Natural Hazards (2006) 38: 321–338
DOI 10.1007/s11069-005-0263-0

Agent-Based Modeling and Analysis of Hurricane Evacuation Procedures for the Florida Keys

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(Received: 12 April 2005; accepted: 17 June 2005)

Abstract. The unique geography of the Florida Keys presents both high risk of hurricane landfall and exceptional vulnerability to the effects of a hurricane strike. Inadequate hurricane shelters in the Keys make evacuation the only option for most residents, but the sole access road can become impassable well in advance of a major storm. These extraordinary conditions create challenges for emergency managers who must ensure that appropriate emergency plans are in place and to ensure that an orderly exodus can occur without stranding large numbers of people along an evacuation route with inadequate shelter capacity. This study attempts to answer two questions: (1) What is the minimum clearance time needed to evacuate all residents participating in an evacuation of the Florida Keys in advance of a major hurricane for 92,596 people – a population size calculated based on the 2000 US Census population data, census undercounts, and the number of tourists estimated to be in the area? (2) If a hurricane makes landfall in the Keys while the evacuation is in progress, how many residents will need to be accommodated if the evacuation route becomes impassable? The authors conducted agent-based microsimulations to answer the questions. Simulation results suggest that it takes 20 h and 11 min to 20 h and 14 min to evacuate the 92,596 people. This clearance time is less than the Florida state mandated 24-h clearance time limit. If one assumes that people evacuate in a 48-h period and the traffic flow from the Keys would follow that observed in the evacuation from Hurricane Georges, then a total of 460 people may be stranded if the evacuation route becomes impassable 48 h after an evacuation order is issued. If the evacuation route becomes impassable 40 h after an evacuation order is issued, then 14,000 people may be stranded.

Key words: hurricane, evacuation, agent-based microsimulation, Florida Keys

1. Introduction

Development of an evacuation strategy for populations at risk from natural disaster is often problematic due to unstable and hectic conditions

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that accompany a natural disaster. Traditional static modeling tools are not sophisticated enough to accommodate realistic scenarios that include dynamic conditions and varying evacuee response rates typically found in an evacuation. Many of the existing tools use macrosimulation techniques that are unable to determine location and duration of bottlenecks along an evacuation route. Agent-based microsimulation modeling holds the promise of being able to create realistic scenarios that incorporate choices made by evacuees regarding not only evacuation times, but also route choices and other driving decisions. When properly used, agent-based modeling can create a reasonably realistic and workable forecasting model that emergency managers and planners can use to improve the effectiveness of evacuation procedures.

Previous studies using agent-based methodologies have simulated the time required to evacuate populations at risk using idealized models of road systems or small real world populations (Cova and Johnson, 2002; Chen and Zhan, 2004). This study expands on this line of research by modeling the Florida Keys, a large existent region with unique hazard vulnerabilities and a challenging evacuation route. One important issue related to hurricane evacuation in the Florida Keys is the estimation of the total time required to evacuate the population in the keys. A recent study of hurricane evacuation by Miller Consulting for the Florida Department of Transportation indicates that the entire population of the keys *cannot* be evacuated in less than the state mandated maximum of 24 h (Miller Consulting, 2001). This result has significant policy implications because it may be used as the scientific basis for determining the maximum number of hours needed for evacuating the population in the Keys by the Florida Legislature. Our observation is that the Miller Study used a macrosimulation methodology to determine evacuation clearance times based on static network flows. In addition, the Miller Study assumed an average speed for each segment and did not take into account behaviors of individual drivers at intersections, bottlenecks or other congested areas. These simulation conditions do not necessarily reflect real transportation conditions during an evacuation in the Keys. Because of these limitations in the Miller Study, it is important to conduct additional simulations that more closely reflect real world conditions and use results from these additional simulations to validate the results of the Miller Study. The study reported in this article uses an agent-based modeling approach to simulate evacuation dynamics that more closely reflects actual traffic flows and driver behaviors in an evacuation. In this study, vehicle travel time and speed on each road segment are based on posted speed limits and congestion factors of the transportation networks in the Keys which closely reflect actual traffic and road conditions.

