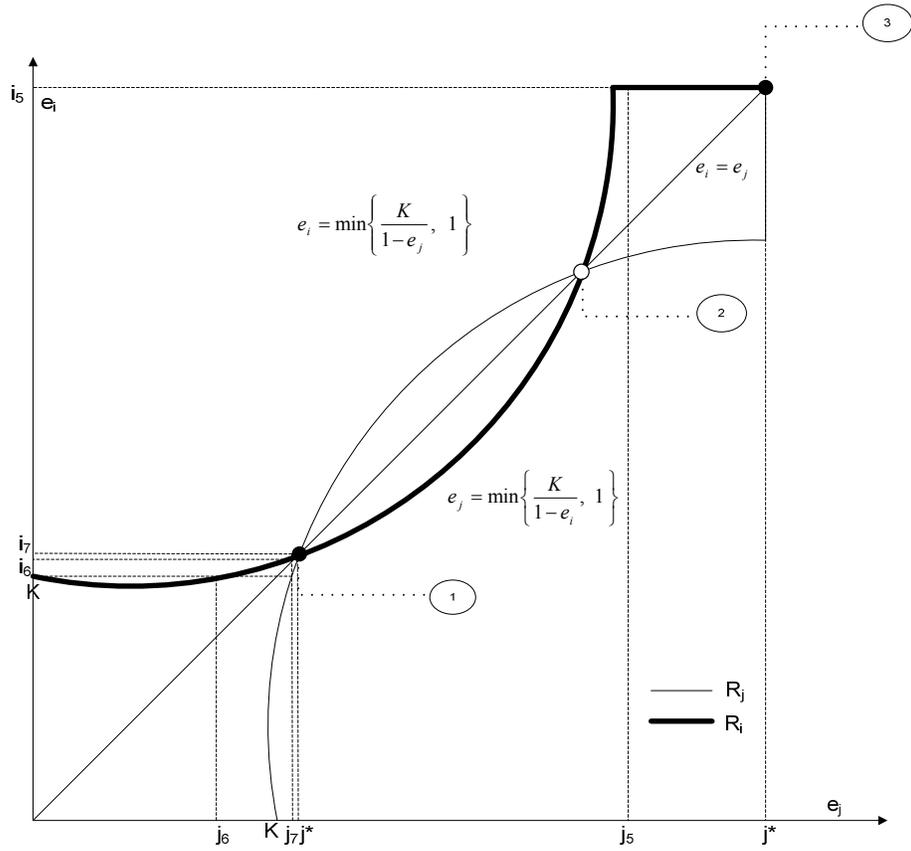
Next, I will now examine the stability of the first and third Nash equilibrium. Suppose player j starts at j_6 in Figure 4(ii). Player i 's reaction to this strategy would be to choose i_6 . Player j responds to this decision by choosing j_7 on his reaction curve R_j . Both players continue this game, until the probabilities of evacuation for both players converges to the first Nash equilibrium. Using the same techniques, one can demonstrate why the third Nash equilibrium $(1,1)$ is a stable Nash equilibrium. For an indefinite number of games, $K < \frac{1}{4}$, if the probability of evacuation for player j is

$0 \leq e_j \leq \frac{1}{2} [1 + \sqrt{1 - 4K}]$, the e^* converges to the first equilibrium (j^*, i^*) . If the

probability of evacuation e_j is $\frac{1}{2} [1 + \sqrt{1 - 4K}] \leq e_j \leq 1$, the e^* converges to $(1,1)$.

¹³ Our process of determining the stable equilibrium points is similar to the Cournot adjustment process whereby two reaction curves are used to determine the equilibria and assess their stability.

Figure 4(ii) : The Nash equilibrium when $K < 1/4$:



By summing up the results I derived, we find that ;

$$e^* = \begin{cases} 1 & \text{if } K > \frac{1}{4} \\ \frac{1}{2} [1 - \sqrt{1 - 4K}] & \text{if } 0 \leq K \leq \frac{1}{4} \end{cases} \quad (24)$$

K is defined to be $K = \frac{\alpha v - c}{w\gamma(1-\alpha)}$. I have concluded that for large values of K ,

probability of evacuation is equal to 1. K increases when v , α increases or when c , γ or \bar{w} decreases. When people value their lives very highly, when the severity of the hurricane is high, or when the cost and the crime rate are significantly low, evacuation occurs with an absolute probability in a uniform distribution of wealth.

Welfare Analysis: Voluntary vs. Mandatory Evacuation

Given our payoff functions for evacuation behavior, we can determine expected welfare implications for mandatory and voluntary evacuation. Suppose there is a mandatory evacuation order. In this case whether $w_i \leq w_i^*$ or $w_i > w_i^*$, an individual i has to evacuate the city. All individuals with varying wealth levels, $w_i \in [0, \bar{w}]$, will evacuate. Since everyone will have evacuated the city, there are no looting concerns, thus an individual will protect his life, v , incur a cost, c , and will leave his wealth to be subject to damage due to the severity of the hurricane, αv .

