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Hurricane Evacuation Decision-Support Model for Bus Dispatch

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Abstract
According to the National Hurricane Center, the intensity of hurricanes seasons is expected to increase for the next decade. Thus, national, state, and local governments need to have a well-engineered evacuation plan to reduce the consequences of natural disasters. Coastal cities in particular must be prepared to respond to evacuate its populations as well as to provide necessary assistance pre- and post a hurricane hitting the local area. Rita, Katrina, and Wilma put to the test existing government's evacuation plans, and proved them inadequate, especially more so when using public transportation. Thus, the government plans need to be reviewed, analyzed, and improved, but many local governments lack the tools to evaluate different scenarios and develop a detailed public transportation plan before a hurricane warning has been issued. This project sought to develop a scalable and flexible deterministic evacuation decision-support model to assist Miami-Dade county officials in establishing evacuation strategies. This is a first step in developing a comprehensive decision support systems that will enable decision makes to maximize the number of people evacuated in case of hurricane threat.

Keywords
Emergency Evacuations, Hurricane preparedness, Optimization.

1. Introduction

The terrible consequences in the Gulf Coast from Katrina and the endless traffic jams created by Hurricane Rita in cities such as Houston revealed serious deficiencies in the ability of government to execute an efficient evacuation. The NY Times describes the evacuation of Houston due to Hurricane Rita in the following manner: *"Colossal 100-mile-long traffic jams left many people stranded and out of gas as the huge storm bore down on the Texas coast"* (Blumenthal and Neilan, (2005). While politicians debate over who is to blame, lack of preparation, bureaucratic rivalries, power struggles, and lack of leadership only lead to huge losses of money and, most importantly, lives. TIME Magazine estimates that in New Orleans, there were around 100,000 residents without a means of transport (Ripley, 2005). Many citizens are aware that government officials could have planned better, as is evident from a survey conducted in the same article that indicates that 52% of the people interviewed were dissatisfied with the government preparations for Katrina.

Section two of this paper provides a description of the problem addressed in this paper and the goal and scope to address part of the problem. Section three discusses issues regarding data collection. Section four describes the model, the user interface designed for it. Section five discusses the model usage of the model and results. Lastly, section six summarizes our conclusions and proposes future directions for this research.

2. Problem Background, Goal and Scope

2.1. Background

The incidence of hurricanes disasters have been increasing during the past 10 years for states in the Atlantic and Gulf coast's of United States. From 1995 to 2005 the area have had the highest average of hurricanes per year in history (Blake et al., 2005), with the 2005 hurricane season being the most active, one of the deadliest, and probably the costliest. This increase in the frequency of hurricane hits has coincided with a significant growth in population along the coast, which "will lead to serious problems for many areas during hurricanes" (Blake et al., 2005),. These problems are further complicated because the increase in population has not been followed by sufficient improvements in infrastructure to handle the abnormal amount of traffic generated during an emergency evacuation, or to activate adequate resources such as shelters to open, response personnel to activate, and so forth. It is evident that there are serious deficiencies in evacuation plans that governments currently use. This fact becomes even more evident when we observe government plans to evacuate using public transportation. The Victoria Transport Policy Institute described New Orleans's public transport evacuation as an ad hoc activity with no detailed plan (Litman, 2006):

A good plan is needed in order for the government to properly evacuate cities and ensure the safety of the inhabitants. Currently, there is no tool that will allow local and state government officials to test different scenarios and develop a detailed public transportation plan before a hurricane warning has been issued. The lack of such a tool is a serious deficit in government strategies to effectively evacuate. Therefore, we have begun researching ways in which Operations Research tools can be used by local officials without them having to master the Operations Research methods and specialized tools.

We have focused on one aspect of preparedness. FEMA has defined emergency management as "organized analysis, planning, decision-making, and assignment of available resources to mitigate, prepare for, respond to, and recover from the effects of all hazards", and has defined the goals of it as "save lives and prevent injuries, and protect property and the environment" (FEMA, 2003). From this definition, it is evident that there are many factors to consider, many activities to carry out; however, these activities can be group in 4 phases: mitigation, preparedness, response, and recovery (FEMA, 2003). In the context of hurricane-driven emergencies, these phases are:

(1) Mitigation, includes the actions taken to eliminate or reduce the risk to people and properties if a hurricane makes landfall,
(2) Preparedness, involves the actions taken to minimize the impact of the disaster when a hurricane is expected to hit,
(3) Response, involves all the activities, following an emergency or disaster, taken to save lives and reduce damage, and
(4) Recovery includes the activities taken to return community's systems and activities to normal. Governments must be much more efficient in the evacuation of populated areas in the event of a

hurricane. More people needs to be evacuated in a shorter time and with less money.