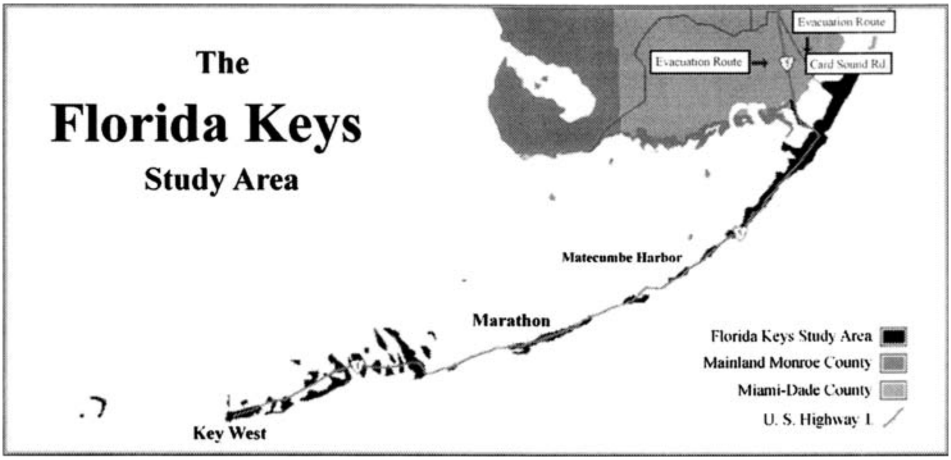

Figure 1. The Florida Keys study area.

1.1. THE FLORIDA KEYS

The Florida Keys consists of a chain of low-lying islands extending for more than 190 miles in a southwesterly direction from the southern tip of the Florida Peninsula (URS Corporation, 2002) (Figure 1). U. S. Highway 1, locally known as the Overseas Highway, is the sole thoroughfare linking the Florida Keys together and it consists of over 112 miles[1] of roadway and serve as the only viable mass evacuation route in the event of a hurricane. In addition there is an 18-mile stretch of highway that passes through a remote, low lying swamp before entering the highway system on the mainland of Florida. The Overseas Highway uses a linear referencing system with markers every mile. Mile Markers begin at mile 0 at the Monroe County Courthouse in Key West and end at mile 112.5 at Cross Key in Key Largo. Over 70% of the roadway is an undivided two-lane highway (80 miles) with some four-lane divided sections in the more populated areas (Monroe County, 2003).

Residents of the Florida Keys tolerate a unique set of liabilities when it comes to risk of hazard from hurricanes and tropical storms. The archipelago lies within an area that experiences one of the highest rates of return for severe tropical weather in the US. The largest concentration of the population lives at the far end of a solitary evacuation route that is vulnerable to congestion and flooding during a storm event. To make matters worse, there are no designated shelters capable of withstanding a Category 3 or higher hurricane in the archipelago and there is insufficient capacity in current shelters to accommodate the population during the smaller, more common Category 1 and 2 storms.

[1] One mile equals 1.6 km.

Given that the residents of the Keys live in a high risk area for hurricane strikes, with the associated threat of severe flooding, a single, highly exposed evacuation route and lack of adequate hurricane shelters, one might think that the Keys residents are predisposed for a major disaster. While this may indeed be the case, there is another aspect of this area that has not been widely considered. Many hazard researchers have hypothesized that perception of hazard changes with familiarity and time of exposure to a hazard. Several researchers argue that the greater the time that has elapsed since a hazardous event and the less experience with such events that the public has, the lower the public perception of the threat (White and Haas, 1975; Meleti *et al.*, 1975; Drabek, 1986). Additionally, communities that have not had a recent, direct hit by an intense hurricane, but have had near misses and brushes with minor storms are said to gain an ''artificial hurricane experience'' (Windham *et al.*, 1997).

However, contrary to these findings, Cross (1990) found that local residents were knowledgeable about tropical cyclones and that their perception of the risk involved actually increased over time. More recently, Dash and Morrow (Dash and Morrow, 2001) conducted a study in the wake of Hurricane Georges and found that residents followed reports on the storms, made their own assessments, and that those assessments were generally correct. Even a study commissioned by the Army Corps of Engineers found evidence that evacuation decisions by residents of the Keys were made independently of the mandatory evacuation orders from emergency management officials (Post, Buckley, Schuh and Jernigan, 1999).

According to the U. S. Census Bureau, the estimated population of Monroe County for year 2000 was 79,589 people living in 51,563 housing units (U.S. Census Bureau, 2004)). The Miller report assumed that a total of 92,596 would evacuate the Keys in a Category 3–5 storm. The additional population from the Miller report accounted for tourists and census undercounts. In order to correlate our data and compare outcomes with those of the Miller report, this study used the same figures.