Consequently, his payoff function $H_m(w)$ will be the following:

$$H_m(w) = (1 - \alpha)w + v - c. \quad (25)$$

Since this will be true for individuals from all different income levels, the Expected Welfare for the city can be calculated as follows:

$$EW(\text{mandatory}) = \int_0^{\bar{w}} [(1 - \alpha)w + v - c] dF(w) \quad (26)$$

By integrating the formula above, we can find that:

$$EW(\text{mandatory}) = \frac{1}{w} \left[(1 - \alpha) \frac{w^2}{2} + (v - c)w \right]_0^{\bar{w}} \quad (27)$$

$$EW(\text{mandatory}) = \left[(1 - \alpha) \frac{\bar{w}}{2} + (v - c) \right] \quad (28)$$

Notice that as the cost of evacuation decreases and the value of life increases, the expected welfare under a mandatory evacuation order increases. The most interesting component of equation (28) is the \bar{w} . The variable \bar{w} is an indicator of income

distribution in the city. As \bar{w} increases, the heterogeneity of wealth increases since there are more people with greater levels of income. From our formula, we can see that as \bar{w} increases, the expected welfare increases. If the city has a heterogeneous distribution of wealth, mandatory evacuation increases the welfare of the city by minimizing the coordination problems.

The expected welfare derivation for a voluntary evacuation looks a little different.

$$EW(\text{voluntary}) = \underbrace{\int_0^{w^*} [(1-\phi)(1-\alpha)w + v - c] dF(w)}_1 + \underbrace{\int_{w^*}^{\bar{w}} (1-\alpha)(w+v) dF(w)}_2 \quad (29)$$

By integrating equation (29), I find that the $EW(\text{voluntary})$ is:

$$EW(\text{voluntary}) = \underbrace{\frac{1}{w} \int_0^{w^*} [(1-\phi)(1-\alpha)w + v - c] dw}_1 + \underbrace{\frac{1}{w} \int_{w^*}^{\bar{w}} (1-\alpha)(w+v) dw}_2 \quad (30)$$

$$EW(\text{voluntary}) = \frac{1}{w} \underbrace{\left[\frac{(1-\phi)(1-\alpha)w^2}{2} + (v-c)w \right]}_1 \bigg|_0^{w^*} + \frac{1}{w} \underbrace{\left[\frac{(1-\alpha)w^2}{2} + (1-\alpha)vw \right]}_2 \bigg|_{w^*}^{\bar{w}} \quad (31)$$

I showed that if $w_i \leq w_i^*$, an individual chooses to evacuate the city. The first term represents this scenario. If an individual leaves his property unprotected, his wealth is under two risks. The first risk comes from the severity of the hurricane, α and the second risk stems from the fact that his neighbor might break into his house with a probability of ϕ_j to rob his house. His payoff function also involves the value of his life, v , which will not have been harmed since he has evacuated the city prior to the hurricane. Finally, he will have to face a cost, c , during evacuation. Thus the payoff function for all

individuals whose wealth lies in between 0 and w_i^* will be equal to

$$[(1 - \phi_j)(1 - \alpha)w + v - c].$$

The second term in equation (29) represents the case in which an individual does not evacuate the city prior to the hurricane under a voluntary evacuation order. If

$w_i^* \leq w_i \leq \bar{w}$, an individual i decides to stay. This individual will not incur any costs, c , however, his wealth and life will be under risk due to the severity of the hurricane. Thus, the payoff function for him will be equal to $(1 - \alpha)(w + v)$.

Let us take another look at the example we considered previously.

$$\begin{aligned} v &= 1000; \\ c &= 100; \\ \alpha &= 0.5; \\ \bar{w} &= 95000; \\ \gamma &= 0.05; \\ \phi_j &= 0.04 \\ N &= 2 \end{aligned}$$

Under these conditions, the government calls for a mandatory evacuation. By using equation (28), we find that the Expected Welfare is equal to 24,650. Further suppose that given these conditions, the government calls for a voluntary evacuation. In this scenario, the Expected Welfare is equal to 24,503. In this case, it is socially optimal for a government to order a mandatory evacuation. In general, if all these variables are known numerically, one can derive the $EW(\text{voluntary})$ and $EW(\text{mandatory})$ to find which evacuation behavior is socially optimal for the city. If $EW(\text{voluntary}) > EW(\text{mandatory})$, the government official should call for a voluntary evacuation, however if $EW(\text{mandatory}) < EW(\text{voluntary})$, the government officials should order a mandatory evacuation. On the other hand, if both expected welfare values are the same, the

government officials should be indifferent between a voluntary and a mandatory evacuation order.

IV. Extending the Model for N-people:

In my model, for the sake of simplicity, I have assumed that $N=2$. However, assuming that there are only two individuals in a given city is not realistic. In this section, I will extend my model to $N>2$.