2.2. Goal and Scope of the Project

The goal of this project was to formulate a model that could be utilized as part of a decision-support to develop an optimal evacuation plan in case of a hurricane threat.
The project would be focused on Miami-Dade County (Florida). Further, the study has:

- Was limited to the study to one of the main evacuation zones of the Miami-Dade county area, namely zone B (Figure 1).
- Was focused on the allocation of public transportation throughout the zone. We have used a generic definition of "public bus". A *bus* is a vehicle, of any size that is not rail dependent, and that is owned or operated by the city or the state. Hence, a city car fits this definition too.
- Excluded the modeling of Private vehicles. However, the road demand (traffic congestion) generated by them had to be taken into account by the model.

Supporting data was obtained from different government entities, such as the National Oceanic & Atmospheric Administration (NOAA), the Miami-Dade Office of Emergency Management (OEM), and the Federal Emergency Management Agency (FEMA) to name a few.
Our expectations were that even though the study would be limited to this area, the findings could be extrapolated to other counties or zones. The main purpose of the project is to create an evacuation decision-support model for the allocation of public transportation that could result in *saving lives*. This objective will be accomplished by making evacuation more efficient: by assessing and *optimizing evacuation strategies* of the Miami-Dade County for better planning of future evacuations.\

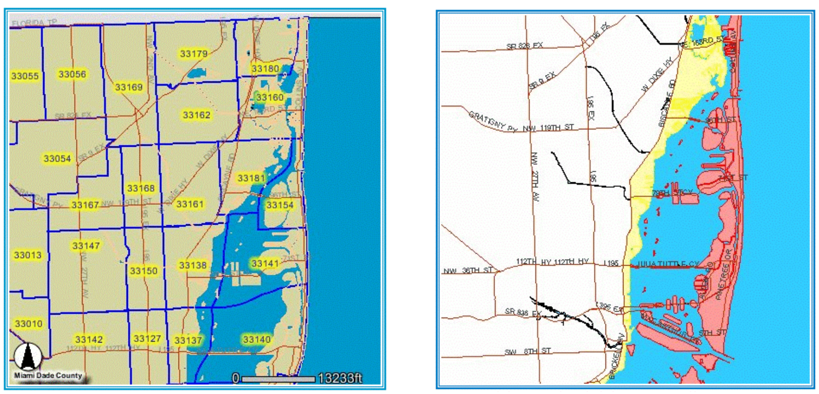

Figure 1: Miami Dade County Zone B

3. DATA COLLECTION

3.1 Population by zip code

Demand for each pickup point was estimated, but for future applications it must be collected or extracted directly from the census. In this effort, the zip codes belonging to the Miami-Dade County evacuation zone B (east of Biscayne blvd. up to the coast) were determined. These are the six zip codes on the first column of the table. The total population for each zip code was obtained from the US Census Bureau. The next step was to determine what percentage of each zip code was inside the evacuation zone B. These percentages were estimated by mapping the zip codes with the corresponding evacuation zone. The total population for each zip code was multiplied by the corresponding percent to obtain the population in zone B. One of the assumptions made was that people will go to the closest pickup point. Therefore, people will go to the pickup point within their zip code area. If more than one pickup point resides inside a zip code area, the population from that zip code was evenly distributed for all those the pickup points.

3.2 Time-Capacity-Demand Matrix

The Miami-Dade County Office of Emergency Management estimates that approximately 15% to 25% of the people evacuate using public shelters during a hurricane evacuation. From this percentage, approximately 95% of them will evacuate using public transportation. These values appear on the column labeled Adjusted Demand (95%). Additionally, the table shows the capacity for each shelter and the adjusted capacity taking into consideration those who evacuate with private vehicles.

3.3 Rush Conditions

In order to obtain the percent inflation due to traffic congestion (TPERCENT) and the time it takes for a passenger to get in and out of the bus (ULT) time studies were conducted. For the TPERCENT a data collection form was created and handed over to different people in order to have variability in the study. They were asked to record the time it took them to go from one place to another during regular traffic hours and during rush hour times. Then these values were analyzed and it was found that it usually takes double the time to perform the same trip during rush hour Therefore, a TPERCENT of 92% was used for the model. For the ULT variable, a time study was performed by observing the 'FIU Cats' bus and recording the time it took for each passenger to get in and out of the bus. After analyzing these data, it was found that on average it takes 7.95 seconds per passenger to load and unload the bus.