1.2. EVACUATION ASSESSMENT

Human behavior is linked to the environment. With regard to evacuation planning, details of individual travel plans, such as trip initiation time and route choice depend on congestion as well as other factors. However, congestion is dependent on the cumulative impact of time and route choices for all persons involved in the evacuation. Agent-based microsimulations are able to capture individual and collective behaviors in a complex and dynamic environment and have thus received significant attention in recent years (Anderson, 1999; Ebeling and Schweitzer, 2001; Bonabeau, 2002a, 2002b; Gilbert and Bankes, 2002). As a result of the actions and interactions of the agents, the emergence, or the group behavior can often be obtained through the outcome of a simulation. Agent-based simulation can help a researcher study how changes in individual behaviors would affect the collective behavior of a group of agents, and how different environmental settings can influence the collective group behavior.

It was not the intention of this study to simulate an evacuation in progress in real time. Rather, this study was designed to create scenarios and to evaluate evacuation plans in order to aid emergency managers in their decision-making for organizing an evacuation, and to validate the results of the Miller Study. To be effective, the simulations should realistically model the behaviors of evacuees based on reasonably realistic scenarios. These simulations can test not only the effectiveness of the proposed evacuation plans, but they can also help improve the effectiveness of the policies through the identification of potential problematic areas and bottlenecks. In the case of the Florida Keys, this is especially critical because of a number of unique safety factors along the evacuation route. The entire extent of the Overseas Highway is within the floodplain with much of it exposed to the ocean. As an intense hurricane approaches, the weather conditions deteriorate well in advance of the storm and the evacuation route may become impassable. For example, Hurricane Betsy in 1965, a Category 3 hurricane, caused a storm surge that washed out two sections of the Overseas Highway preventing further evacuation (Perkins and Enos, 1968). Therefore, it is very important for us to have a better understanding as to how we may mitigate adverse weather conditions and develop better evacuation strategies. Agent-based microsimulations of different scenarios can help us to achieve this goal by extending neighborhood and community-level models to evacuation of a large regional population over a greater time span.

This study attempts to answer two specific questions: (1) What is the minimum clearance time needed to completely evacuate 92,595 persons (residents plus transient tourist population) from the Florida Keys in advance of a major hurricane? (2) If a hurricane makes landfall in the Keys while evacuation is in progress, how many residents will need to be accommodated in the event that the evacuation route becomes impassable? An answer to the first question is important to emergency managers and planners because it dictates how far in advance of a hurricane landfall that evacuation orders need to be declared in order to achieve adequate clearance times, and it is also important to serve as a validation to the results from the Miller report for reasons indicated in the discussions above. Answers to the second question inform emergency preparedness personnel about the need for alternate resources, such as last resort shelters for travelers who might become stranded along the evacuation route or alternative evacuation procedures such as air lifting.

2. Background

A study of evacuation response for 12 hurricanes over a period of 3 decades indicated that the variation in the decision of individuals about whether to evacuate is determined by the hazardousness of the area, actions taken by public authorities, type of housing, perception of personal risk, and storm-specific threat factors (Baker, 1991). However, the decision of individuals about when to evacuate has been poorly documented despite the fact that it influences the rate of trip generation in the face of an approaching hurricane. In the absence of better data, most researchers used conventional models with a relatively simple sigmoid loading curve to simulate travel demand (Fu and Wilmot, 2004).

In the real world, the evacuation response function is much more complex. A recent study developed a dynamic model for hurricane evacuation and validated the assumptions using data from Louisiana following Hurricane Andrew (Fu and Wilmot, 2004). This study finds that time of day is the most significant determining factor in describing the pattern of evacuation. There is a low probability of evacuation at night followed by an increasing evacuation rate in the morning with a peak in the afternoon (Fu and Wilmot, 2004). This diurnal mobilization pattern modifies the evacuation loading curve and thus the nature of trip generation in the face of an approaching hurricane.

Traditional studies of emergency evacuation procedures used static analysis tools to estimate clearance time from an affected area. Due to the computationally challenging task of modeling traffic flows at the individual vehicle level, these studies were performed using macrosimulation techniques (Moeller *et al.*, 1981; Sheffi *et al.*, 1982; Hobeika and Jamei, 1985; Farahmand, 1997; Cova and Church, 1997; ORNL, 1998; Urbanik II, 2000). Macrosimulation technology does not attempt to track detailed behaviors of individual vehicles. Instead, the simulations are based on equations that treat traffic as flows on networks (Pidd *et al.* 1996).

With the advent of newer computer technology and more advanced software systems, there has been a surge of traffic flow studies using microscopic simulations. Using a behavioral-based micro traffic simulation model, Sinuany-Stern and Stern (1993) and Stern *et al.* (1996) examined the sensitivity of network clearance time to several traffic factors and route choice mechanisms in a radiological emergency situation. They considered interactions with pedestrians, intersection traversing time, and car ownership as major traffic factors influencing evacuation, and assumed that evacuees use the shortest path to evacuate and follow a myopic behavioral pattern. They found that the simulated evacuation time is closer to that found in reality when interaction with pedestrians is taken into consideration and a uniform distribution of intersection traversing time is assumed.