Assume that the hurricane were to definitely hit the city. Further suppose that there are N people in the city. If individual i decides not to evacuate the city, his payoff function will not be any different from the scenario when $N=2$. As long as he is in his house, regardless of whether there are 2 people or N people in the city, he will be able to protect his property. Let U_0 , the payoff function for individual i who decides not to evacuate the city, be defined as follows:¹⁴

$$U_0^i = (1 - \alpha)(w_i + v) \quad (32)$$

When we consider the payoff function for an individual i who decides to evacuate the city, the payoff function changes slightly. When a person evacuates the city and leaves his property unprotected, his property is under the risk of being looted. Recall that when $N=2$, the only risk of looting stems from the neighbor, however when $N=N$, there are $N-1$ people who could break into individual i 's house. Consequently, the probability that someone loots individual i 's property increases. Let U_1 , the payoff function when you decide to evacuate, be defined as follows:

¹⁴ Equation (28) is equivalent to Equation (1). See Section III. for further explanation.

$$U_1^i = \underbrace{\left[\prod_{j=1}^{N-1} (1 - \phi_j) \right]}_1 \underbrace{\left[(1 - \alpha)w_i + v \right]}_2 + \underbrace{\left[1 - \prod_{j=1}^{N-1} (1 - \phi_j) \right]}_3 v - \underbrace{c}_4 \quad (33)$$

where $j \neq i$

If individual i decides to evacuate the city, he is faced with two different scenarios. In the first scenario, no one will break into his house and his wealth will be safe. For an individual j , there is $(1 - \phi_j)$ that he will not break into individual i 's house. Since there are $N-1$ people, (excluding individual i), who could break into individual i 's house, the cumulative probability is illustrated by the first term, $\prod_{j=1}^{N-1} (1 - \phi_j)$ in equation (33). The second term in equation (33) demonstrates that the only danger on individual i 's wealth originates from the severity of the hurricane. Furthermore, since he has already evacuated the city, his value of life, v , will not change.

The third term in equation (33) represents the scenario in which at least one person breaks into his house. Since the probability that no one will break into individual i 's house is $\prod_{j=1}^{N-1} (1 - \phi_j)$, the probability that at least one person will break into his house will be $1 - \prod_{j=1}^{N-1} (1 - \phi_j)$. Given that at least one person breaks into the house, individual i will save his value of life, v , but lose all his wealth. Therefore, the total payoff function is shown in equation (33). Finally, anyone who evacuates the city incurs a cost, c .

Equation (33) can further simplified as follows:

$$U_1^i = \left[\prod_{j=1}^{N-1} (1 - \phi_j) \right] \left[(1 - \alpha)w_i \right] + v - c \quad (34)$$

A utility-maximizing decision-maker evacuates the city if $U_1^i \geq U_0^i$. By plugging our payoff functions into this inequality, we find that this individual evacuates if the following inequality holds true.

$$\left[\prod_{j=1}^{N-1} (1 - \phi_j) \right] [(1 - \alpha)w_i] + v - c \geq (1 - \alpha)(w_i + v) \quad (35)$$

We can further simplify the equation above as follows:

$$w_i \leq \frac{\alpha v - c}{(1 - \alpha) \left[1 - \prod_{j=1}^{N-1} (1 - \phi_j) \right]} \quad (36)$$

$$\text{Let } w_i^* = \frac{\alpha v - c}{(1 - \alpha) \left[1 - \prod_{j=1}^{N-1} (1 - \phi_j) \right]} \quad (37)$$

I defined w_i^* to be the cut-off point which helps us determine our evacuation behavior. If w_i^* increases, the probability of evacuation decreases since evacuation occurs when $w_i \leq w_i^*$. Does this statement make intuitive sense? We know from equation (37) that w_i^* increases when α or v increases or when c , ϕ_j , or N decreases. This is a reasonable finding since as a hurricane becomes more damaging or as individuals start valuing their lives more, they will be more willing to evacuate. On the other hand, as the cost of evacuation increases or as the probability of someone else breaking into your house increases, cut-off point w_i^* decreases; making evacuation less likely.

Defining the probability of evacuation e_i

Following the same procedure we have previously used for $N=2$, we can determine the probability of evacuation for an individual i . Using equation (6), we know

that $e_i^* = F(w_i^*)$. Since we have defined $w_i^* = \frac{\alpha v - c}{(1 - \alpha) \left[1 - \prod_{j=1}^{N-1} (1 - \phi_j) \right]}$, we can write

equation (6) as follows :

$$F(w_i^*) = F \left(\frac{\alpha v - c}{(1 - \alpha) \left[1 - \prod_{j=1}^{N-1} (1 - \phi_j) \right]} \right) = e_i \quad (38)$$

Equation (38) can further be modified using the fact that $\phi_j = (1 - e_j) \gamma$. A person can only break into your house with probability ϕ_j , if he has not evacuated the city with probability $(1 - e_j)$ and if he is a criminal with a probability γ . Consequently, equation (38) becomes:

$$F(w_i^*) = F \left(\frac{\alpha v - c}{(1 - \alpha) \left[1 - \prod_{j=1}^{N-1} (1 - (1 - e_j) \gamma) \right]} \right) = e_i \quad (39)$$

Using our assumption that w_i is derived from a uniform distribution of wealth ($w_i^* \in [0, \bar{w}]$) and that $F(w_i) = \frac{w_i}{\bar{w}}$, we can conclude that :

$$F(w_i^*) = \frac{\alpha v - c}{(1 - \alpha) \bar{w} \left[1 - \prod_{j=1}^{N-1} (1 - (1 - e_j)) \right]} = e_i \quad (40)$$

Determining the Nash equilibrium e_i :

As I have previously discussed, a strategy e^* is a Nash equilibrium if no deviation in strategy by any single player is profitable. Thus, a Nash equilibrium takes place when the best response for all players is e^* . Accordingly, at equilibrium, $e_i = e_j = e^*$. I can rewrite equation (40) as :

$$F(w_i^*) = \frac{\alpha v - c}{\bar{w}(1 - \alpha) \left[1 - \prod_{j=1}^{N-1} (1 - (1 - e^*)\gamma) \right]} = e^* \quad (41)$$

