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**Analysis and Modeling of Cape May County  
Roadway Elevations and Evacuation Routes**

FINAL REPORT  
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Submitted by

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16. Abstract This study determined the evacuation times under varying population, behavioral response, hurricane levels, and Routes 47/347 reversal lane operation scenarios for Cape May County, New Jersey. Roadway elevations throughout the Routes 47/347 Corridor study area were established via a GPS survey to verify whether the roadways are usable in the event of a hurricane.  Results of the study show that the current State Police reversal plan is ineffective due to the limited time savings. The reversal plan needs to be revised as the bottleneck during evacuation would exist south of Route 83, the initiation point of the current reversal plan.					
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## **SUMMARY**

While the threat of terrorist attacks has become a prominent issue for residents and visitors of New Jersey since the events of September 11, 2001, catastrophic weather events have long been part of New Jersey's history. In a previous study that focused on providing state and local emergency management agencies with a basis for developing emergency evacuation plans, the extent and severity of potential flooding, vulnerable populations, public shelter locations, and evacuation clearance times were determined and a traffic assignment model was developed to estimate evacuation times given the existing roadway network. While the model considered the effect of different population scenarios and included roadway link volumes under the various scenarios, it did not take into account the impact of implementing selected evacuation strategies or plans.

This simulation based study was conducted to evaluate the effectiveness of the existing New Jersey State Police Lane Reversal Plan for Routes 47/347 in Cape May and Cumberland Counties in New Jersey. Contraflow strategy, also known as lane reversals, increases roadway capacity and was modeled for the existing Cape May network on Routes 47/347. Roadway elevations throughout the Routes 47/347 corridor study area were established by a Global Positioning System (GPS) survey to verify whether the roadways are usable in the event of a hurricane. An analysis of the data collected from the elevation survey revealed that evacuation plans can reasonably rely on storm surges reported on the Hurricane Evacuation Study (HES) maps assuming that the U.S. Army Corps of Engineers (USACE) storm surge calculations are correct. Estimates of evacuation time for various scenarios considering traffic operations, seasonal area population, hurricane intensity, and behavior response scenarios were determined. Results of the study show that under the assumed parameters the current reversal plan is ineffective and needs to be revised as the bottleneck during evacuation would exist south of Route 83.

## INTRODUCTION

Disaster response, to both manmade and natural catastrophes, in areas of high population density, is centered on evacuating people quickly and efficiently. Made up of 566 separate municipalities, 21 counties, and being the most densely populated state in the country, New Jersey faces considerable challenges in effectively coordinating and responding to emergencies. While New Jersey's geographic configuration largely spares the state from direct hurricane hits, even the effects of a hurricane offshore can be disastrous. New Jersey faces serious storm events, particularly Northeasters. New Jersey experiences on average three Northeasters per year, any of which could strike at Class 2 or higher on the Dolan-Davis scale.

In a previous study in 1992 by the US Army Corps of Engineers (USACE) in conjunction with the New Jersey State Police Office of Emergency Management (NJOEM), the Federal Emergency Management Agency (FEMA) and the National Weather Service (NWS), the extent and severity of potential flooding, vulnerable populations, public shelter locations, and evacuation clearance times were determined and a traffic assignment model was developed to estimate evacuation times given the existing roadway network.<sup>(1)</sup> While the model considered the effect of different population scenarios and included roadway link volumes under the various scenarios, it did not consider the impact of implementing selected evacuation strategies or plans.

In this project, a microscopic traffic simulation-based model was developed to evaluate the effectiveness of the existing NJ State Police "Routes 47/347 Reverse Lane Plan" for Cape May County. This contraflow strategy, also known as lane reversal, was modeled to maximize roadway capacity for the existing network on Routes 47/347. Contraflow can be particularly helpful in reducing travel time by increasing roadway capacity during hurricane evacuation for long travel distances.<sup>(2)</sup> This study determined the evacuation time estimates for various scenarios considering different levels of traffic operations, seasonal area population, hurricane intensity, and behavior response. The behavioral response curves, also called the S-curve models, which have a longer history than some of the recent models and have been extensively used in several evacuation studies, were applied in this study to approximate behavior responses and to load demand onto the network throughout the evacuation.<sup>(3,4,5,6,7,8)</sup>

In addition to the traffic analysis of evacuation scenarios, a detailed GPS survey was completed within this project to provide a better estimate of the elevations of the evacuation roadways. Accurate estimates of the roadway elevations are needed in order to determine what roadways will be inundated under varying storm surge conditions associated with different levels of hurricane strikes. This is of particular concern regarding the low-lying nature of many of the roadways in the Cape May area, including several that would be relied upon in an evacuation situation.

Results of this study show that the current reversal plan provides very little help in alleviating congestion and reducing evacuation time, as the bottleneck during evacuation occurs south of Route 83, which is the initiation point of the current plan.

Consequently, the existing plan is termed ineffective and it is suggested that the plan be revised to extend the contraflow initiation point farther south of Route 83. An analysis of the surveyed roadway elevation data for the Routes 47/347 Corridor revealed that the current evacuation plan can reasonably rely on the Hurricane Evacuation Study (HES) maps assuming that the USACE storm surge calculations are correct.

## **RESEARCH APPROACH**

The research approach can be summarized by the following steps:

- 1. Literature Review**
- 2. Establishing Roadway Elevations with GPS**
- 3. Development of Studied Simulation Network**
- 4. Evacuation Demand Generation**
- 5. Modeling Behavioral Response**
- 6. Formulation of Evacuation Scenarios**
- 7. Calculation of Evacuation Times**

### **Literature Review**

A comprehensive literature review of the previous studies and current practices, development, and implementation work on modeling emergency evacuations was conducted. Also, evacuation plans and strategies developed by various states, and Cape May and Cumberland Counties were reviewed. Furthermore, the review evaluated various behavioral models used for loading evacuation demand and chose the traditional S-curve model to be employed as the loading model in the study. A detailed discussion of the literature review is presented in Appendix A.

### **Establishing Roadway Elevations with GPS**

A critical issue in any evacuation plan is to determine which roadways would be available to carry out the evacuation plan. Available evacuation routes are those routes that are passable under the anticipated weather conditions. An evacuation route is deemed usable if the road elevation is higher than the predicted storm surges at the time of the evacuation. The objective of this part of the project was to establish the roadway elevations throughout the Routes 47/347 corridor study area and to verify whether the roadways are usable in the event of a hurricane. It was also necessary to establish the storm surge elevations for various hurricane categories in order to ascertain the usability of the roads under adverse weather conditions.

To establish the elevations along the study roadways, a detailed GPS survey was conducted on March 7, 2005. The GPS survey was done in kinematic mode. The kinematic GPS survey mode provides the ability of establishing positions and elevations of new points while the GPS receiver is in motion. A kinematic GPS survey is performed by placing a stationary GPS receiver at a known point (a point with known horizontal positions/coordinates and elevation) that provides accuracy control for other newly established points. New points are points on the ground whose positions and elevations are unknown and are to be determined. To establish the positions and elevations of new points, a second GPS receiver is utilized. This GPS receiver, which is used while in motion, is called a rover.

### **The GPS Elevation Survey**

To complete the GPS elevation survey for this project, two base stations were established; the first at the intersection of Route 9 and Route 47 in Rio Grande, New Jersey, and the second at the intersection of Route 9 and Route 83 in Clermont, New

Jersey. Two roving GPS receivers were mounted on the roof of a vehicle which was used to travel the Routes 47/347 corridor. Safety vehicles provided by the Cape May County Engineering office allowed the survey to be performed at an approximate speed of 20 mph without causing any traffic hazards. The Routes 47/347 corridor was traveled three times from the intersection of Route 47 and Route 347 in Dennis Township to the intersection of Route 47 and Route 9 in Rio Grande. The two base stations and three trips along the surveyed roadway were done in order to provide ample redundancy for accuracy analysis of the survey results.

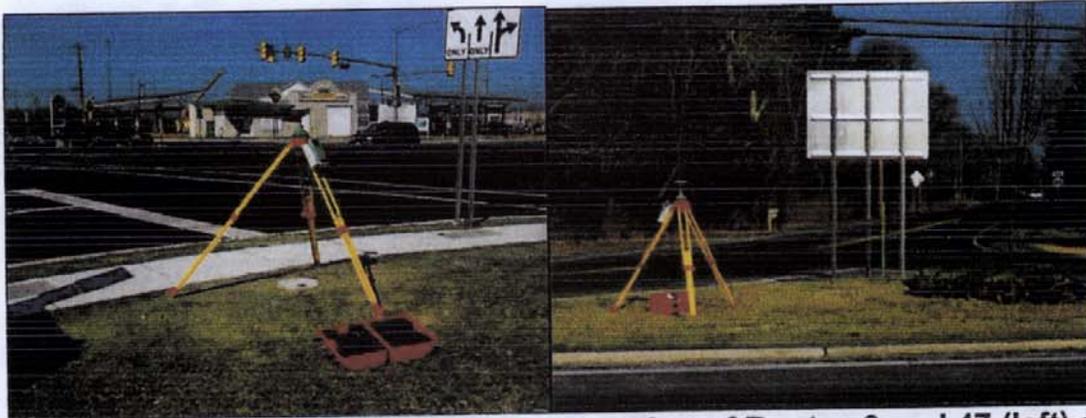


Figure 1. Control GPS receivers at the intersection of Routes 9 and 47 (left) and at the intersection of Routes 9 and 83 (right)



Figure 2. GPS roving units mounted on the roof of the survey vehicle

### **Storm Surge Elevations**

The storm surge elevations for different hurricane categories were obtained from the Hurricane Evacuation Study or HES map provided by the Philadelphia District of the U.S. Army Corps of Engineers (USACE). The map shows storm surge elevations at selected points around Cape May County and the areas that are predicted to be inundated by the anticipated storm surge from different categories of hurricanes. One concern the study team had with the HES map was that the elevations posted on the map were in the NGVD'29 (National Geodetic Vertical Datum of 1929) datum rather

than in NAVD'88 (North American Vertical Datum of 1988) datum which is the vertical datum currently used by NJDOT. The difference between these vertical (elevation) datums is more than one foot in the Cape May area. Given the general characteristics of the area (very flat topography), an elevation error of one foot could have a significant impact on whether the roadways are passable or not. Therefore, a datum conversion from NAVD'88 to NGVD'29 was performed for the GPS surveyed elevations in order to ensure compatibility with the information provided by the USACE. The datum conversion was made from NAVD'88 to NGVD'29 rather than from NGVD'29 to NAVD'88 because the GPS data could be converted, but the study team had no way to recreate the HES map on the NAVD'88 datum.