Another notable emergency evacuation research at the micro scale was done by Pidd *et al.* (1996). By linking a geographic information system (ARC/INFO) with a specially written object-oriented micro-simulator, Pidd *et al.* developed a prototype spatial decision support system (SDSS) that can be used by emergency planners to evaluate contingency plans for evacuation from disaster areas. The system enables a vehicle to find the way to a destination via available roads without congestion. However, this system does not take the interactions between individual vehicles into consideration and hence cannot account for the effect of the collective behaviors of all evacuating vehicles.

2.1. NEIGHBORHOOD AND COMMUNITY EVACUATION SIMULATIONS

Evacuation issues associated with the Oakland Hills, CA fire of 1991 motivated some researchers to study evacuation of specific neighborhoods. Cova and Church (1997) used bulk lane demand techniques to create a map of potential evacuation vulnerability for the Santa Barbara, CA area. Church and Sexton (2002) developed a microsimulation model for the Mission Canyon neighborhood to test evacuation scenarios for this area and confirmed that a neighborhood is exposed to significant risk of evacuation problems if a fast moving wildfire should start in immediately adjacent areas (Cova and Johnson, 2003). Another study used commercially available microscopic traffic simulation software to test neighborhood evacuation plans in an urban environment and assessed the effect of a proposed second access road on household evacuation time (2002). Chen and Zhan (2004) used agent-based microsimulation techniques to study the relative effectiveness of simultaneous and staged evacuation techniques in three different environments. Another study used five scenarios to analyze the issues involved in the evacuation of the Los Alamos National Laboratory along with the surrounding communities (Jha *et al.*, 2004).

2.2. SIMULATION METHODOLOGY

2.2.1. *Simulation environment*

The authors performed the simulations in VISSIM V3.70 (PTV Planung Transport Verkehr AG, 2003), a behavior-based microsimulation system developed by Planung Transport Verkehr (PTV) in Germany. The system utilizes a discrete, stochastic psycho-physical driver behavior model developed by Wiedemann (Wiedemann, 1974). This model defines four basic driving modes – free driving, approaching, following, and braking – according to the speed difference between vehicles and the psychological characteristics of individual driver-vehicle units. The simulations were conducted on a DELL computer with the Pentium 4 2.4G processor and 1.0G of RAM running under the Windows XP operating system. The authors conducted two sets of simulations based on different evacuation response curves (see the Evacuation Timing Subsection below for more details.). Each simulation was repeated 10 times to eliminate the effect of randomness in the simulation models. The average evacuation clearance time of the 10 simulations was then reported and used as the simulated evacuation clearance time.

2.2.2. *Road network preparation*

In order to compare the results from this study with those from the Miller Study (Miller Consulting, 2001), the authors used the same road links described in the Miller report as the evacuation roadways for the Florida Keys. The Miller report defined a total of 31 links according to changes in cross section. Using 1-m Digital Orthophoto Quadrangles covering the Keys, the authors constructed the digital version of the evacuation roadways in VISSIM. The evacuation roadways start at the northern boundary of Keywest and end at the intersection of U. S. Highway 1 and the Homestead Extension of the Florida Turnpike. Attributes associated with each link include link type, number of lanes, lane width, and speed limit. These attributes were adopted from those used in the Miller Study.

2.2.3. *Evacuation zones and trip generation*

Based on the Miller Study, the authors defined the same seven evacuation zones according to the Monroe County Emergency Management Division. Then for each zone, following the same approach used by the Miller Study (Miller Consulting, 2001), the study calculated the number of evacuating vehicles for a population of 92,596 people. The number of evacuating vehicles was determined based on a formula developed by Nelson *et al.* (1989) as shown in Expression (1).

$$N_{\mathrm{v}} = N_{\mathrm{u}} * N_{\mathrm{vu}} * R_{\mathrm{p}} * R_{\mathrm{o}} * P_{\mathrm{vu}} \qquad (1)$$

where, N_{v} is the number of evacuating vehicles; N_{u} is the number of housing units; N_{vu} is the number of vehicles per housing unit; R_{p} is the percentage of people participating in an evacuation; R_{o} is the occupancy rate of the housing units; P_{vu} is the percentage of vehicle usage.