Since the probability of evacuation is fixed and no longer dependent on individual j , equation (41) becomes the following :

$$F(w_i^*) = \frac{\alpha v - c}{\bar{w}(1 - \alpha) \left[1 - [1 - (1 - e^*)\gamma]^{N-1} \right]} = e^* \quad (42)$$

$$\frac{\alpha v - c}{\bar{w}(1 - \alpha)} = e^* \left[1 - [1 - (1 - e^*)\gamma]^{N-1} \right] \quad (43)$$

$$\text{Let } K = \frac{\alpha v - c}{\bar{w}(1 - \alpha)} \quad (44)$$

$$K = e^* \left[1 - [1 - (1 - e^*)\gamma]^{N-1} \right] \quad (45)$$

Determining the Nash equilibrium e_i for different values of N :

Consider the case I previously investigated :

$$\begin{aligned}v &= 1000; \\c &= 100; \\ \alpha &= 0.5; \\ \bar{w} &= 95000; \\ \gamma &= 0.05; \\ K &= 0.00842\end{aligned}$$

Using equation (45), I should be able to determine e^* for different values of N holding other variables such as v , c , α , \bar{w} and γ fixed. Table 1 demonstrates how probability of evacuation differs as N increases.

Notice that the findings in this table support our hypothesis that as the number of people increases, the probability of evacuation decreases. Using these values for e_i , I can calculate the values of w_i^* .

Table 1 : Probability of evacuation for different values of N .

N	e_i
2	0.21
3	0.095
4	0.063
5	0.047
10	0.023
20	0.014
50	0.0092
100	0.0085
1,000	0.0084
50,000	0.0084
470,000	0.0084

Given the fact that \bar{w} is assumed to be 95,000 and the fact that $F(w_i^*) = e_i = \frac{w_i^*}{w}$, I can

conclude that $w_i^* = e_i * \bar{w}$. Table 2 summarizes the findings for w_i^* .

Table 2 : Probability of evacuation and the cut-off points w_i^* for different values of N

N	e_i	w_i^*
2	0.21	19,950
3	0.095	9,025
4	0.063	5,985
5	0.047	4,465
10	0.023	2,185
20	0.014	1,330
50	0.0092	874
100	0.0085	808
1,000	0.0084	798
50,000	0.0084	798
470,000	0.0084	798

What do these results suggest to us ? As stated before, individual i has no knowledge about the wealth of his neighbor, j , thus he can only make inferences about the cut-off point, w_j^* , individual j uses to determine his evacuation behavior. In city where $N=100$, if individual i believes that individual j will use the cut-off point $w_j^* = 808$, it is in the best interest of individual i to use the same cut-off point. In other words, individual i should use $w_i \leq w_i^* = 808$ to decide whether he should evacuate or stay given that individual j uses the cut-off point $w_j \leq w_j^* = 808$. Notice that in Table 2, as the number of people increases, the cut-off point, w_i^* and the probability of evacuation decrease.

Welfare Analysis: Voluntary vs. Mandatory Evacuation

I have analyzed the welfare implications for N=2 to determine whether voluntary or mandatory evacuation is more socially optimal. The same procedure can be used for N>2 to analyze the two different welfare implications. Recall Equation (28) which states

that expected welfare a mandatory evacuation is $EW(\text{mandatory}) = \left[(1 - \alpha) \frac{\bar{w}}{2} + (v - c) \right]$.

Further recall Equation (31) which states that the expected welfare for a voluntary

evacuation is $EW(\text{voluntary}) = \frac{1}{w} \left[\underbrace{\frac{(1 - \phi)(1 - \alpha)w^2}{2} + (v - c)w}_0 \right]^{w^*} + \frac{1}{w} \left[\underbrace{\frac{(1 - \alpha)w^2}{2} + (1 - \alpha)v w}_2 \right]^{w^*}$

Using equations (28) and (31) along with Table 2, I find the expected welfare values to differ for mandatory versus voluntary evacuation.

Table 3: Welfare Implication for Mandatory vs. Voluntary Evacuation

N	e _i	w _i [*]	Mandatory	Voluntary
2	0.21	19,950	24,650	24,503
3	0.095	9,025	24,650	24,373
4	0.063	5,985	24,650	24,334
5	0.047	4,465	24,650	24,313
10	0.023	2,185	24,650	24,282
20	0.014	1,330	24,650	24,269
50	0.0092	874	24,650	24,263
100	0.0085	808	24,650	24,262
1,000	0.0084	798	24,650	24,262
50,000	0.0084	798	24,650	24,262
470,000	0.0084	798	24,650	24,262

Table 3 displays the welfare value for voluntary and mandatory evacuations for different values of N. The values derived in the fourth and fifth columns are expected welfares for a single individual. Notice that for all values of N, the expected welfare is greater for a

mandatory evacuation than for a voluntary evacuation. Furthermore, the expected welfare decreases as N increases for a voluntary evacuation, even though, for a mandatory evacuation, it stays constant even when N increases. As N increases, it is more socially optimal to call for a mandatory evacuation order.