Another challenge with the USACE storm surge data was that storm surge elevations are not constant throughout the entire area. Storm surge elevations are determined from hydraulic/hydrographic modeling based on local characteristics of the water body, the shape of the shore, the underwater and shore topography, and other factors. Thus, as the local conditions change, so do the predicted water levels under different hurricane categories. The map that the study team was provided by the USACE had different storm surge elevations reported at various points along the shore and at some points inland. Thus, the comparisons that were made between the USACE data and the GPS survey results were localized. The entire surveyed route was divided into several smaller sections to ascertain that only compatible data was compared and analyzed.

### **The Accuracy of the GPS Survey**

As previously mentioned, the Routes 47/347 corridor was surveyed three times; twice in the southbound direction and once in the northbound direction. To assess the accuracy of the elevations obtained from the GPS survey, elevation measurements of the same point from different survey runs were compared. For the purpose of this study, the definition of the "same point" was any point with a measured elevation that fell within 10 feet laterally of another point from another survey run. This was a valid assumption for this study given that the Cape May area has rather flat topography and one would not expect a change in elevation at the center of roadway to be more than a couple of inches within a stretch of 10 feet. The intended elevation accuracy for this study was about  $\pm 0.5$  feet.

Over 3000 GPS elevation measurements were collected and compared. It was found that on average the accuracy of the GPS survey was  $\pm 0.1$  feet with a maximum elevation difference of 0.6 feet. The maximum difference occurred on the northbound survey. This elevation difference could have resulted from temporary poor satellite geometry or poor GPS signal reception that occurred when that measurement was taken. However, the average difference of 0.1 feet between the points measured in three different surveys provided sufficient evidence that the elevations collected during the GPS surveys were very accurate.

### The Accuracy of the USACE HES Map

Following the validation of the survey, the GPS derived elevations were compared to the USACE HES map. As mentioned earlier, the storm surge elevations vary as a function of their locations along the study area. A total of five comparison points were selected along the Routes 47/347 corridor for this study. The selection of comparison points was dictated by the number of data points shown on the HES map with explicit elevation data. To facilitate a meaningful comparison study, the study area was divided into five sub-study areas. The sub-study areas were established by selecting the nearest GPS surveyed points to the five HES map data points. These sub-study areas and the associated HES map data points are shown in Figure 3.



**Figure 3. Five sub-study areas and the associated GPS points**

At each study area the storm surge elevations were selected to have the same value as those shown on the HES map for each hurricane category. Using this information, the GPS points were classified as being always dry or always inundated at a given hurricane category. For example, if the HES map showed storm surge elevation of 4, 6, 8 and 10 feet for hurricane categories 1, 2, 3 and 4, respectively, and the GPS point was at elevation 11.25 feet, this point was deemed to remain dry under any conditions.

If, however, the GPS point was at elevation 6.48 feet, it was classified as a point that will be inundated in the event of a hurricane of level 3. The results of the classification of the GPS surveyed points into various hurricane categories are shown in Figure 4.



**Figure 4. Classification of the GPS surveyed points into various hurricane levels**

The results of the classification of the GPS surveyed points were then superimposed on the data represented on the HES map. As stated earlier, the HES map displays the minimum category of hurricane strength that would cause the area to be inundated by storm surge. This information is shown on the HES map as shaded polygons in different colors. The superimposition of the GPS surveyed points on the HES map was done to evaluate the accuracy of the HES map. Since it is assumed that this map will be used if a real hurricane event occurs in the Cape May County area, it is extremely important to verify whether the inundation levels shown on the map are correct. In other

words, it must be ascertained that road segments shown to be inundated in the event of a hurricane will in fact be impassable and alternative evacuation routes will have to be considered. The results of this evaluation are presented in Table 1.

**Table 1. Comparison between the inundated points based on the GPS survey and those of the HES map**

<b>Category Difference Between Location Area Value and Closest Surge Value</b>		
<b>Difference*</b>	<b># of Pts</b>	<b>% of Pts.</b>
-2	7**	0%
-1	1013	32%
Same	1877	59%
1	275	9%
2	0	0%

\*Difference = HES Category – Survey Category

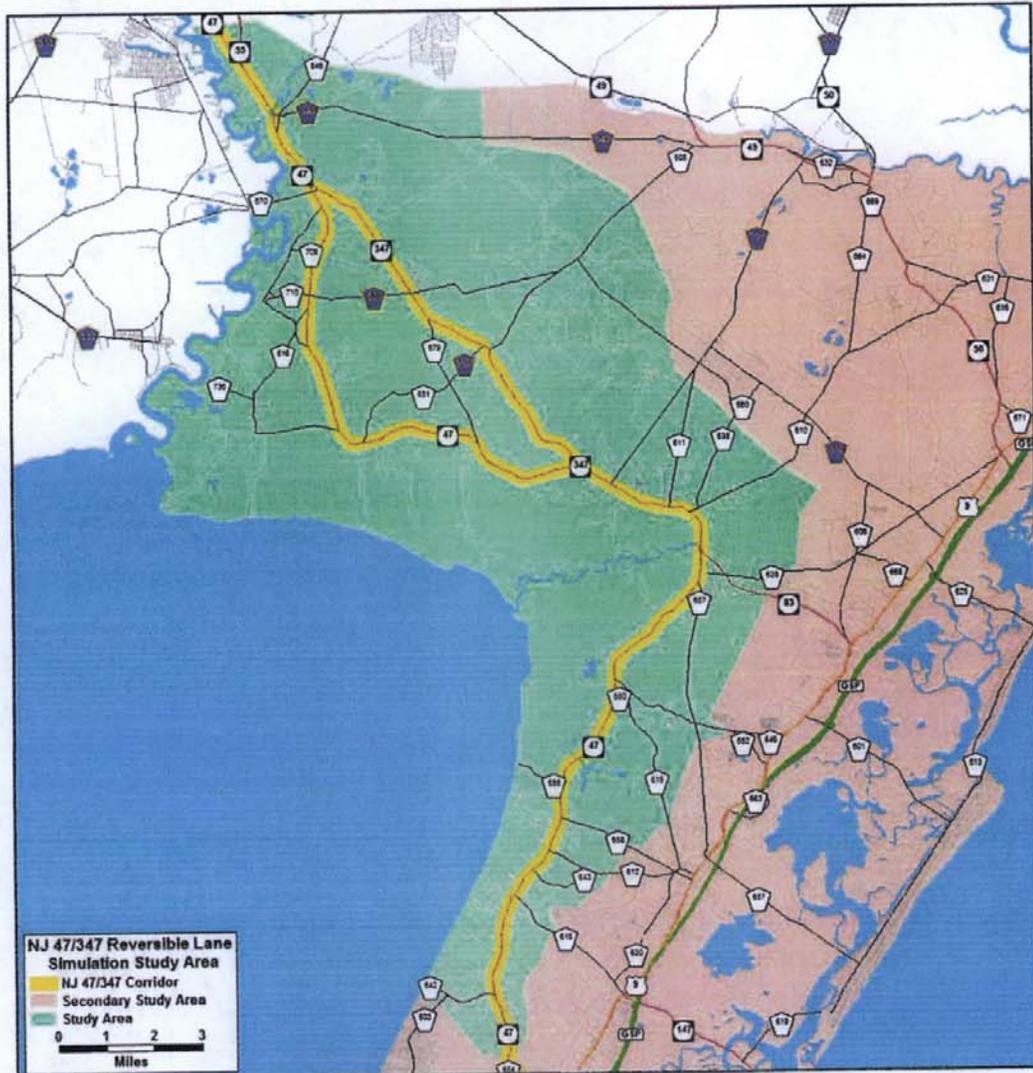
\*\*Discrepancy where GPS survey point located on elevated bridge surface

From Table 1 it can be seen that nearly 60% of the GPS surveyed points matched exactly those shown on the HES map. About 40% of the GPS surveyed points are one category removed from the hurricane categories shown on the HES map; usually in the higher (less flood prone) category than what appears on the map. It is important to realize that being one hurricane category removed from the HES map does not mean that the elevation difference between the map point and the GPS point is high. A GPS point can be tagged as being one hurricane category removed from the HES map even if the elevation difference between the data sets is only a couple of inches or less. For example, if the elevation of category 2 surge was determined to be 6.00 feet and the elevation of the GPS points was 6.01 feet this point will be classified as category 3 even though the elevation difference is just 0.01 feet. There were seven cases (out of over 3000 that were evaluated) of points where the survey reported an inundation level two category levels higher than what appears on the HES map. In each of these cases the HES map depicts the area as being at sea level (due to a creek or other waterway) while the GPS survey points were recorded on a bridge surface. This could explain the apparent difference of two hurricane categories between the map elevations and those determined by GPS.

### **Development of Studied Simulation Network**

The first step in preparing the simulation network to test the different evacuation scenarios was to establish the study area that would be explicitly modeled by simulation. Figure 5 shows the studied evacuation region. The simulated study area, shown in green, begins in Rio Grande, New Jersey in the south (at approximately milepost 5.5 of Route 47) and extends to the north and ends shortly after Route 55 begins. The simulation network includes every public road (state, county, and local

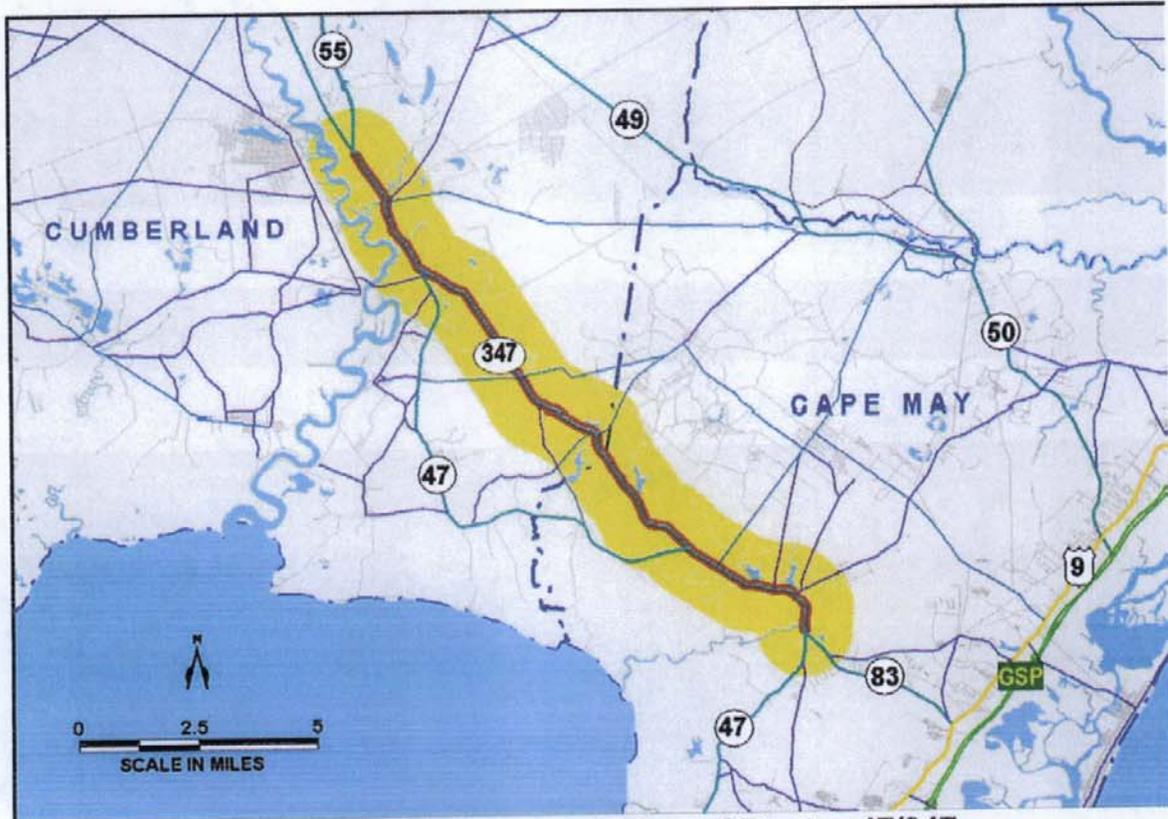
jurisdictions) within the study area. The secondary study regions, shown in pink, are areas within Cape May County but were not included in the simulation network. However, traffic that feeds from the secondary study areas into the Routes 47/347 corridor was included in the simulation. The evacuation routes (Routes 47/347) are highlighted in yellow.