This study assumed that evacuation takes place for a Category 3–5 hurricane, which means that most people need to be evacuated from Monroe County. Table I shows the values of the parameters in Expression (1) corresponding to a Category 3–5 hurricane for a population size of 92,596. The evacuees were divided into three groups: dwelling units, mobile units, and tourist units. The evacuation destinations were

Table I. Evacuation parameters (hurricane Category 3–5 for year 2000).

Zone	# of units				% of occupancy			Evacuation participation rate (%)			Destination percentages (non-tourist)		Destination percentages (tourist)	# of vehicles per unit		Vehicle usage (%)	
	Dwelling	Mobile	Tourist	Total	Dwelling	Mobile	Tourist	Mobile home	Tourist units	Others	Out of country	Motel/ Friend's home	Out of county	Dwelling	Tourist	Dwelling	Tourist
1	15,400	1,323	5,611	22,334	86	100	72	95	100	60	95	5	100	1.35	1.04	69	100
2	6,720	792	1,759	9,271	71	100	64	95	100	60	95	5	100	1.76	1.04	69	100
3	7,773	917	2,334	11,024	69	100	64	95	100	80	95	5	100	1.39	1.05	71	100
4	2,441	199	1,457	4,097	57	100	70	95	100	85	100	0	100	1.65	1.1	71	100
5	5,174	395	557	6,126	66	100	70	95	100	85	100	0	100	1.76	1.1	71	100
6	7,173	1,358	2,487	11,018	65	100	70	95	100	85	100	0	100	1.61	1.1	71	100
7	1,745	3	185	1,933	42	100	70	95	100	85	100	0	100	1.58	1.1	71	100

Note: data were determined and compiled according to the Miller Study (Miller Consulting, 2001).

divided into two groups. One is to Monroe Motel/Friend's home and the other is to a location outside Monroe County. Based on the percentages of destination choices, the trips to different destinations for each zone are shown in Table II. There are a total of 41,016 evacuating vehicles. Among these evacuating vehicles, 40,113 will head for the destination outside Monroe County. According to the Miller report, evacuating vehicles from each evacuation zone enter U. S. Highway 1 through one of 16 links (Figure 2). Therefore, there are a total of 16 trip origination zones in the simulation. The number of evacuating vehicles assigned to the 16 zones is determined by the percentages defined in the Miller report.

2.2.4. *Evacuation timing*

Evacuation timing is closely related to the behaviors of evacuees. The Miller Study employed three evacuation response curves – early, normal, and late response curve – developed by Baker (2000) to determine the percentages of vehicles leaving at different time periods after an evacuation order is issued. This study simulated the evacuation using two evacuation response curves. In the first set of simulations, the study used the late response curve and compared the results with those in the Miller report (Figure 3).

In the second set of simulations, the study extrapolated evacuation rates from the first 2 days of the actual evacuation for Hurricane Georges, a Category 2 storm (Post, Buckley, Schuh & Jernigan, 1999) (Figure 4). Using northbound traffic counts for U. S. Highway 1 during the evacuation of Hurricane Georges (Post, Buckley, Schuh & Jernigan, 1999), the

Table II. Numbers of vehicles leaving.

Zone	Non-tourist				Tourist		Out of county subtotal	Total vehicles leaving
	Dwelling unit	Mobile unit	Total	Out of county	Motel/ Friend's home	Out of county		
1	7,402	1,171	8,573	8,144	429	4,202	12,346	12,774
2	3,476	914	4,390	4,171	220	1,171	5,341	5,561
3	4,234	860	5,094	4,840	255	1,568	6,408	6,663
4	1,385	221	1,607	1,607	0	1,122	2,729	2,729
5	3,627	469	4,096	4,096	0	429	4,525	4,525
6	4,530	1,475	6,005	6,005	0	1,915	7,920	7,920
7	699	3	702	702	0	142	844	844

Note: Data were determined and compiled according to the Miller Study (Miller Consulting, 2001).

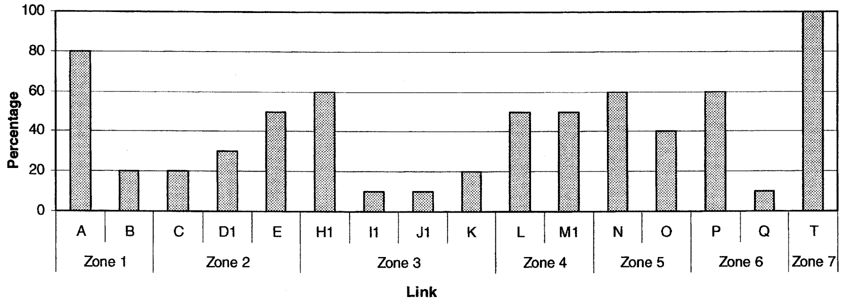

Figure 2. Percentages of vehicles in each zone leaving from the links (Note: Key West is located in Zone 1 and the zones are numbered sequentially from Key West. Based on a report from Miller Consulting, Inc. (Miller Consulting, 2001)).