Robinson Crusoe Model, N=1

In this section, I want to investigate how a single individual in a city would behave given the threat of a hurricane. I chose to analyze this case independently of the previous cases where $N > 2$ since it is a unique scenario. When $N=1$, a lot of risks and issues discussed in the previous cases disappear. First of all, an individual i 's property is no longer prone to looting or robbery. Secondly, the coordination problem that arose due to lack of information about the evacuation decisions of others no longer exists. If I show that a single individual would definitely evacuate the city, I can conclude that coordination problems and property concerns are the major determinants in evacuation decisions for cases where $N > 2$.

For a single individual model, if you substitute $N=1$ into the the equation

$$e^* = F\left(\frac{\alpha v - c}{(1 - \alpha)[1 - (1 - (1 - e^*)\gamma)^{N-1}]}\right), \text{ you can see that } e^* = F(\infty). \text{ By definition,}$$

$F(\infty) = \Pr(w \leq \infty)$. Since the maximum level of wealth in the city is $\bar{w} < \infty$, $F(\infty)$ will always hold true. Consequently $e^* = F(\infty) = 1$. What does this finding indicate? This result suggests that if an individual were living by himself, independently of others, he would always choose to evacuate. In this case, there would be no need for mandatory evacuation given that, independent of any order, individual i would always choose to evacuate. Using equations (28) and (31), I can compute the expected welfares for

mandatory and voluntary evacuation orders in our Robinson Crusoe model. Not surprisingly, we find that $EW(\text{voluntary}) = EW(\text{mandatory}) = 24,650$.

V. Extension to all cumulative distribution functions $F(w)$

In previous sections, I have used the uniform distribution function to come to the conclusion that as N increases, probability of evacuation decreases. In this section, I will state the same claim about the relationship between N and probability of evacuation e for any cumulative distribution function $F(w)$.

In my model, I am assuming that all wealth levels are represented. The probability density function $f(w)$ gives the probability per unit length value for values near w . If dw is an infinitely small number, the probability that W is included within the interval $(w, w + dw)$ is equal to $f(w)dw$. In other words;

$$P(W \in dw) = f(w)dw \quad (46)$$

where dw is an infinitely small interval. $(W \in dw)$ stands for the event that W falls in an infinitesimal interval of length dw near w . In my evacuation model, I assume that the distribution of wealth is continuous and all wealth levels are present in the city. In other words;

$$\forall dw_i, \exists W_i \text{ such that } (W_i \in dw_i) \quad (47)$$

Thus, $P(W \in dw) = f(w)dw > 0$. Assuming f is continuous I can conclude the following,

$$f(w) = \frac{dF(w)}{dw} = F'(w) \quad (48)$$

In summary, since $f(w) > 0$ and continuous, the cumulative distribution function $F(w)$ is monotone increasing for my model.

Hypothesis: As N increases, probability of evacuation, e^ , decreases.*

Proof:

I am trying to show that $\frac{de_{(N)}}{dN} < 0$, and conversely that $e'_N < 0$. I derive the

probability of equation from $e_{(N)}^* = F\left(\frac{\alpha v - c}{(1 - \alpha)[1 - (1 - (1 - e_{(N)}^*)\gamma)^{N-1}]}\right)$. I can rewrite

this equation as follows:

$$H(e_{(N)}^*, N) = F\left(\frac{\alpha v - c}{(1 - \alpha)[1 - (1 - (1 - e_{(N)}^*)\gamma)^{N-1}]}\right) - e^* = 0 \quad (49)$$

Since, $H(e^*)$ is a function of both e and N , I partially differentiate equation (49) with respect to N and e .

$$\frac{dH}{de} \frac{de}{dN} + \frac{dH}{dN} \frac{dN}{dN} = 0 \quad (50)$$

$$\frac{dH}{de} \frac{de}{dN} + \frac{dH}{dN} = 0 \quad (51)$$

$$\frac{de}{dN} = - \left(\frac{\frac{dH}{dN}}{\frac{dH}{de}} \right) \quad (52)$$

$$\frac{de}{dN} = - \left(\frac{H_N}{H_e} \right) \quad (53)$$

Let us start by showing how H changes as N changes. As N increases,

$$w_i^* = \frac{\alpha v - c}{(1 - \alpha) \left[1 - (1 - (1 - e_{(N)}^*) \gamma)^{N-1} \right]} \text{ decreases. Since } F(w) \text{ is a monotone increasing}$$

functions, as w_i^* decreases, $F(w)$ decreases. Consequently, $H_N < 0$.

Secondly I will evaluate how H changes as e changes. I know that when $e^* = 0$,

$$H(0) = F\left(\frac{\alpha v - c}{1 - \alpha}\right) > 0. \text{ Let us investigate how } H \text{ changes as } e \rightarrow 1^- . \text{ According to}$$

equation (49), $H(e) = F(e) - e$. Thus, $\lim_{e \rightarrow 1^-} \frac{1 - F(e)}{1 - e}$ will help us determine the behavior of

H as $e \rightarrow 1^-$.

$$\lim_{e \rightarrow 1^-} \frac{1 - F(e)}{1 - e} \tag{54}$$

$$\lim_{e \rightarrow 1^-} \frac{1 - F\left(\frac{\alpha v - c}{(1 - \alpha) \left[1 - (1 - (1 - e_{(N)}^*) \gamma)^{N-1} \right]}\right)}{1 - e_{(N)}^*} \tag{55}$$