**Figure 5. Simulation study area**

Figure 6 highlights the portions of Routes 47/347 in Cape May and Cumberland Counties where the lane reversal option would be implemented under the current NJ State Police and NJDOT reversal plan. The lane reversal section begins at the junction of Route 83 in the south and continues along Route 47 and Route 347 to the north, ending at the junction of Route 55 and Route 47. The reversal does not include those sections of Route 47 that are parallel to Route 347. This section currently consists of a single travel lane in each direction with a shoulder on each side of the roadway. Under the lane reversal strategy, both travel lanes would be used to accommodate traffic flow in the northbound direction. The shoulders would be used to accommodate emergency

response and disabled vehicles. Upon arriving at the junction of Route 47 and Route 55, the two lane contraflow section transitions into the existing two northbound lanes on Route 55. There are a number of local and county roads that feed into Routes 47/347.



**Figure 6. Reverse lane section of Routes 47/347**

The simulation software Paramics was selected for modeling the studied evacuation region. The selection of Paramics was based on a review of previous studies and current practices of widely used traffic simulation tools. Paramics was selected for modeling the studied network due to its outstanding capabilities in handling large simulation networks, in animating traffic operations in a 3D environment and visualizing simulation results, and its functionalities of dynamic routing.<sup>(2)</sup> Figure 7 shows the study area roadways (yellow lines) as developed in Paramics.



**Figure 7. Cape May simulation network**

The base topology of the network was taken from the NJDOT GIS database of all roadways, cleaned and modified for the needs of a traffic simulation network, and converted into a Paramics format. The details of the network were then manually coded in Paramics based on a combination of details from the NJDOT Straight Line Diagrams, New Jersey Department of Environmental Protection (NJDEP) 2002 Orthophotos, and notes taken during site visits. Origin zones were created at various vehicle generation locations along the edges of the network (to load traffic entering the network from the secondary study areas) and within the study area (to load traffic residing in the study area). A single destination zone was located at the northern end of the network on Route 55 to receive all evacuating traffic. Once the existing or normal operations network was completed, the details of the current Routes 47/347 reversal plan were coded to create a second network, the current reversal network.

### **Evacuation Demand Generation**

A critical input to the evacuation analysis is the determination of the population needing to be evacuated. The determination of this number includes estimating the affected population, the evacuee participation rates, and evacuee routings and distributions. As the primary focus of this study was to estimate the time required to evacuate the regional population, the decision was made that the unit of the evacuating population

would be vehicles. All estimates of the evacuation population would be converted into vehicles to be applied to the simulation network.

### **Demand Estimation of Evacuating Vehicles**

Data from U.S. Census 2000 and an extensive estimation by the USACE of vulnerable housing units was used as the basis of determining the number of vehicles that would potentially need to be evacuated. The vulnerable household data, summarized on the USACE HES maps, estimates the number of housing units and hotel/motel units by an evacuation district and the storm surge inundation level. The evacuation districts, defined by the USACE and used in this analysis, are subsets of municipalities with main roadways as internal boundaries dividing the districts. The vulnerable housing unit data estimates the number of permanent housing units, mobile homes, seasonal housing units, and hotel/motel units located in each of the five inundation levels (Category 1 through 4 plus uplands) within each evacuation district.

This housing unit data was then converted into the number of vehicles that will potentially evacuate. The total vehicular demand in each evacuation district was estimated using a vehicle per housing unit factor. Following the methodology of the Delmarva Evacuation Study, the number of vehicles per housing unit for permanent housing units was taken from the Census 2000 data. While varying slightly by location within the county, the regional average of vehicles per housing unit of 1.54 was calculated. The use of a factor of 1 vehicle per unit was assumed for the hotel/motel units, also consistent with the Delmarva Study. However, based on knowledge of the tourist / seasonal activities in the Cape May region, the Census 2000 vehicles per housing unit used for permanent housing (1.54) was also used as an estimate of the number of vehicles at seasonal units. The assumption of 1 vehicle per seasonal housing unit used in the Delmarva Study was deemed too low by the study team.

While the USACE vulnerable housing data is a good estimation of the potential evacuation population, it has one shortcoming in that it does not include any information about campgrounds. This is of particular interest for Cape May, as a significant number of campground sites are located within the county and are frequently full during the summer months. Information on the number of campground sites and details was collected by the study team. The investigation identified approximately 15,000 campsites located within Cape May County. The majority of these campgrounds are concentrated in Cape May (along Route 9), Cape May Courthouse, Ocean View, and Woodbine. Based on campground locations, 12,600 campgrounds were estimated to generate volumes in or entering the simulation study area. For vehicle generation, an assumption was made that one vehicle existed per campsite.

While many people take day trips to the Cape May County region during the peak summer season, the assumption was made that day trips would not add to the evacuation demand. This assumption was developed assuming that all day trips would be cancelled due to the threat of an arriving hurricane.

**Participation Rates**

The evacuee participation rates vary by the area of inundation that the housing unit is located in, the category of storm, and the type of housing unit. For lack of information specific to Cape May, the participation rates estimated from the Delmarva Evacuation Study were used in determining the number of evacuating vehicles from areas under different levels of inundation. Table 2 presents the participation rates under various categories of hurricane. Campgrounds were assumed to always have a 100% participation rate, regardless of the inundation level the site is located in.

**Table 2. Participation rates**

Category 1 Hurricane			
Inundation Level*	Permanent Units	Mobile Homes	Seasonal Units
1	100%	100%	100%
2	2%	70%	90%
3	1%	50%	50%
4	1%	50%	50%
No Flood	1%	50%	50%

Category 2 Hurricane			
Inundation Level*	Permanent Units	Mobile Homes	Seasonal Units
1	100%	100%	100%
2	100%	100%	100%
3	5%	70%	70%
4	1%	70%	70%
No Flood	1%	70%	70%

Category 3 Hurricane			
Inundation Level*	Permanent Units	Mobile Homes	Seasonal Units
1	100%	100%	100%
2	100%	100%	100%
3	100%	100%	100%
4	2%	100%	100%
No Flood	2%	100%	100%

Category 4 Hurricane			
Inundation Level*	Permanent Units	Mobile Homes	Seasonal Units
1	100%	100%	100%
2	100%	100%	100%
3	100%	100%	100%
4	100%	100%	100%
No Flood	5%	100%	100%

\*The Inundation Level corresponds to the minimum category of hurricane that would result in storm surge flooding of the housing unit.

**Demand Distribution and Vehicle Routing**

It was assumed that all evacuees depart from home or temporary residence (seasonal, hotel/motel) in the studied region. Once the demand originating from each evacuation district was estimated, the districts were subdivided into smaller zones in the primary study area (origin zones for simulation model) on the basis of the density of the roadway network and housing density. These smaller sub-district areas were used as the origin traffic assignment zones in the simulation model. If the evacuation district straddled the division between the simulation study area and the secondary simulation area, the share of the traffic internal and external to the simulation network was again estimated based on network and development densities.

The routing of the evacuating traffic was determined on a district by district basis, based on the roadway network available for the evacuating traffic, the assumed police intervention to force routing of evacuees (barricades, detours, etc.), the ultimate destination of the evacuating traffic, and the presumed traffic loadings outside of the

study area. The trip generation/routing for all origin zones was done by using the following guidelines:

***External Demand***

1. For the evacuation districts falling south of the study area (i.e. districts 17 to 27), 20 to 40 percent of the traffic was assumed to feed into Route 47 from the origin zone located at Nummytown near the Cape May Wildlife Refuge, while the remaining traffic (60% to 80%) was assumed to enter Route 9 or the Garden State Parkway (GSP).
2. For the evacuation districts located at the lower east side of the study area (i.e. districts 9 to 16), traffic was distributed between Route 47 and other routes (Route 147, Route 9, Route 83, GSP, and County Routes 618, 615, 657, 658, 646) that were assumed to serve as the primary entry points to the Routes 47/347 evacuation corridor.
3. Demands originating from evacuation districts located on the upper east side of the study area (i.e. districts 1 to 8), were assumed not to enter into the simulation network.

***Internal Demand***

1. For the evacuation districts present within the study area (i.e. Districts 28 to 36), traffic volumes were assigned to routes feeding to Route 47 (Route 83, and County Routes 603, 618, 658, 646, 615, 657, 628, 611, 550) and the remaining traffic was assumed to enter Route 9 or the GSP.
2. For the evacuation districts present in the northern part of the study area (Cumberland Districts 1 to 4), a majority of the zones were assumed to feed traffic into Route 47 directly, while a portion from Cumberland District 1 was assumed to have traffic leaving on County Route 616.

The resulting percentage of vehicles from each district assumed to be evacuating through the Routes 47/347 corridor (and thus explicitly modeled in the simulation model) are summarized in the map in Figure 8. The volumes shown in Figure 8 are for the highest level, a category 2+ hurricane storm during the peak tourist season.