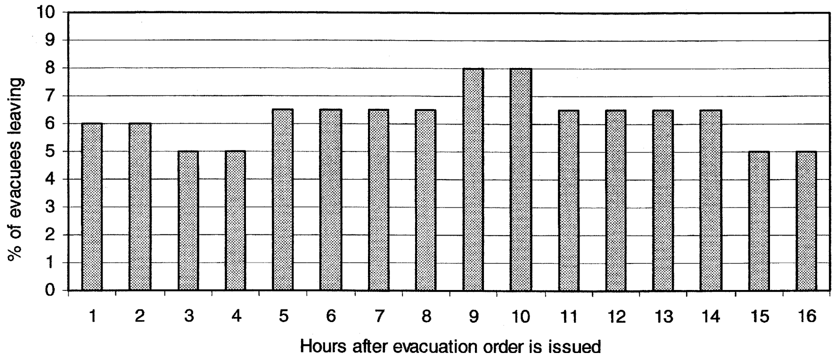

Figure 3. Late response curve of evacuation in Florida Keys (Source: Miller Consulting, Inc. (Miller Consulting, 2001)).

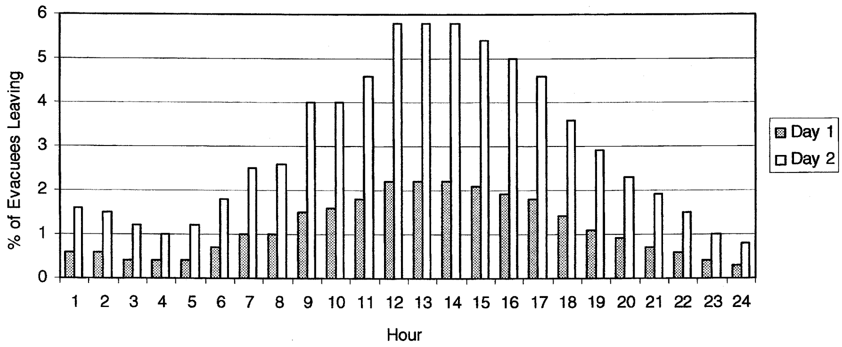

Figure 4. Revised evacuation rates during a 2-day (48-h) period (after Post, Buckley, Schuh and Jernigan, 1999).

study increased the participation rates to the levels assumed by the Miller Study (Miller Consulting, 2001). The simulation period was 48 h in advance of the storm. This simulation resulted in 11,208 vehicles evacuating on Day 1 of the simulation and 28,905 on Day 2. At peak travel in the period from Noon to 2 p.m. on Day 2, it is estimated that 2,310 vehicles per hour would evacuate the Keys.

2.2.5. *Route and destination choice*

The evacuation destinations were divided into two groups. One was to Monroe Motel/Friend's home and the other was out of the county. Given the evacuation roadways in the Florida Keys, U. S. Highway 1 and Card Sound serve as the evacuation routes out of the county with U. S. Highway 1 carrying most of the traffic. The destination was set at the junction of U. S. Highway 1 and the Homestead Extension of the Florida Turnpike. Dynamic routing was used in the simulation. It assumes that drivers adjust their routes dynamically based on real time traffic conditions while en route, which means drivers are free to choose Card Sound Road to evacuate when they get close to the Florida mainland (Figure 1) if they estimate that travel time using Card Sound Road is less than using U. S. Highway 1 to reach their destinations.

3. Results and Analysis

3.1. EVACUATION TIME

As indicated in discussions above, the authors performed two sets of simulations, each attempting to answer one of the two questions stated in the introduction. As VISSIM is based on a STOCHASTIC driver behavior model, it is necessary to perform multiple runs in order to account for randomness in the results. Elapsed times for the models depend on network complexity, the number of vehicles to be simulated, and the level of congestion encountered along the evacuation routes. The congestion level is higher in the first set of simulations, with an elapsed time for each simulation of approximately 56 h of computer time. Although the simulation period was greater for the second set of simulations, congestion was less, requiting on average 33 h and 30 min to complete the each simulation run. Therefore, the authors performed 10 runs for each set of simulations. The study calculated confidence intervals at 95% confidence level for the simulation results to account for the randomness in the results (Table III).