Since the limit in equation (55) has an indeterminate value, $\frac{0}{0}$, I can use

l'Hôpital's rule to determine the limit.

$$\lim_{e \rightarrow 1^-} \frac{-F'\left(\frac{\alpha v - c}{(1 - \alpha) \left[1 - (1 - (1 - e_{(N)}^*) \gamma)^{N-1} \right]}\right)}{-1} \tag{56}$$

$$\lim_{e \rightarrow 1^-} \frac{-F'(w^*)}{-1} \tag{57}$$

$$\lim_{e \rightarrow 1^-} \frac{dF}{dw} \frac{dw}{de} \quad (58)$$

$$\lim_{e \rightarrow 1^-} f(w) \frac{dw}{de} \quad (59)$$

$$\lim_{e \rightarrow 1^-} f(w) \frac{(\alpha v - c)(N - 1)(1 - 1 - e_{(n)}\gamma)^{N-2}}{[1 - (1 - (1 - e_{(n)}\gamma))^{N-1}]^2} = \infty \quad (60)$$

Even though equation (60) looks really complicated, the basic premise is that the

limit approaches ∞ . Consequentially, $\lim_{e \rightarrow 1^-} \frac{1 - F(e)}{1 - e} = \infty$, which suggests that

$$1 - F(e) \gg 1 - e. \quad (61)$$

$$F(e) \ll e \quad (62)$$

Since $H(e) = F(e) - e$,

$$\lim_{e \rightarrow 1^-} H(e) < 0 \quad (63)$$

Since H is a continuous function on a closed interval [0,1], and 0 is a number between H(0) and H(1), using the Intermediate Value Theorem, I conclude that there is at least one number e in the closed interval [0,1] $H(e)=0$.

Figure 5: $H(e)$ versus e : Nash equilibrium:

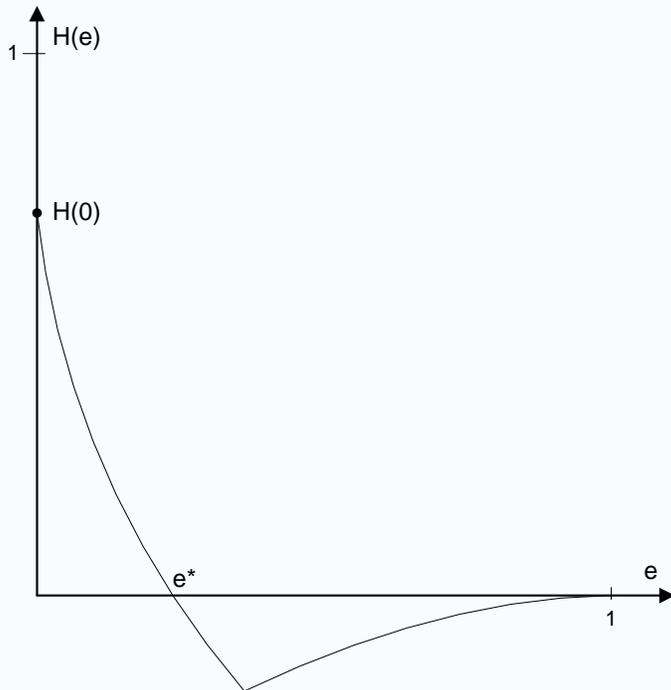
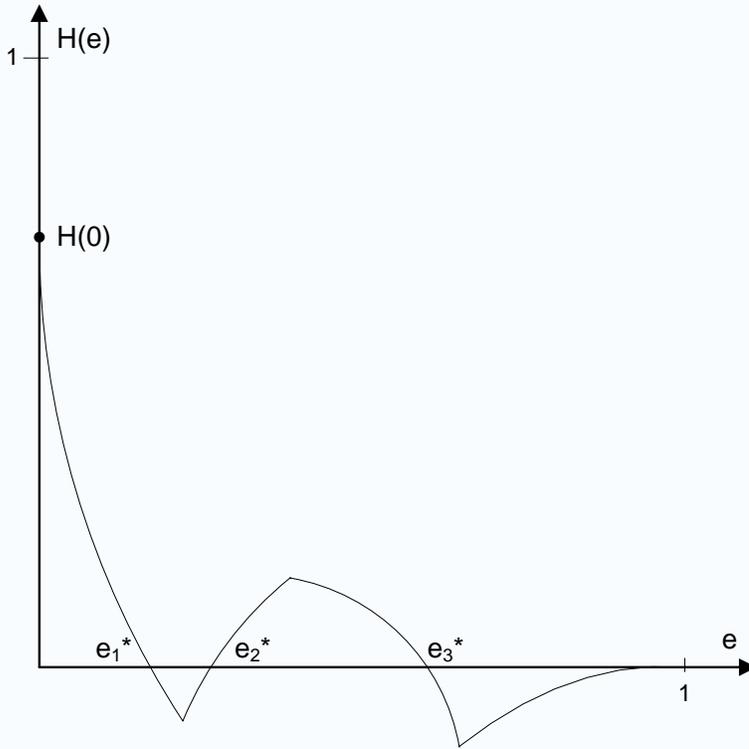


Figure 5 is a possible illustration of how H varies as e changes. Notice that $H(0)$ starts at an arbitrary point greater than zero and approaches $e=1$ from values smaller than zero, thereby yielding a Nash equilibrium e^* for which $H(e^*)=0$. Until e approaches e^* , $H(e)$ is a decreasing function starting from positive values at $e=0$. Thus at point e^* ,

$$\frac{dH}{de} = H_e < 0.$$

It is important to note that the finding $\frac{dH}{de} = H_e < 0$ holds true even when there is more than one value of e^* for which $H(e^*)=0$. Suppose that instead of a single Nash equilibrium as in Figure 5, there are multiple Nash equilibriums as demonstrated in Figure 6.