4. Model Development

Given a massive disaster situation, the *evacuation time* (referring to the time it takes for a person to start evacuating and get to a safe destination) will be needed in order to execute the appropriate evacuation plans in the available time. According to data received from the Miami-Dade County Office of Emergency Management, people that will evacuate inland should evacuate 24 hours prior to the hurricane arrival, while people that will leave the area to evacuate should be evacuated 36 hours prior to arrival.

There is no way to evacuate more people than the shelters can accommodate, or that the buses can handle. This is why the model is constrained by the *capacity* and *availability* of the *buses* and *shelters*. The number of people in need of public transportation in order to evacuate, or evacuees demand, is considered as a model constraint as well.

The developed model seeks to maximize the number of people evacuated in a given timeframe by effectively allocating buses to specific pick-up point to shelter routes. The model was developed in such a way that it would be scalable and flexible. Scalable means that users will be able to easily adjust the model to make the zone under consideration larger, smaller, or change the zone completely. Flexible means that there is a straightforward and quick way of changing parameters that will have an effect on the output of the model. This flexibility will allow the user to run different scenarios using the same model in order to prepare a better plan. For example, the model could be run a first time assuming that 10% of all resident will use public transportation and run a second time assuming 25%, comparing what the effect of this change will have on an evacuation.

4.1 Assumptions

1. *The time it takes to go from a pick-up point to a shelter is fixed.* Once a time value is defined for a trip from pick-up point "I" to shelter "J", it will take the same amount of time for all the buses to perform this trip. This is because this is a deterministic model. Even though the model takes into account a coefficient for traffic congestion, once that value is set, there is no way to change it while the model is running.
2. *There is a maximum amount of trips that a bus can make.* The maximum number of trips a bus can do

is determined by the length of the "m" set. Hence, the length of the "m" set has to be chosen wisely, and it has to be large enough to allow the buses to perform as many trips as possible in the given timeframe under the stated model constraints.

3. *Refuel delays are negligible or taken into account in the loading/unloading variable.* The model assumes that all the buses and public transportation resources have a full fuel tank at the beginning of the model. There is no additional variable in the model to account for refueling delays during the evacuation period. If there is a need to model those delays, they could be included in the ULT variable, originally defined to account for delays in loading and unloading the buses with passengers.
4. *People will go to the closest pick-up point.* This is believed to be a safe assumption. In the cases where there was more than one pick-up point within zip code, the zip-code population was evenly distributed between those points, which may have ended up placing some people not in their closest pick-up point, but one "close enough" (in the same zip code).
5. *All bus demand is concentrated at the pickup points.* The bus makes only one stop in its round trip from the shelter.
6. *Demand at the pick-up points is present from the start of the model timeframe.* The model does not take into account any delays or waiting times for the people to get to the pick-up point.

4.2 Nomenclature

The following indexes were chosen in order to make the model scalable and transferable from one geographic zone to another For example, if the user would like to add more buses, all he would have to do is change the number of members in the 'buses' set and define their capacity; if the user would like to change the city from Miami to New Orleans, all he would have to do is redefine the shelters, pick-up points, buses, and the corresponding attributes.

Given a set **I** of all shelters $(\mathrm{S1}, \mathrm{S2}, \mathrm{S3}, \cdots, \mathrm{S_i} \cdots)$, a set **P** of pickup points $(\mathrm{P1}, \mathrm{P2}, \mathrm{P3}, \cdots, \mathrm{P_J} \cdots)$, a set **K** of buses $(\mathrm{B1}, \mathrm{B2}, \mathrm{B3}, \cdots \mathrm{B_k} \cdots)$, and a maximum value of trips **M** $(\mathrm{Trip_1}, \mathrm{Trip_2}, \cdots \mathrm{Trip_m})$, we defined the following variables:

i = Index for shelters
j = Index for pickup points
k = Index for buses
m = Index for trips
C_k = Capacity of bus *k*
$C\%$ = Estimate of how full (on average) the buses would be as a percentage of total capacity
Q_j = Capacity of shelter *j*
$Q\%$ = Percentage of shelters that is allocated to people using public transportation.
$A\%_j$ = Percentage of shelter *j* available at the start of the timeframe considered by the model (a shelter might be partially filled at the start of the timeframe)
O_j = Binary attribute that indicates whether shelter *j* is opened (1) or closed (0)
D_i = Total population that could potentially arrive at pick-up point *i*
$D\%_i$ = Percent of the total population that need public transportation at pick-up point *i*
T_{ij} = Roundtrip time from i to j and back to i under normal driving conditions
$T\%$ = Percent time inflation of trips due to road congestion
ULT = Average bus unloading time at shelter plus bus loading time at pick-up point (per passenger)
$ULT\%$ = Percent time inflation of loading/ unloading due to nervousness, etc.
$T_{\max}$ = Maximum time available for evacuation

4.3 Model

The model seeks to maximize total number of people evacuated. The objective function was determined as the sum of all the people evacuated during all the trips (k) by all the buses (m) from all the pick-up points (i) to all of the shelters (j). The number of people evacuated by each bus depends on the capacity of each bus k and the percentage to which this bus is filled. The following variables were chosen as the decision variables in the model.

$$x_{k,m,i,j} = \begin{cases} 1 & \text{if bus } k \text{ makes trip } m \text{ from pick-up point } i \text{ to shelter } j \\ 0 & \text{Otherwise} \end{cases}$$

$$\text{Max} \quad z = \sum_k \sum_m \sum_i \sum_j \left(X_{k,m,i,j} * C_k * C\% \right)$$

Subject to:

$$\sum_{m=1}^{M} \sum_{i=1}^{I} \sum_{j=1}^{J} \left[\left(T_{i,j} (1 + T\%) + (ULT(1 + ULT\%) * C_k * C\%) \right) * X_{k,m,i,j} \right] \leq T_{\max} \quad \forall k \qquad \leftarrow \text{(C1 - time)}$$

$$\sum_k \sum_m \sum_i X_{k,m,i,j} * C_k * C\% \leq Q_j * Q\% * O_j * A\%_j \quad \forall j \qquad \leftarrow \text{(C2 - shelter capacity)}$$

$$\sum_k \sum_m \sum_i X_{k,m,i,j} * C_k * C\% \leq D_i * D\%_i \quad \forall i \qquad \leftarrow \text{(C3-pick-up point demand)}$$

$$\sum_i \sum_j X_{k,m,i,j} \leq 1 \quad \forall k, m \qquad \leftarrow \text{(C4 - one destination/trip)}$$

$$X_{k,m,i,j} = binary \quad \forall k, m, i, j \qquad \leftarrow \text{(C5 - binary)}$$

Each of these five constraints defines the boundaries of the search space from their unique perspective:

(C1) Limits the number of trips that each bus can make based on the maximum time available for the evacuation. The time for all of the trips that each bus makes is set less than or equal to the maximum time. The time for each trip has two components: the traveling time and the loading/ unloading time. The traveling time is calculated as the time that it takes a bus to go from a pick-up point to a shelter and back under normal road conditions multiplied by a congestion coefficient. The loading at a pick-up point and unloading at a shelter is calculated by multiplying a standard loading/unloading time by a coefficient and multiplying this number by the total number of passengers in the bus.

(C2) Limits the number of evacuees on all buses, all trips, and from all pick-up points to a shelter. The maximum number of people for each shelter is decided by the shelter capacity multiplied by the percentage of the shelter that is empty at the beginning of the timeframe multiplied by the percentage of the shelter that is allocated to people using public transportation. This value is multiplied by a binary attribute that is 1 if the shelter is open and is zero if the shelter is closed. Therefore, if the shelter is closed, maximum number of people that can evacuate to that shelter becomes zero.

(C3) Limits the number of people that buses can collect at each pick-up point to be less than the number of people at this pick-up point. The number of people at each pick-up point is determined by the total potential demand at each pick-up point multiplied by the percentage that will be using public transportation.

(C4) Based on the definition of 'trip,' each bus can only go from one pick-up point to one shelter and back on each 'trip'. This constraint sums all of the origins (pick-up points) and all of the destinations (shelter) for each trip performed by each bus.

(C5) This constraint declares the decision variable as a binary variable.