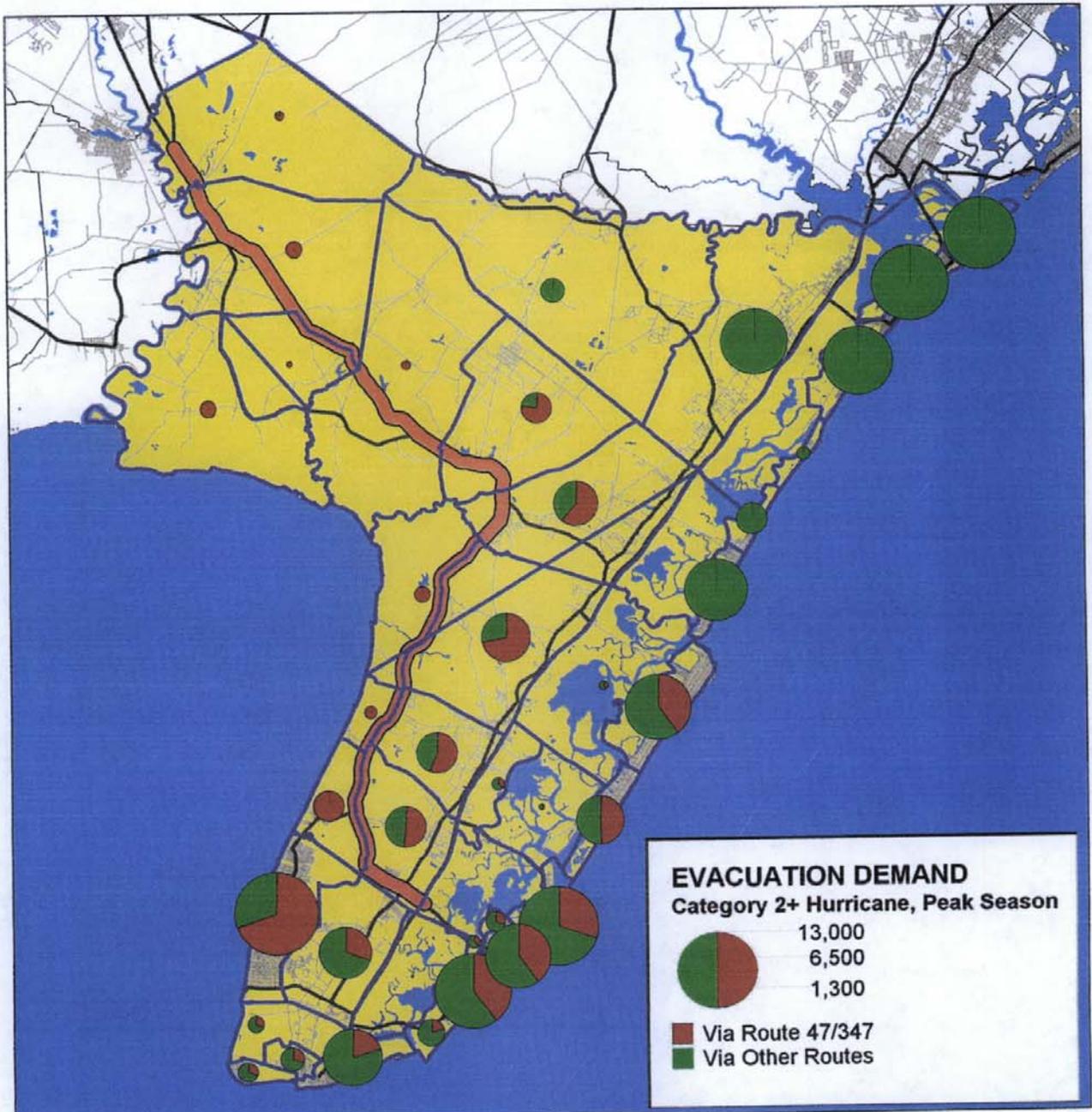


Figure 8. Percentage of vehicles from each district assumed to be evacuating via the Routes 47/347 corridor

### Modeling Behavioral Response

As a result of the research efforts completed for this project by Rutgers University (see Appendix B), the behavioral response curves or S-curve model was selected for loading traffic temporally to the simulation model in this study. A response curve (also referred to as a loading curve) portrays the assumed departure time distribution of evacuees. The loading curve is usually represented as the cumulative percentage of evacuees evacuating by time period, and takes on a sigmoid or "S" shape. Three types of responses were simulated; fast, medium, and slow. The response rate signifies how readily the evacuees are expected to respond to an order to evacuate. As illustrated in Figure 9, the time point of zero is when the evacuation order is issued. The graph illustrates that initial values of 8, 5 and 3 percent of the total demand have loaded even six hours prior to the issuance of the evacuation order for the slow, medium and fast responses respectively. This initial evacuation reflects the proportion of the population who left before the order was given (also know as shadow evacuation).

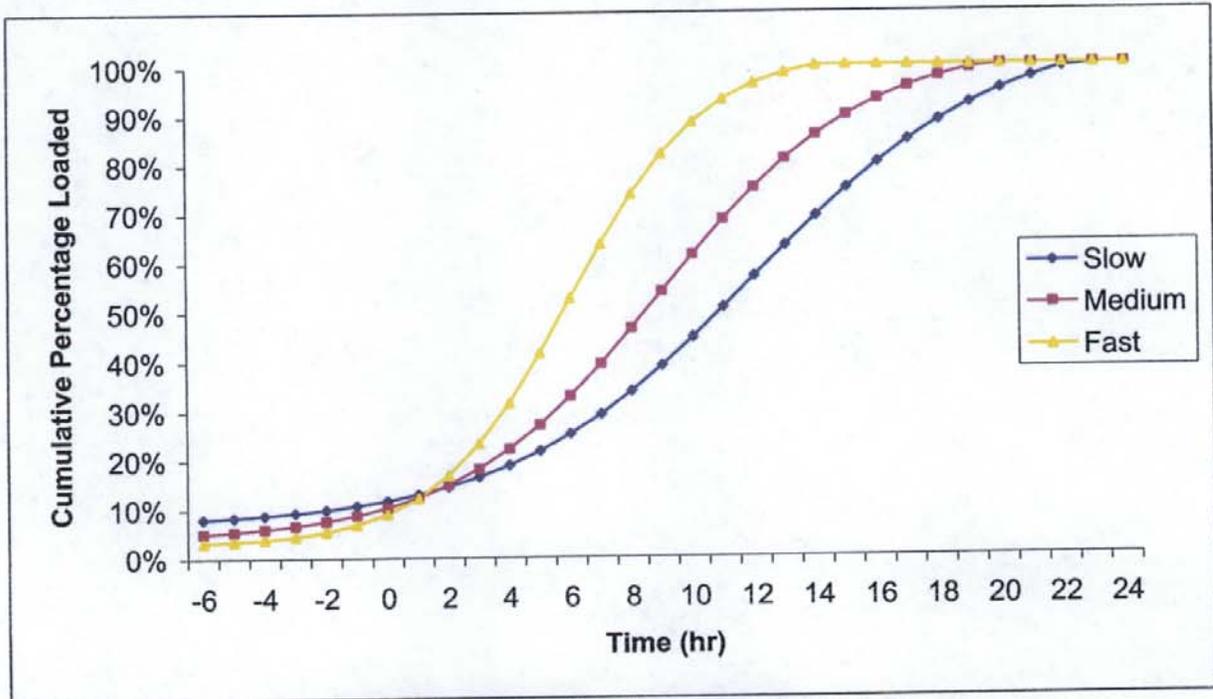


Figure 9. Behavioral response curves

**Table 3. S-curve parameters for network loading**

<b>PARAMETERS</b>	<b>Slow</b>	<b>Medium</b>	<b>Fast</b>
Initial value	0.08	0.05	0.03
$\alpha$	0.25	0.3	0.45
H	12	9	6

Table 3 shows the values that were used for generating the loading curves. The “ $\alpha$ ” parameter represents the response of the public and alters the slope of the cumulative traffic loading curve. The parameter “H” is the half loading time; the time at which half of the vehicles in the system have been loaded onto the studied network.

**Formulation of Evacuation Scenarios**

The scenarios for analysis in the study can be broadly categorized as the following:

- Traffic Operations - 2 Alternatives
- Area Population - 2 Alternatives
- Hurricane Intensity - 2 Alternatives
- Behavior Response - 3 Alternatives

**Traffic Operations**

The traffic operations were carried out in two methods

1. Normal operations (no reversal):  
This alternative assumes normal lane usage (predominantly one travel lane in each direction), but assumes police are directing traffic at key intersections to allow side street traffic to enter the evacuation corridor.
2. Lane Reversal (currently plan):  
This network alternative assumes the operation of Routes 47/347 under contraflow conditions between the junctions of Route 83 in the south to Route 55 in the north. This alternative follows the instructions specified in the State Police Routes 47/347 Reverse Lane Plan.

**Area Population**

Two alternatives were tested based on the population to be evacuated

1. Peak Season (estimated Labor Day weekend)  
This alternative assumes that 100% of permanent residents and 100% of seasonal / tourist housing units are occupied and will contribute to the potential evacuating population.
2. Off-Peak Season (estimated late September)  
This alternative assumes that 100% of permanent residents and 50% occupancy of seasonal / tourist housing units.

### **Hurricane Intensity**

Two alternatives based on the category level of hurricane are considered:

1. Category 1 Hurricane:  
In this scenario, the evacuation prior to a category 1 hurricane strike is examined. The scenarios includes the evacuation of all category 1 inundation areas, plus volunteer evacuees based on the participation rates for a category 1 storm (as previously discussed).
2. Category 2 (and up) Hurricanes:  
In this alternative a full scale evacuation of the county was considered. To test the worst case scenario, this scenario includes the evacuation of all housing units in a category 4 or lower inundation level, plus voluntary evacuations from uplands or dry locations. This results in the application of the category 4 participation rates.

### **Behavior Response**

Three alternatives were tested based on the vehicle release rates, as previously discussed.

1. Fast Response Rate
2. Medium Response Rate
3. Slow Response Rate

All combinations of the scenarios were tested. Thus, a total of 24 scenarios were analyzed based on various categories:

2 Traffic Operations  
x 2 Area Population  
x 2 Hurricane Intensity  
x 3 Behavior Response Profiles  
= 24 Scenarios

### **Calculation of Evacuation Times**

After the evaluation of all the scenario parameters were decided upon and calculated, the running of the computer simulations was conducted. As with any microsimulation software, Paramics is stochastic in nature and uses a random number generator to initiate the simulation procedure and to determine vehicle interactions. As a result, no two runs will produce identical results (unlike a deterministic model). In an attempt to minimize this statistical variability between runs, standard practice requires the production of several simulation runs for one scenario, identical in all inputs and parameters except for a random seed. These runs are referred to as iterations of a scenario. The average result of the scenarios iterations is then taken as the results for that scenario. Based on testing of the simulation network and the observation of small variations existing between different iterations of one scenario, it was determined that five iterations per scenario would be sufficient to remove the variability of results due to a random seed. This increases the number of simulation runs that are required to be produced fivefold.