Figure 6: $H(e)$ versus e : Multiple Nash equilibrium



In Figure 6, there are three Nash equilibrium, e^*_1 , e^*_2 and e^*_3 , however only one of these equilibria is stable. Recall that when $N=2$, we only chose the first equilibrium displayed in Figure 1 since it was the only stable equilibrium. Similarly, in Figure 6, we will once again choose the first equilibrium, e^*_1 as it is the only stable Nash

equilibrium. For all e^*_1 , $\frac{dH}{de} < 0$; $H(0)$ is always greater than 0.

Using equation (53), $\frac{de}{dN} = -\left(\frac{H_N}{H_e}\right)$ and our findings that both H_e and H_N are

negative values enable us to determine that $\frac{de}{dN} < 0$. This finding supports my

hypothesis that as the number of residents increase, probability of evacuation decreases.

Finding the limit of the probability of evacuation:

I have shown that as N increases, probability of evacuation decreases. As N increases, by equation (37), w_i^* approaches 0. In other words, $\lim_{N \rightarrow \infty} w_i^* = 0$. I have repeated several times that $e_i^* = F(w_i^*)$. Since $e_i^* \geq 0$, the cumulative distribution function $F(w_i^*)$ is bounded below by 0. On the other hand, since $F(w_i^*)$ is monotone increasing, it must converge to a limit as $F(w_i^*)$ near its lower bound 0. In other words,

$$\exists a_0 \text{ such that } \lim_{w \rightarrow 0} F(w) = \lim_{w \rightarrow 0} e^* = a_0. \quad (64)$$

By finding a_0 , I can determine the value to which e^* converges to as N increases and w_i^* decreases. If I modify equation (41), I find that

$$F(w_i^*) = F\left(\frac{\alpha v - c}{(1 - \alpha)[1 - [1 - (1 - e^*)\gamma]^{N-1}]}\right) = e^* \quad (65)$$

We know that as $N \rightarrow \infty$, $w_i^* \rightarrow 0$. We further know that from equation (64)

$\lim_{w \rightarrow 0} F(w) = \lim_{w \rightarrow 0} e^* = a_0$. Consequently, as $N \rightarrow \infty$, equation (65) takes on the following form.

$$a_0 = F\left(\frac{\alpha v - c}{(1 - \alpha)[1 - [1 - (1 - a_0)\gamma]^{N-1}]}\right) \quad (66)$$

$$^{15} a_0 = F\left(\frac{\alpha v - c}{1 - \alpha}\right) \quad (67)$$

Since I already made that assumption that $\alpha v - c > 0$, a_0 will be strictly greater than 0. Despite the fact that the lower bound of e^* is equal to 0, as N increases, the limit will not converge to 0.

$$\text{In fact, } \lim_{N \rightarrow \infty} e^* = F\left(\frac{\alpha v - c}{1 - \alpha}\right) \neq 0 \text{ for all } N \quad (68)$$

The validity of equation (68) is confirmed in Section IV. As N increases, the probability of evacuation converged towards the value 0.0084 which is equal to $F\left(\frac{\alpha v - c}{1 - \alpha}\right)$

for uniform distribution.¹⁶ This is an interesting finding, because one would expect the limit to converge to 0 as $N \rightarrow \infty$. Notice that equation (67) is the same equation as (7) where $\phi_j = 1$. Intuitively, equation (67) is the scenario in which someone will definitely break into your house and loot your property. Why do some people evacuate when in fact they know for sure their property will be looted? In other words, why is $F\left(\frac{\alpha v - c}{1 - \alpha}\right) = 1$ for

some individuals? Remember that $F\left(\frac{\alpha v - c}{1 - \alpha}\right)$ is equal to $\Pr\left(w_i \leq \frac{\alpha v - c}{1 - \alpha}\right)$. Thus the

wealth of these individuals who choose to evacuate is definitely less than $\frac{\alpha v - c}{1 - \alpha}$. For

¹⁵ As N increases, since $[1 - (1 - a_0)\gamma] < 1$, $[1 - (1 - a_0)\gamma]^{N-1}$ goes to 0. Thus $1 - [1 - (1 - a_0)\gamma]^{N-1}$ goes to 1.

these individuals, it is not worth staying behind to protect their property at the expense of their lives. Even if a thief deprives them of all their belongings, they do not have much to lose as their wealth, w_i , is really small.

Another reason why some people choose to leave their property vulnerable to looting threats by evacuating is related to the severity of the hurricane. Notice that as the severity of the hurricane is close to 1, $\lim_{\alpha \rightarrow 1} F\left(\frac{\alpha v - c}{1 - \alpha}\right) = F(\infty)$. Since $F(\infty) = \Pr(w_i \leq \infty) = 1$, everyone would choose to evacuate. This makes intuitive sense since when an individual stays behind, the hurricane will deprive him of all his belongings and his value of life.