4.4. Interface Design

A Graphic User Interface (GUI) was created in order to help the end user identify the inputs and enter the data into the model in an easy and simple way. It was necessary to give the end user the tools and power to play with the model, without exposing the code of the model itself to preserve its integrity and functionality. The model runs on an Excel spreadsheet. Hence, we used VBA for Excel to develop the interface. A form has been created to facilitate the data entry (Figure 2). The form enables the possibility of entering the number of buses, pickup points, and shelters respectively. Once those numbers are entered and confirmed, the appropriate arrays are created in which the user simply completes the attributes for those buses, pick-up points and shelters. In the case of the buses, the capacity of each bus had to be entered. The number of people at each pick-up point was a required field. For the shelters case, the capacity of each one had to be completed.

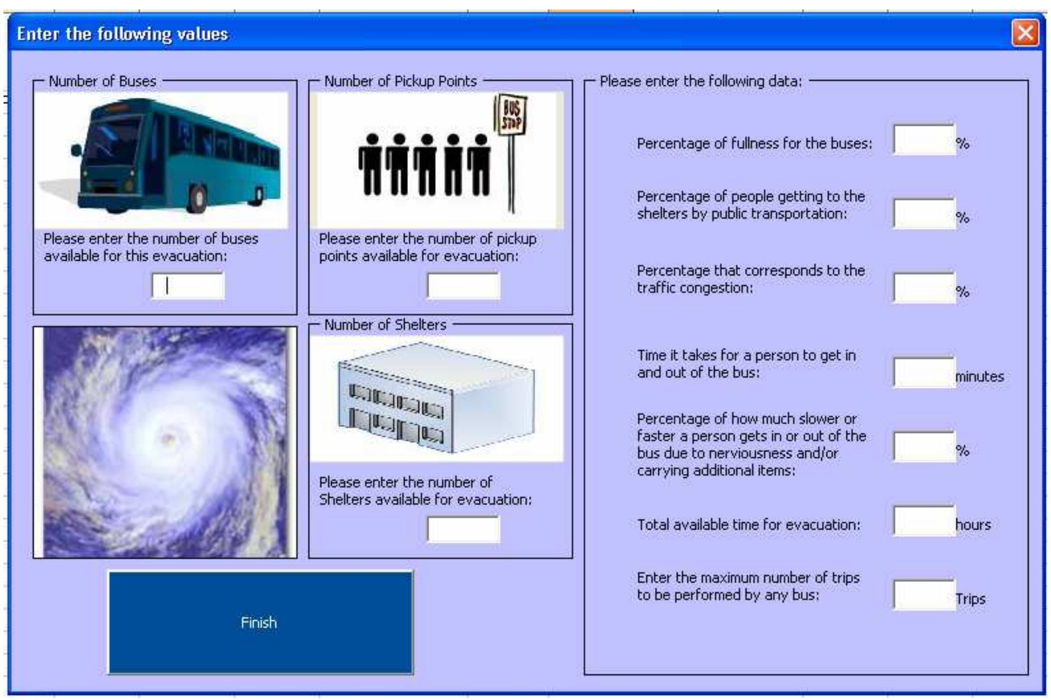

Figure 2: Form to enter the number of buses available

The form also permits the user to input the values for the variables the model has to increase its flexibility and scalability. Here the user enteres the values for the percentage capacity of fullness of the bus, the percentage of people arriving to the shelters using public transportation, the coefficient due to traffic congestion, the bus loading/unloading time and its coefficient due to nervousness and the maximum time available to evacuate prior to the hurricane arrival.

5. Discussion of Model Usage and its results

The model developed can be used to compare the effectiveness of different evacuation strategies. The model can handle different scenarios depending on the number of buses, shelters, buses and their respective capacities. In addition to that, the different constants the model allows as inputs can be modified on each run in order to create a different evacuation context. Running the model under different conditions by a specific method (for example, changing one factor at a time) could reveal information about how each one of the inputs impacts on the result of the evacuation.

The output of the model is actually the total number of people evacuated, in addition to the buses routes assignment. This assignment refers to which bus makes which trip from pick-up point “I” to shelter “J”. The number of trips per bus can also be computed from the model output. For some of the percentages, such as the usage of the buses and the availability of shelters, a value was assumed, since data was not available or not accessible. For these two cases in particular, a better percentage number can be achieved by performing sensitivity analysis on each parameter setting every other attribute fixed.