In the first set of simulations, total clearance time for each run was consistent (Figure 5). The average clearance time is 20 h, and 12 min. At the

Table III. Steps for calculating confidence interval.

1.	Calculate mean value, $\bar{x}$ of the results
2.	Calculate standard deviation σ of the results
3.	Select significance level ($\alpha = 0.05$ in our study)
4.	Calculate confidence interval as $1.96 * \frac{\sigma}{\sqrt{n}} (n = 10)$

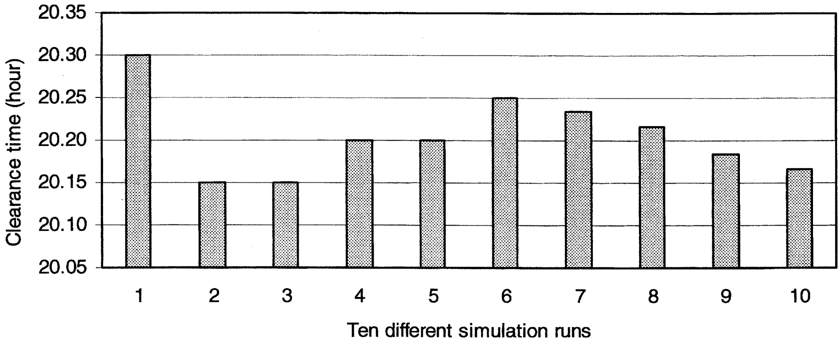

Figure 5. Clearance time for the first set of simulations.

95% confidence level, the evacuation time is expected to range from 20 h and 11 min to 20 h and 14 min. This clearance time is much shorter than the 26 h and 8 min obtained by the Miller Study. In contrast to the Miller Study, this study made no provisions for deteriorating weather conditions, accidents or issues other than those encountered in the course of normal driving. The Miller Study, however, estimated the clearance time based on a "worst case" scenario and is more conservative.

As expected, simulation results from this study indicate that the most severe congestion may occur in the upper Keys between Mile Markers 100 and 106 where the road narrowed from a four-lane road in Key Largo to a two-lane road that makes up the majority of the 18-mile stretch. The simulations also suggest that a bottleneck may appear in the area of Matecumbe Harbor (Figure 1). A significant benefit of microsimulation methodology is that the estimated travel time for the last car to evacuate from the Keys is available in the resulting files of a simulation. In the first set of simulations, it took on average 4 h and 37 min (±4 min at the 95% confidence level) for the last vehicle to evacuate from the Keys.

In the second set of simulations, when trip generation rates are assumed to follow the traffic flow from the Keys that was observed from the evacuation of Hurricane Georges (Post, Buckley, Schuh and Jernigan, 1999; Fu and Wilmot, 2004), no significant delay was found in any area. In addition, for all 10 simulations, the average time for the last evacuating vehicle from its origin to its destination is 2 h and 56 min (±5 min at the 95% confidence level), significantly reducing the critical exposure time along the evacuation route. Unlike the last evacuating vehicles in the first set of runs, those in the second set of simulations experience no congestion and are able to travel at the posted speeds. Another measure of the relative lack of congestion in the second set of simulations is the average network speed. This is the mean speed for all vehicles throughout the simulation. In the first set of simulations, the mean speed ranges from 40.87 to 41.83 km/h. In the second set of simulations, the mean speed varies from 63.56 to 73.37 km/h.

3.2. VEHICLES STRANDED ON THE EVACUATION ROUTE

The study conducted the second set of simulations to answer Question 2 corresponding to an evacuation time of 48 h, meaning people in the Keys would evacuate during a 48-h time period starting in mid-night. An important benefit of microsimulation methodologies is that we can examine details about bottlenecks, congestion or the progress of individual vehicles from the resulting files corresponding to any time slice during the evacuation. Information on the progress of individual vehicles can help emergency managers anticipate how many people might be stranded along certain sections of highway in the event that the evacuation route becomes impassible. For the purposes of demonstration, this study selected two time slices to analyze the progress of evacuating vehicles.

The first time slice analyzed was at 4 p.m. of Day 2, 40 h into the simulation. At that time a significant number of vehicles were exiting the Keys. The majority of vehicles that would be stranded along the highway were in the Middle and Lower Keys. If the evacuation route became impassible at the Long Key Bridge (Mile Marker 64), more than 14,000 people would be stranded in 5,666 vehicles on average (±14 vehicles at the 95% confidence level) (Figure 6(a)). The second time slice analyzed corresponds to midnight on the second day (i.e., 48 h into the simulation) after all the evacuation traffic for the simulation is already en route. About 460 people would be stranded in 184 vehicles on average (±4 at the 95% confidence level) near the Long Key Bridge (Figure 6(b)).