A restriction in the simulation software (Paramics) required running the simulation in 24 hour segments. The software will not allow the specification of a temporal distribution of traffic releases (i.e. the loading curve) for more than a single 24 hour period, therefore any simulation extending beyond 24 hours must be run in sections. This requires running for each instance of each scenario the first 24 hours (day one run), interpreting the day one run performance, creating the day two simulation using the end of the day one simulation as a 'starting point', and then running the day two simulation run. While this still maintains the integrity of the analysis and does not prohibit a multi-day simulation run, but it does considerably lengthen the time frame required to run the simulations.

The end result of all scenario combinations, random seed iterations, and additional day two simulations produced a total of 210 individual simulation runs. With each simulation run taking several hours, the required computation time was significant. Several high end desktop computers utilized multiple licenses of the software to complete the simulations in a reasonable time. Approximately 7 GB of simulation result data was collected for analysis in the form of numerous text files. The data was then processed with custom processing scripts to extract and calculate the needed performance measures (evacuation time, percentage cumulative demand evacuated with time) for each scenario to allow for the comparison of the results between all scenarios.

The estimated total evacuation time required to completely evacuate the Cape May County area varies between approximately 16.5 and 24.5 hours. The times are reported for each of the 24 scenarios in Table 4. A dramatic result to be derived from this table is that the assumed behavior response (or loading curve) dictates the time to evacuate the population in all cases except the heaviest demand combination of a category 2+ hurricane striking during the peak tourist season. This does not mean that congestion and delay are not experienced during a category 1 hurricane or off-peak evacuation, but implies that any congestion delay and queue buildups that are experienced during the evacuation midpoint when the heaviest demands are experienced are dissipated before the last vehicle to evacuate leaves home.

A more dramatic result can be found by looking at the difference between the total evacuation times for the normal operations scenarios and the current reversal scenarios (reported in Table 4 in the column 'Reversal Savings'). This difference is the reduction in the total evacuation time that would be experienced by implementing the current Routes 47/347 reversal plan. The small differences indicate that implementing the current reversal plan has a negligible effect on the total evacuation time compared to an evacuation with normal traffic operations (no contraflow), and the current reversal plan is ineffective.

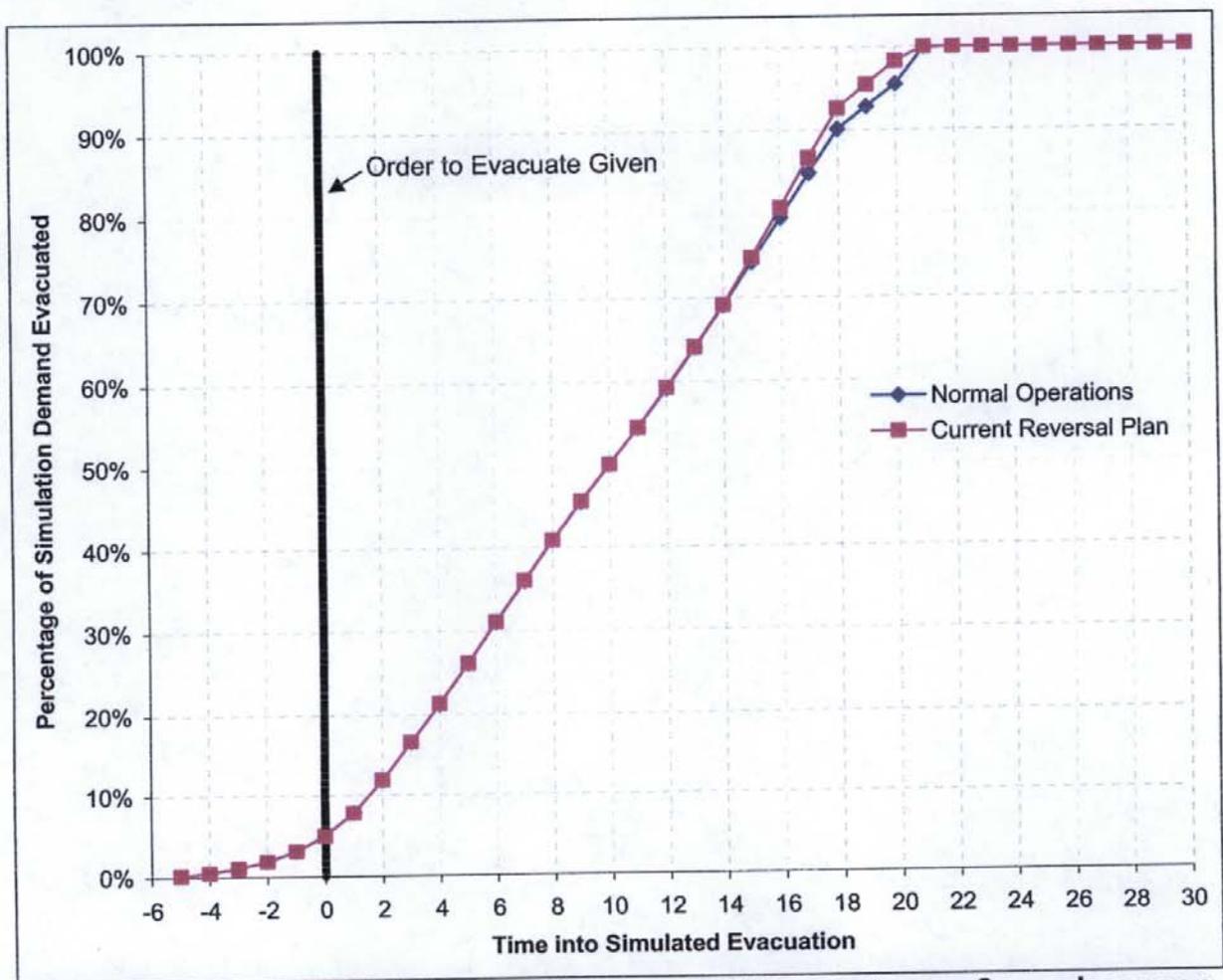
Table 4. Simulation result summary

Hurricane Intensity Level	Seasonal Evacuation Population	Assumed Behavior Response	Normal Operations			Current Reversal Operations			Differences	
			Total Evacuation Time* (hr:mm)	Last 'Scheduled' Demand** (hr:mm)	Total Congestion Delay*** (hr:mm)	Total Evacuation Time (hr)*	'Scheduled' Demand** (hr:mm)	Total Congestion Delay*** (hr:mm)	Reversal Savings (min)	Reversal Savings (hr:mm)
Cat 1	Off Peak	Fast	16:25	16:00	0:25	16:24	16:00	0:24	0.8	0:00
Cat 1	Off Peak	Med	21:31	21:00	0:31	21:31	21:00	0:31	0.4	0:00
Cat 1	Off Peak	Slow	24:30	24:00	0:30	24:30	24:00	0:30	0.5	0:00
Cat 1	Peak	Fast	16:29	16:00	0:29	16:29	16:00	0:29	0.0	0:00
Cat 1	Peak	Med	21:31	21:00	0:31	21:31	21:00	0:31	0.2	0:00
Cat 1	Peak	Slow	24:31	24:00	0:31	24:31	24:00	0:31	0.0	0:00
Cat 2+	Off Peak	Fast	16:30	16:00	0:30	16:29	16:00	0:29	0.9	0:00
Cat 2+	Off Peak	Med	21:31	21:00	0:31	21:31	21:00	0:31	0.0	0:00
Cat 2+	Off Peak	Slow	24:32	24:00	0:32	24:31	24:00	0:31	0.5	0:00
Cat 2+	Peak	Fast	20:52	16:00	4:52	20:27	16:00	4:27	25.2	0:25
Cat 2+	Peak	Med	22:20	21:00	1:20	22:18	21:00	1:18	1.9	0:01
Cat 2+	Peak	Slow	24:32	24:00	0:32	24:32	24:00	0:32	0.0	0:00

Notes:

- Time reported are based on the evacuation order being given at time 0:00. The simulations performed included the simulation of the shadow traffic preceding the order to evacuate, but those hours are excluded from the evacuation times reported here.
- \* The 'Total Evacuation Time' columns report the time on the simulation clock at which the last vehicle exits the simulation network. This is the total duration of the evacuation.
- \*\* The 'Last Scheduled Demand' columns report the hour during which the last evacuee enters the network. This is a direct result of the behavior assumptions and is independent of other alternative parameters.
- \*\*\* The 'Total Congestion Delay' columns are calculated as the 'Total Evacuation Time' minus 'Last Scheduled Demand'. This value represents the amount of time that capacity restraints add to the evacuation time. Alternatively, it can be thought of as the time that the evacuation would be reduced by if there was unlimited capacity to accommodate the evacuation demand.

While the total evacuation time may not be reduced by implementing the reversal plan, it does have the potential of evacuating more people more quickly. To determine if this was true, the cumulative percentage of the evacuated population as a function of the time into the evacuation was plotted. Figure 10 shows this comparison for the heaviest and quickest demand loading scenario, a category 2+ hurricane during the peak season with fast behavior loadings assumed. The figure shows that the cumulative percentage demand evacuated under the current reversal plan is slightly higher under normal operations between the 15<sup>th</sup> and 21<sup>st</sup> hour of the evacuation, showing that the current reversal can get more vehicles out sooner. However, the difference again, is very small and would be difficult to rationalize the implementation of the current reversal plan based on these results.



**Figure 10. Percentage of population evacuated for a category 2+ peak season hurricane with a fast behavior response**

## **CONCLUSIONS AND RECOMMENDATIONS**

The following summarizes the conclusions and recommendations that were derived from the analysis completed during this study.

### **Elevation Survey**

The objective of this part of the project was to evaluate the usability of the Routes 47/347 corridor for the evacuation of Cape May in an event of a hurricane of ranging from category 1 to category 4. The study team found that the USACE has calculated and mapped the inundated areas in Cape May as a function of various hurricane categories that might reach this area. Assuming that the storm surge calculations are correct, it was found that the evacuation plans can reasonably rely on the information provided on the Cape May HES map. Sections of the Routes 47/347 corridor that are shown to be inundated on the HES maps for a given level of hurricane should not be used for evacuations if a hurricane of that category should occur.

### **Evacuation Simulations**

The objective of this part of the project was to estimate the total time required to evacuate the affected population during several combinations of hurricane strike levels, seasonal population, and traffic operation plans under different behavioral response possibilities. The evacuation times were estimated by performing multiple simulation runs on a network of the Routes 47/347 corridor and the surrounding roadway system. Based on simulation runs of the considered scenarios, an evacuation of the Cape May County area for a hurricane strike would require between 16 and 25 hours to complete after the order to evacuate is given. The primary factor affecting the duration of the evacuation was determined to be the assumed behavior responses. In almost all analyzed scenarios, this factor determined when the last evacuee exited the network. The demand varied under the combinations of both hurricane intensity and the seasonal population present at the time of the evacuation, but only the combination of a category 2+ hurricane during the peak season experienced extensive congestion, delays, and queues and required additional time for the evacuation to be completed. The implementation of the existing Routes 47/347 reverse lane plan proved to have negligible effect on reducing the total evacuation time required. Analysis of the evacuated population over the duration of the evacuation showed that the existing reversal plan does allow slightly more vehicles to traverse the evacuation corridor sooner, however, this benefit of the reversal is minor.