The value of the model resides in that it enables comparison of different strategies or scenarios. By varying various parameters into the model, different evacuation strategies may be compared and analyzed. For example, the number of shelters that are opened or closed and different buses availability can be tried to see how the model reacts. In addition to changing some parameters, the model could be run in different stages, such as from a pickup point to an intermediate point, and then executed again from that intermediate point to the final shelter destination. The intermediate point could be a pickup point for another bus or perhaps even a train station. In the case of a train, the model would have to be executed three times: one from the first pickup point to the train station, then from the train station to the destination station, and finally from that station to the shelter. All these options are extremely valuable to be able to plan ahead of time and have a better evacuation strategy in the case of a hurricane threat.

When the model was programmed, it was noted that the model is too large and computationally demanding. In order to deal with a reasonable size area, the model would consist of millions of variables. We executed this project with academic version of the software. Due to the limitations of the hardware employed in the model execution and the variables limitations imposed by the modeling software, only a small scale model was run in order to check its functionality. However, there are several alternatives that could be followed to overcome this problem.

- One alternative is the “divide and conquer” strategy. The big evacuation zone could be broken down into smaller areas (ex. instead of examining counties, examine zip codes) that would be computationally feasible using the software tools at hand. The problem with this approach is that the results from solving these smaller problems would only yield local optimal solutions. The combination of all the local optimal solutions does not necessary mean that a global optimal has been reached. The opportunity of crossing from one of these smaller zones to another is lost.

- A second alternative is to develop heuristics. The heuristics will greatly reduce the computational demand of the model and, like the first strategy mentioned, would yield ‘good enough’ solutions.

- The third alternative would be to acquire more powerful software solver tools. If the software is large enough, a global optimal solution can be reached. However, as with any other decision, there is a trade-off. Larger software tools might be very expensive. In addition to this, supercomputers might need to be purchased in order to support the computational demands of the model. One last consideration is that a global optimal solution might not be significantly better than the set of local optima obtained using the divide-and-conquer strategy.

6. Conclusions

The main purpose of this project has been to set the foundations for further research, while developing a deterministic linear model to allocate free-path public transportation resources for hurricane evacuation purposes. The development of the model has given a better understanding of the problem and an initial tool for a future comprehensive decision support system. A scalable deterministic decision-support model has been developed. This model determines the optimal buses allocation for specific pick-up-point-to-shelter routes while maximizing the number of people evacuated on a given timeframe. In addition to the model, a graphical user interface has been created, which allows the users to easily input model parameters from a spreadsheet and read the output and/or report of it in an understandable format. The model itself can be executed directly from the spreadsheet.

There is much more that still needs to be done. In addition to the development of deterministic and stochastic models that will help decision makers to effectively plan a public transportation evacuation, there needs to be other models that help decision makers properly prepare for other aspects of a natural disaster, both pre-hurricane preparedness and post-hurricane relief. The evacuation of people using private vehicles has attracted the attention of many researchers. However, private vehicle evacuation, although not as efficient as public transportation could be, is currently the most widely method of evacuation and research in this area needs to be continued. Models that determine an efficient allocation of other resources such as fuel, water, and food also need to be developed. Finally, in order to complement these areas, research needs to be conducted in the area of post-hurricane relief (ex. food distribution, medical assistance, evacuee relocation, etc.).

References

Blake, E. S., J. D. Jarell, C. W. Landsea, and E. N. Rappaport (2005), “The Deadliest, Costliest, and Most Intense United States Tropical Cyclone from 1851 to 2004”, *National Oceanic & Atmospheric Administration, NOAA Technical Memorandum NWS TPC-4.* http://www.nhc.noaa.gov/Deadliest_Costliest.shtml [Last Accessed 12/12/05]

Blumenthal, Ralph and Neilan, Terence "As Texans Flee Rita, Forecasters Warn of Coastal Surges". The New York Times. September 23, 2005

Cenziper, Debbie. "Widespread Hurricane Warnings Can Breed Complacency. Miami Herald 11 Oct. 2005. 14 Jan. 2006 <http://www.miami.com/mld/ miamiherald/12868445.htm?template=contentModules/printstory.jsp>.

FEMA - Federal Emergency Management Agency (2003), “Principles of Emergency Management”, Emergency Management Institute, Independent Study IS230, March 2003

Litman, Tom. “Lessons from Katrina and Rita.” Victoria Transport Policy Institute. February 7, 2006

Ripley, Amanda. "4 Places Where the System Broke Down." TIME Magazine. September 19, 2005

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