VI. Conclusion:

In this paper, I set out to answer the following question: How did robbery and looting concerns in New Orleans affect the evacuation behavior of Louisianans during Hurricane Katrina? I had two different hypotheses. The first one was that as property concerns increase, probability of evacuation decreases. The second one was that as the number of residents increase in a given city, coordination problems yield a lower probability of evacuation. The effect of property-related concerns on evacuation patterns has not found much support from previous literature. By modeling a theory of evacuation based on individuals' property related concerns, which I define in terms of any valuables they leave behind, I have been able to support the two aforementioned hypotheses.

My findings explain why a need for a mandatory evacuation evolved. As N increases, the probability of evacuation converges to the limit $F\left(\frac{\alpha v - c}{1 - \alpha}\right)$. For large values of N , probability of evacuation is mainly dependent on the cost of evacuation, the

value of life and the severity of hurricane. Even though the value e depicts the probability of evacuation for a single individual, it can also be interpreted as the proportion of the population who choose to evacuate.¹⁷ As the cost of evacuation increases, the severity of hurricane and the value of life decrease, the probability of evacuation decreases; a smaller proportion of the city evacuates.¹⁸ Since individuals voluntarily do not choose to evacuate, a mandatory evacuation order was put in place to maintain order in the city.

In this paper, I give an initial framework and the tools to enable the evaluation of the current evacuation legislation. One of the reasons why there the number of studies on hurricane evacuation behavior is limited is the lack of precise definitions for different evacuation orders. How could further research be pursued if there is very little consensus on what exactly a mandatory evacuation order entails? Using my model, policy makers can establish more precise guidelines to lay out which parameters should be utilized prior to an announcement of an evacuation order. In my model, I analyzed expected welfare implications for a uniform distribution of wealth. For a uniform distribution, I find that as the value of life increases, the welfare associated with a mandatory evacuation increases. Under a voluntary evacuation order, an individual who might choose to stay behind to protect his belongings at the expense of his life is obliged to evacuate under a mandatory evacuation order. By enforcing mandatory evacuation, the government officials allow the citizens to enjoy their high values of life. In contrast, as the cost of evacuation increases, the welfare associated with a mandatory evacuation decreases. By enforcing a mandatory

¹⁷ Each person independently has a probability of evacuation e^* , however for N people, the probability of evacuation is equal to Ne^* . In order to find the average probability of evacuation in the city, we can divide Ne^* by N . Consequently, the average proportion of the city who choose to evacuate is also equal to e^* .

¹⁸ I believe that the effect of cost of evacuation on the probability of evacuation is likely to outweigh the effect of the severity of hurricane and the value of life since the two latter parameters cannot be assessed using nominal values, whereas, the former parameter can be. In other words, a person can unconsciously undervalue his value of life or the severity of the hurricane, but he cannot unconsciously reduce the nominal cost he has to incur.

order, the government compels the citizens to undergo high evacuation costs; reducing the total welfare of the city.

For a uniform distribution, the maximum level of wealth in the city has essential repercussions on welfare. In a uniform distribution, any level of wealth is equally likely to be present in a given city. As the maximum level of wealth increases, a greater range of wealth levels are present in the city; the distribution of wealth is more heterogeneous. A government enforces a mandatory evacuation to reduce coordination problems that arise from property-related concerns. Consequentially, for a city with a greater range of wealth levels, mandatory evacuation is more efficient because it diminishes a greater number of the coordination problems and property-related concerns.

In a Robinson Crusoe model, the single individual would always choose to evacuate, therefore welfare associated with a mandatory evacuation and a voluntary evacuation is exactly the same. For a hypothetical scenario where there is one person, there is no need for the enforcement of a mandatory evacuation, because this individual voluntarily evacuates the city. However, as N increases, the need for a mandatory evacuation order increases as well. As $N > 1$ the probability of evacuation decreases significantly as shown in Table 3. This suggests that the presence of other individuals factors an individual's evacuation decisions. Thus, for cities with large populations, government intervention in the form of a mandatory evacuation is vital. The officials should be responsible for imposing a mandatory evacuation to eliminate coordination problems and increase each individual's likelihood of evacuation.

One of the limitations of my model is the assumption that when a hurricane strikes, the wealth of an individual is reduced due to the severity of the hurricane.

However, in real life, insurance companies can partially or fully undertake the losses and damages during a hurricane strike. According to the Harvard School of Public Health Survey (2005) conducted amongst evacuees residing in Houston shelters, 72% of the evacuees who did not evacuate prior to the hurricane had no insurance to cover their losses even partially. Since property-related concerns can be reduced through insurance benefits, further research could concentrate on how the entitlement to insurance benefits alters evacuation decisions.

Another limitation of my model is the assumption that cost is fixed for every individual. However, cost is a decreasing function of wealth, $c(w)$. As wealth increases, the real cost of evacuation decreases. For example, an evacuation cost of \$500 might be cheap for a high-income individual, but an evacuation cost of \$250 might not be affordable for a low-income individual. Thus, further studies should consider modeling cost as a decreasing function of wealth to expand the current welfare implications.

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