The analyzed scenarios showed that the current reversal plan for the Routes 47/347 corridor is ineffective in helping evacuate the region. The reasoning behind the ineffectiveness of the reversal plan is that the majority of the traffic that will be evacuated via the Routes 47/347 corridor was assumed to enter the corridor at the southern end of the corridor. This is well to the south of the beginning of the planned contraflow section at Route 83. Therefore, while the addition of capacity in the northern section of the corridor aids the evacuation of those residing near Route 83 and further north, the majority of the evacuating traffic must still utilize the existing one northbound

lane on the southern section of the corridor to reach the additional capacity provided by the reversed lane.

Based on the results of the simulation analysis, the study team cannot recommend using the Routes 47/347 Lane Reversal Plan as it currently exists. The lengthy evacuation time and delays incurred during a category 2+ hurricane strike can be considered unacceptable, and another solution to evacuate people from the Cape May County area should be found. Short of permanently adding capacity to roadways exiting Cape May County, a revised reversal plan is required to reduce evacuation times. Expanding the work effort beyond the current scope to include an investigation of new reversal plans within the Routes 47/347 evacuation corridor would not require extensive efforts.

An expanded version of this study could be undertaken to extend the simulation study network to include other major roadways in the area, predominantly Route 9 and the GSP. Assumptions regarding the use and traffic conditions of these possible evacuation routes were made in order to complete the project under current time and budget constraints. However, after seeing the apparent ineffectiveness of the existing reversible lane plan, investigations into using this corridor to evacuate vehicles from the populated southern areas of Cape May County should be completed. In addition to adding the Routes 9 / GSP corridor to the simulation study network, extending the network scope further to the north could address the possible conflicts between evacuees from Cape May with the large evacuating population of Atlantic City. While this would be a significant undertaking, it would provide a much greater understanding of what could happen in during a hurricane evacuation across South Jersey and would provide a good tool for NJ State Police and NJDOT to develop new and modify existing evacuation plans.

Further work could also be done to determine the effectiveness of a staged evacuation for the Cape May County area. This effort would also require an investigation into the logistics and human behavioral factors that would be encountered in planning and implementing a staged evacuation plan.

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## APPENDIX A: LITERATURE REVIEW

### Introduction

This review sought to understand the current practices employed during Emergency Evacuations during natural disasters (hurricane, floods etc). Results of previous studies were utilized to better model evacuation operation for Cape May. The following sections spotlight the types of evacuation, emergency preparedness actions, evacuation strategies, and measures of effectiveness, and behavioral modeling. The review also presents methods and tools for analyzing impacts and the current practices employed in evacuations.

### Types of Evacuations/ Preparedness Actions

The level of evacuation urgency depends on the characteristics of the storm and clearance times required to evacuate the population endangered by the storm.

Typically, evacuations are classified into three levels as:

1. **Voluntary:** Voluntary evacuations are focused on people who are most susceptible to the hurricane storm. Traffic regulatory measures are not undertaken in this case.
2. **Recommended:** Recommended evacuations are issued when a storm has a high probability of causing a threat to people living in at-risk areas.
3. **Mandatory:** During Mandatory evacuations authorities persuade evacuation to the residents and limit ingress to coastal areas. Transportation plans and traffic regulatory measures are implemented in these situations.

The state emergency management authorities are responsible for coordinating preparedness activities for an evacuation. These actions include a series of weather observations, readiness, and response procedures. Emergency management agencies may adopt suitable guidelines for conducting evacuations but their implementation varies in terms of the timing and sequencing of events depending on the nature of a storm.<sup>(9)</sup>

The following are a general sequence of response activities prior to commencement of an evacuation process:

1. The first phase of the evacuation process involves routinely monitoring tropical weather patterns that have the likelihood to strike coastal areas.
2. If a storm appears likely, specific actions are undertaken based on the level of urgency. These actions could include the configuration and control of routes for evacuation and recommendations to evacuate.
3. The forecasts issued by the National Hurricane Center (NHC) serve as primary decisive factors in deciding the urgency of evacuation and the size of area to evacuate.
4. A combination of clearance time and pre-landfall hazard times are used for issuing evacuation orders. Clearance time is the time required to configure all traffic control elements on the evacuation routes, initiate the evacuation, and clear the routes of vehicles once deteriorating conditions warrant its end. Pre-landfall hazards time is the time during which hazardous conditions exist prior to

actual hurricane landfall. Table 5 shows the minimum evacuation order advanced notification times for some coastal states.

**Table 5. Preferred minimum evacuation order advanced notification time (in hours) (Wolshon et al, 2001)**

State	Hurricane Category				
	1	2	3	4	5
Massachusetts	9	9	12	12	12
Rhode island	12-24	12-24	12-24	12-24	12-24
Maryland	20	20	20	20	20
Virginia	12	18	24	27	27
South Carolina	24	24	32	32	32
Georgia	24-36	24-36	24-36	24-36	24-36
Mississippi	12	24	24	48	48
Louisiana	24	48	72	72	72

### **Contraflow Strategies/ Measures of Effectiveness**

Contraflow or lane reversal operation plans have been studied for the states that are threatened by hurricanes. Contraflow is the reversal of traffic flow in one or more inbound lanes to accommodate the traffic in the outbound direction with the goal of increasing outbound capacity. The method of contraflow is also used to accommodate the unbalanced flow during the peak hours, during gaming and other recreational events. For example, in New Hampshire, contraflow operation is used twice a year to lessen congestion during Winston Cup NASCAR races at the New Hampshire International Speedway (NHIS). It is also used during special events like ball games, concerts, shows etc. In 1998, only the Florida and Georgia DOTs had plans in place to reverse the traffic flow on their interstate freeways to expedite evacuations. Eleven of the 18 mainland coastal states threatened by hurricanes plan to use contraflow based evacuation strategy.<sup>(9)</sup> Contraflow was implemented for the first time in Georgia during Hurricane Floyd in 1999 with generally positive results.<sup>(11)</sup> There was severe congestion on Interstate 26 between Charleston and Columbia, as Emergency management authorities had not agreed upon a contraflow plan. Travel times ranged from 14 to 18 hours than the normal 2-3 hours. After a strong public outcry from the evacuees trapped in congestion on I-26 from Charleston to Columbia contraflow was improvised in South Carolina during Floyd. During emergency evacuations, as the travel distances are considerably long and the need to evacuate people in the quickest time possible is overriding, contraflow operations need to be practicable.

### **Limitations and Costs of Contraflow**

Besides the advantages, several drawbacks are also experienced with contraflow strategies. Reverse flow operations are likely to be inconvenient and confusing for drivers. Contraflow operations are also labor intensive to initiate, difficult to enforce, and potentially dangerous for drivers.<sup>(9)</sup> Apart from for the cost of capital infrastructure

improvements, the primary source of cost for contraflow evacuation is related to the personnel requirements for the implementation and enforcement of the operation. Once the evacuation plan is initiated, field operations personnel will be required to set up all temporary traffic control devices and ramp barricades. NJ State Police, National Guard, and other law enforcement personnel will need to be stationed at all inbound entrance ramps to prevent traffic flow into the contraflow lanes. Upgrades in states where infrastructure improvements were required to facilitate contraflow evacuation involved only minimal capital investments. The only significant infrastructure enhancements required for contraflow in the Carolinas and Louisiana were the construction of permanent paved crossover lanes between the outbound to inbound lanes. The NCDOT estimated the total cost of construction items for the reversal of I-40 at \$275,000 (NCDOT 2000). However, the costs and benefits of contraflow in terms of its safety, manpower requirement of operation, and actual capacity improvements remain largely unknown.<sup>(10)</sup>

### **Contraflow Design Attributes**

Due to the lack of recognized standards or guidelines for the design, operation, and location of contraflow segments, most contraflow designs have been adopted from standard design practices and past evacuation experiences.

1. Contraflow sections are initiated with a median crossover or traffic control configuration that redirects or splits a portion of the outbound traffic stream into the inbound lanes. These designs vary by location. The precise location of these crossover points is dependent on the roadway geometry, the approximate beginning of congestion during past evacuations, and the proximity of the location to other evacuation routes. For Cape May County, 14 command posts will be established along the evacuation routes. The contraflow operation will be commenced from the post at the southern end located at Route 47 and Route 83 (Dennis Twp).
2. The factor that decides the location of a termination point is the prevention of merging congestion. This location can be determined in many ways.
  - a. The most commonly employed method is splitting the traffic flows. In this design one traffic stream is diverted onto a separate roadway, while the other continues travel on the original route.
  - b. The other common type of contraflow termination point is the attrition-merge. This design is favored in states having long contraflow segments such as Georgia and Texas. In this design, traffic in the normal and reverse flow lanes is reduced by allowing vehicles to exit to secondary routes at points along the contraflow segment. Through a process of exit attrition, it is assumed that traffic would be reduced to a level at the end of the segment that would allow a merging of the traffic streams without causing bottleneck congestion.

The last command post along the evacuation route i.e. Route 49 and Wade Boulevard (Maurice River Twp) will be used for termination of contraflow for Cape May. The exit ramp traffic will be directed WB on to Route 49 toward the Millville High School (public shelter). Table 6 presents the contraflow routes and the termination types used by some of the coastal states.