4. Conclusions and Future Research

Question 1: Based on the simulation results, it takes 20 h and 12 min on average to evacuate all people in the Florida Keys for a population size of

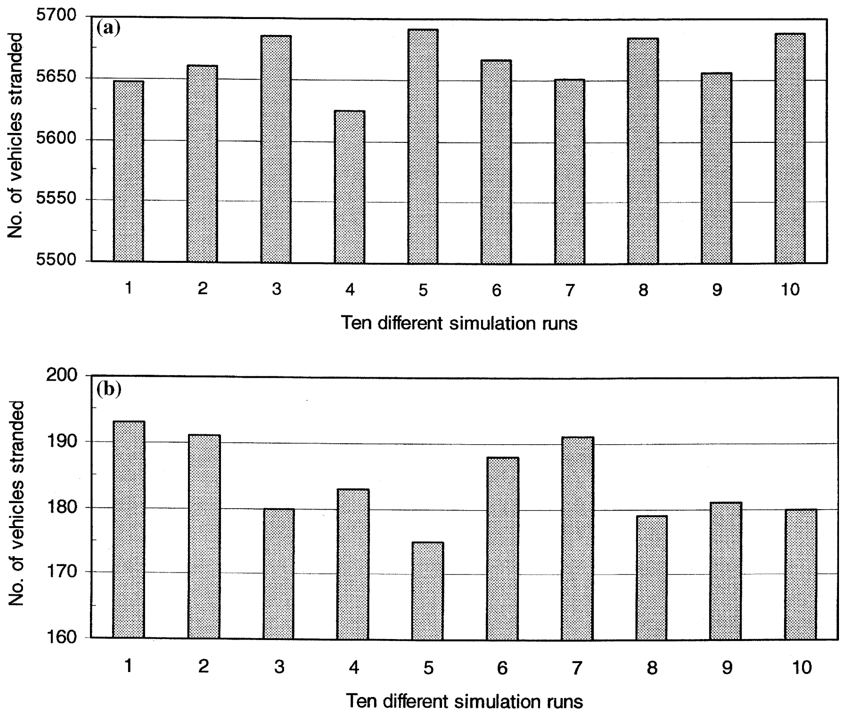

Figure 6. Number of vehicles stranded: (a) Number of Vehicles stranded at the first time slice for the second set of simulations; (b) Number of Vehicles stranded at the second time slice for the second set of simulations.

92,596 as calculated based on the 2000 US Census population data, census undercounts, and the number of tourists estimated to be in the area, provided that the evacuation is organized in an orderly fashion. This clearance time is less than the Florida state mandated 24-h clearance time limit. In other words, the Florida state mandated 24-h clearance time for evacuating all people in the Keys based on the Year 2000 population size is achievable.

Question 2: Assuming that people in the Keys would evacuate during a 48-h period along evacuation rates extrapolated from the first 2 days of evacuation for Hurricane Georges, 460 people in 184 vehicles may be stranded on the evacuation route near the Long Key Bridge if the evacuation route becomes impassable 48 h after an evacuation order is issued. If the evacuation route becomes impassable after 40 h of an evacuation order is issued, 14,000 people in 5,666 vehicles may be stranded near the Long Key Bridge. This result has important policy implications, since it provides specific information as to how many people would have to be accommodated at a given time during an evacuation if the evacuation route becomes impassable.

This study also demonstrates the power of agent-based microsimulation to achieve a better understanding of emergency evacuation. This better understanding provides emergency managers and planners the necessary knowledge in devising evacuation plans that would include services that would reduce risks to the community. In addition, emergency managers and planners can use the specific information about clearance time from the simulations to improve evacuation procedures and assess different evacuation options.

The approach used in this study and the results from the research can be adopted in hurricane evacuation in other areas as well as in planning evacuations from other types of hazard. For example, because urban traffic in many developing countries is usually highly congested and can be chaotic at times, it is a very challenging task for disaster managers to estimate the minimum time that is needed to evacuate residents in urban communities in those developing countries. This study demonstrates that it is possible to use agent-based modeling and simulation to estimate the minimum evacuation time from an approaching disaster. The estimated evacuation time should give disaster managers the necessary knowledge and confidence to plan and organize an evacuation when an evacuation becomes necessary. It is, therefore, advisable that similar agent-based modeling and simulations be conducted in some of the most vulnerable communities where congested traffic is common and estimate the minimum evacuation time for these communities.

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