**Table 6. Review of contraflow termination point designs**

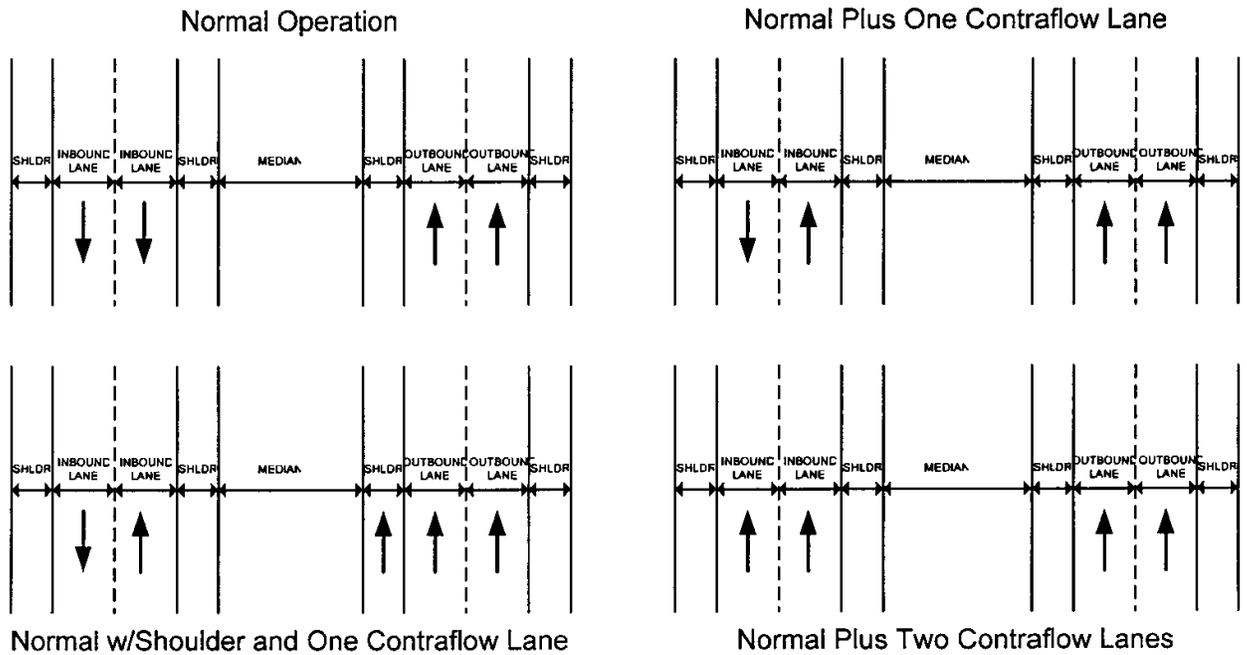
State	Route(s)	Contraflow Termination Type
Virginia	I-64	Median Crossover
North Carolina	I-40	Reversed On-Ramp
Georgia	I-16	Median Crossover
Florida	I-10 Westbound	Reversed On-Ramp
	I-10 Eastbound	Reversed On-Ramp
	I-4	Median Crossover
	I-75 Southbound	Median Crossover
	I-75 Northbound	Reversed On-Ramp
	FL Turnpike	Median Crossover
Alabama	I-65	Median Crossover
	I-10 Westbound	Median Crossover
Louisiana	I-10/I-59 (east/north)	Median Crossover
Texas	I-37	Reversed On-Ramp

3. The lengths of contraflow lanes are dependent upon the evacuation area geography and the road infrastructure. Planned segments range in lengths from 3½ to 180 miles. Short sections are typically used to gain maximum capacity on routes that connect other traffic arteries. Longer segments are used to evacuate coastal cities towards inland locations.

According to a previous study, four types of contraflow operation designs have been in existence for a roadway with two lanes in each direction <sup>(9)</sup>:

- a. Two lanes reversed,
- b. One lane reversed, one lane normal for emergency/service vehicle access,
- c. One lane reversed, one lane normal for inbound traffic entry,
- d. One lane reversed and use of outbound right shoulder.

As shown in Figure 11, various alternatives ranging from normal operation to a complete reversal of both inbound lanes exist.



**Figure 11. Freeway contraflow lane use configurations (Wolshon et al, 2001)**

Table 7 illustrates the estimated average total outbound capacity (vehicle/hr) in one direction

**Table 7. Interstate contraflow flow rates for four-lane freeways (PBS&J, 2000)**

Strategies	Estimated Average Total Outbound Capacity (vehicles/hour) per direction
Normal Two-Way Operation	3,000
Three Lane (one contraflow lane)	3,900
Three Lane (using outside shoulder)	4,200
All- lane Reversed (no shoulder lanes)	5,000

Table 8 shows different types of designs employed by states for effecting contraflow. The approximate length of contraflow lane on Routes 47/347 is about 19 miles.

**Table 8. Evacuation contraflow use strategies (Wolshon et al, 2001)**

<b>Strategy / State</b>	<b>NEW JERSEY</b>	<b>MARYLAND</b>	<b>VIRGINIA</b>	<b>NORTH CAROLINA</b>	<b>SOUTH CAROLINA</b>	<b>GEORGIA</b>	<b>FLORIDA</b>	<b>ALABAMA</b>	<b>LOUISIANA</b>	<b>TEXAS</b>
All lanes outbound		X	X	X	X	X	X	X	X	X
One lane reversed, one lane inbound for emergency/ service vehicle entry only	X								X	
One lane reversed, one lane inbound for traffic entry	X				X					
One lane reversed and use of outbound left shoulder lane									X	

- Capacity gains: Each of the alternative strategies provides 30% to 67% increase in capacity over normal two-way operation. According to one study, a full reversal would provide a near 70% increase in capacity over conventional two outbound lane configurations.<sup>(13)</sup> Single inbound lane reversals are thought to increase outbound road capacity by about 30%. This arrangement helps in maintaining a lane for inbound law enforcement personnel and emergency service vehicles, important for clearing incidents. It can also permit access for people that want to move against the evacuation traffic. This strategy also raises the potential for head-on accidents. Another strategy to improve capacity is to use the outbound left shoulder as an additional outbound lane. This has been estimated to increase capacity by only about 8%.<sup>(13)</sup> The increase in capacity depends on the width and condition of the shoulder, since flow rates are decreased and drivers tend to reduce speeds when they are laterally constrained. This information could be verified by simulation. Alternatives could be compared based on their feasibility for Routes 47/347 to determine optimal gains.

#### **Implementation Procedure**

Survey questions were posed to determine the managerial strategies concerning who would decide when to use contraflow; under what conditions it would be started and

ended; how long it would last, and how would issues associated with safety, accessibility, convenience, enforcement, and cost be addressed.<sup>(9)</sup>

1. Several criteria were identified as affecting decisions on if and when to initiate contraflow operations, including: storm characteristics (size, intensity, track) and potential risks; traffic volume; set up time; and time of day. In cases where the storm was not forecast to make imminent landfall or was of modest strength, most states indicated they would resist the use of contraflow. The other criteria controlling the implementation of contraflow was traffic volume.
2. Because of the inherent difficulties of its use, the majority of states feel that contraflow flow lanes should not be implemented until traffic volumes warranted their use. Officials in these states intend to wait until volumes were at or rapidly approaching, capacity levels before using contraflow. These opinions were not, however, shared by all states. Officials in states of South Carolina and Louisiana plan to initiate contraflow operations as soon as the call for an evacuation is made. It is their opinion that attempts to initiate contraflow operations after the normal outbound lanes are near or at capacity will result in the loss of valuable evacuation time.
3. To initiate contraflow, traffic control devices and barricades must be erected, inbound lanes must be cleared of vehicles over their length, and law enforcement and DOT field personnel must be positioned at their assigned locations. Most states expect this process will take from four to 12 hours. Set up time depends on the length of the segment, the number of interchanges involved, the number of ramps, and merge points that may require control. In a few states, the process could take considerably longer. Authorities in Florida estimate that 49 hours will be needed to prepare for a contraflow operation. The time is so much longer than other states because Florida needs to activate National Guard forces to set up and patrol their segments.<sup>(14)</sup> Most states are reluctant to implement contraflow after nightfall due to the above-mentioned factors.

### **Contraflow on Median Undivided Arterials**

Most of the states employ interstate highways (freeways) for contraflow operations. The application of median undivided arterials is limited. Furthermore, since none of these undivided arterials have known usage in an evacuation, the information of their functioning as contraflow lanes in comparison to contraflow on freeways is not available. Issues involved in the use of undivided arterial contraflow can include reduction in vehicle speeds due to lack of median barrier and hence a reduction in roadway capacity, increase in incidents, change in driver behavior, etc.. Contraflow operations have been used to mitigate traffic congestion in many cities. The reversible lane on Grant Road, which carried WB/EB traffic during peak hours in Tucson, Arizona was eliminated as it led to an increase in accidents, caused confusion among motorists in addition to increasing operating expenditures.<sup>(15)</sup> Behavioral issues that can reduce the roadway capacity on Routes 47/347 during contraflow operation will be addressed.

### **Measures of Effectiveness (MOE)**

The most important Measures of Effectiveness (MOEs) in evacuating the population at risk to safe area is the evacuation time. The evacuation time here is defined as the total time taken for people in the area of threat to prepare to evacuate and the time needed for all vehicles on Routes 47/347 to reach a safe distance (i.e. WB on to Route 49 toward the Millville High School). Other parameters that could be considered as measures of effectiveness are the travel time, link trips and average speed. Evacuation traffic models are expected to provide decision-makers with the necessary information or even real-time information, which can supply to the evacuees better routes and destinations. As a result, human behavior will be improved. This is very helpful during mandatory evacuation. For example, during the nuclear power plant accident at Three Mile Island, PA in March 1979, only 39% (144,000) people evacuated, and the 62% of the people who did not evacuate said they were never informed what to do and how to do it. <sup>(15)</sup>

### **Analysis**

Computer modeling is a widely used tool in planning and preparing for evacuations. With the ubiquity of faster, inexpensive computers and the availability of better evacuation behavioral data, modeling techniques have improved considerably. Simulation programs could be used to model weather, flooding, traffic flow, and evacuation travel behavior. The data that are used in these programs come from the Hurricane Evacuation Studies (HES) instigated by the Federal Emergency Management Agency (FEMA) in 1980s to integrate key aspects of hurricane evacuation planning and to assist in disaster preparedness. The studies comprise of storm hazard and vulnerability analysis, an evacuee behavioral analysis, a sheltering analysis, and a transportation analysis. <sup>(9)</sup>

### **Evacuation Traffic Models**

Several evacuation traffic models have been developed from the trip-based four-step model with slightly different functional requirements. These evacuation traffic models have been modified specifically for population during evacuation. These models have similar databases integrating data on population, socioeconomic characteristics, route network, and other analysis elements. Also the models use similar algorithms of trip generation, distribution and assignment. Some of the prominent macroscopic evacuation simulation models employed in modeling evacuation are Calculated Logical Evacuation and Response (CLEAR), MASS Evacuation (MASSVAC), Hurricane and Evacuation Program (HURREVAC), NETVAC, DYNAMIC EVacuation Model (DYNEV), Oak Ridge Evacuation Modeling System (OREMS).

### **Current Practices (Summary)**

Evacuation begins early on the first day, levels off at evening of the first day, then resumes the following day. Variations in evacuation rates exist. During evacuation of North Carolina in hurricane Floyd, among evacuees from category- 1 and larger surge zones, as many as 98% left their own county. Between 70% and 90% of the respondents said they were familiar with the road systems in the areas through which they were evacuating. <sup>(18)</sup> Information from cumulative loading curves could be used in controlling the loading rate in the simulation.

Channeling flows at intersections to remove crossing conflicts can significantly decrease network-clearing time over no routing plan. The amount of reduction varies depending on the road-network context and scenario. The benefit of channeling flows at intersections to remove merging depends on traffic volumes and the efficiency within which merging can be performed. If this process is very inefficient and intersection v/c ratios exceed 1, then a plan with minimal merging can further decrease network clearing time. If merging can be conducted efficiently, as in the case of demand-sensitive signal control, then reducing the amount of merging in a routing plan appears to have little or no benefit. In this case, a shortest distance plan would serve better.<sup>(19)</sup> Signage at intersections along the evacuation route could be designed to facilitate better flows and reduce conflicts to achieve lower travel times.

The review of contraflow plans must be an iterative and continuing process that recognizes changing geometrics, law enforcement priorities, resource availability, and evolving evacuation travel behavioral trends. The time at which evacuees should be advised to stop entering the routes should be based on actual traffic conditions and not modeled predictions as the region and state's population will respond differently for various storm events. Operational elements of contraflow could be improved by stationing traffic control personnel at the appropriate intersections and dissemination of public information that is clear and understandable for proper guidance.<sup>(20)</sup>

Excess capacity in the contraflow segment can be utilized through additional volumes without exceeding the capacity of the lanes or creating significant congestion upstream of the ramps. The controlling bottleneck appears to be at, or just before the crossover. The rate of flow could be increased by adding additional entry points to the contraflow segment to spread out the entry of demand and phasing evacuations to regulate the demand entering the system.<sup>(21)</sup> Through simulation, underutilized capacity of the evacuation route could be estimated and the model could be improvised to incorporate additional flows.

Merging congestion is likely to occur at the termination point of a contraflow segment. Figure 12 shows the various contraflow termination point designs. The merging conflicts and traffic congestion on the evacuation route inevitably lead to longer delay as well as endanger evacuees' safety. Increasing the exiting vehicles using more available exit-ramps improves the efficiency of the contraflow operations. Maintaining a substantial number of exit opportunities along the intermediate segments of the evacuation section increases the overall evacuation efficiency.<sup>(22)</sup> Alternatives with additional exit ramps on Routes 47/347 could be simulated to realize their effectiveness in reducing merging congestion and travel time.

Traffic flow on controlled access interstate routes (fully controlled access routes) is accomplished by concentrating on interchanges, emergency crossovers and terminus areas as they have the best potential for use in contraflow scenarios. On the other hand, control on limited access routes cannot be easily regulated as they have numerous entrance and exit points, which make it difficult to manage. Therefore limited access routes are not considered for contraflow operations. Additional signage required for traffic

moving on the southbound roadway for northbound movements could consist of signs pertaining to interchange and exit locations, service and non-service interchanges as well as directional signs that may be necessary. Variable messaging signs to notify evacuating public of the plan implementation and arrow boards to direct traffic flow due to closed lanes particularly around crossovers and terminus points can be used. Hurricane Emergency Information Signs could be placed on the ground along the designated hurricane evacuation routes identifying these routes to the traveling public.<sup>(22)</sup> The impact of information dissemination on the evacuating traffic through the above mentioned means could be simulated to demonstrate improvements in driver behavior and hence the flow pattern leading to optimization.

Hurricane evacuation zones could be delineated based on a system of zones of homogeneous elevation that are overlaid on a surge map to identify those that will be flooded in each scenario. The procedure is initiated by creating an area layer in GIS, based on the highest Maximum Envelope of Water (MEOW)s, (MOM) for the region in question. Highways are used to subdivide the portions of ZIP code areas into sub areas. This process helps in identifying, which zones should be evacuated, and which zones should not.<sup>(17)</sup>

The effectiveness of contraflow operations with outbound freeway links show significant improvements when the capacities of the key entrance ramps from the evacuation areas are increased. Evacuation time with contraflow is substantially reduced when the capacities of the key entrance ramps are increased. This result was obtained when the feasibility of applying a dynamic traffic assignment model, Dynasmart-P, for evaluating the effectiveness of alternative strategies for evacuating the traffic in downtown Minneapolis, Minnesota, under a hypothetical emergency situation was studied.<sup>(23)</sup>

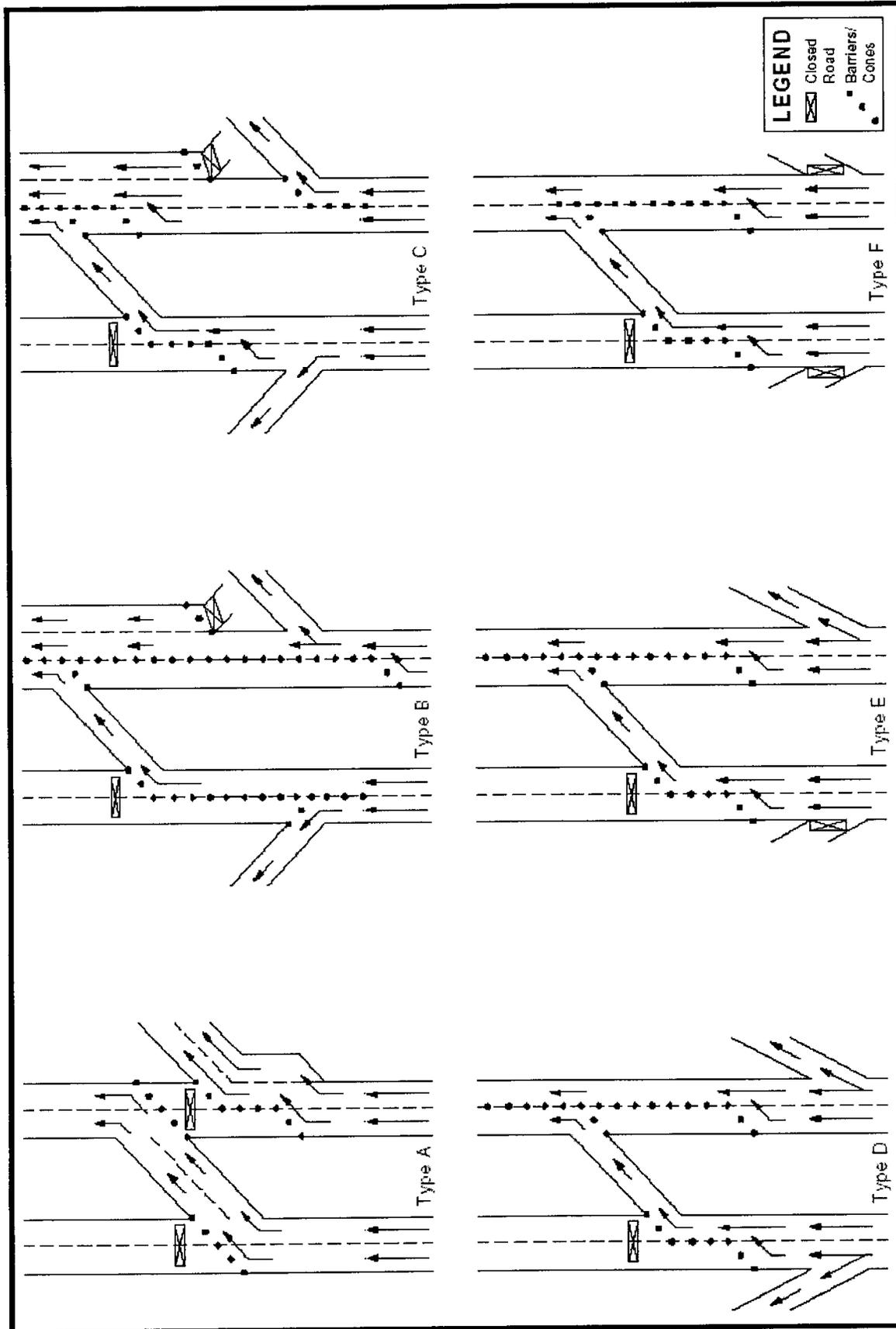


Figure 12. Schematic termination point designs

## APPENDIX B: BEHAVIORAL MODEL RESEARCH

State-of-practice in hurricane evacuation travel demand modeling has two main steps: 1) the estimation of total evacuation demand and, 2) the estimation of departure times<sup>(24)</sup>. 'Participation rates' are the most common method for estimating total evacuation demand. For determining these rates, evacuation behavior is considered homogeneous in geographic subdivisions of the study area and they are assumed to vary among various geographic subdivisions (evacuation zones) depending on the severity of the storm and flood risk. Participation rates are generally established subjectively based on past behavior under different storm conditions<sup>(24)</sup>. Recently, availability of hurricane evacuation and behavior data made the development of more realistic and theoretically sophisticated trip generation models<sup>(25)</sup> possible.

Statistical analysis methods are widely used in trip generation modeling<sup>(26,27,28)</sup>. Logistic regression is also used to model hurricane evacuation demand<sup>(29,30)</sup>. Fu<sup>(24)</sup> proposed a unique approach to evacuation demand modeling by using survival models that are used in a wide range of subjects including medicine, engineering, criminology, sociology and marketing as well as transportation. However, they were not employed for hurricane evacuation modeling before Fu's work. All these studies are still relatively theoretical when current practice in hurricane evacuation travel demand modeling is considered and more research is needed to successfully use them for real-world studies.

Overall, the evacuation demand models proposed in the literature can be classified as follows:

1. Empirical, expertise based approaches<sup>(31)</sup>
2. Behavioral response curves (S-Curves)<sup>(See references 3,4,5,6,7 and 8)</sup>
3. Regression/Logit Models<sup>(See references 24,25, 29 and 30)</sup>
4. Artificial Neural Network Models<sup>(See references 25,32,33, and 34)</sup>
5. Hazard / Survival Models<sup>(24)</sup>

The last three models presented above are mathematically complex and require detailed data for calibration. Below is some brief information about the behavioral models selected as possible alternatives that can be used in the Cape May study.

1. Tweedie's Rayleigh distribution approach is based on professional judgment relating to hurricane experience that does not exist for Cape May County. The distribution depends on only one parameter, which is maximum mobilization time.
2. Behavioral response curves are the most popular loading models by several hurricane evacuation studies. They are employed in almost all nationwide evacuation studies conducted by Army Corps of Engineers<sup>((See references 3, 4,5,6,7 and 8)</sup>. Behavioral response curves (S-Curves), also called Sigmoid or S-Curves, have a much longer history than other more recent models such as, sequential logit model. S-curves are also employed in evacuation decision software packages<sup>(35,36)</sup>. Behavioral response curves have 2 parameters namely, half loading time and response rate. The former determines the time span of the demand loading and the latter determines the rate of the loading. In past studies<sup>(See references 3,4,5,6,7</sup>

and 8) three response parameters are employed, to simulate fast, medium and slow evacuation responses. The values of these response parameters are generally obtained from surveys performed in evacuation regions of interest.

3. Sequential logit model, proposed by Fu<sup>(24)</sup>, is derived from evacuation surveys from Southwest Louisiana and shown to reproduce the real evacuation behavior when compared with real evacuation data. Best feature of the sequential logit model is its ability to capture the five main parameters to affect evacuation behavior stated by Baker<sup>(37)</sup> which are widely agreed upon in the literature. The model is also claimed to be transferable which means that the model can be applied to different situations in terms of hurricane characteristics and geographic locations.

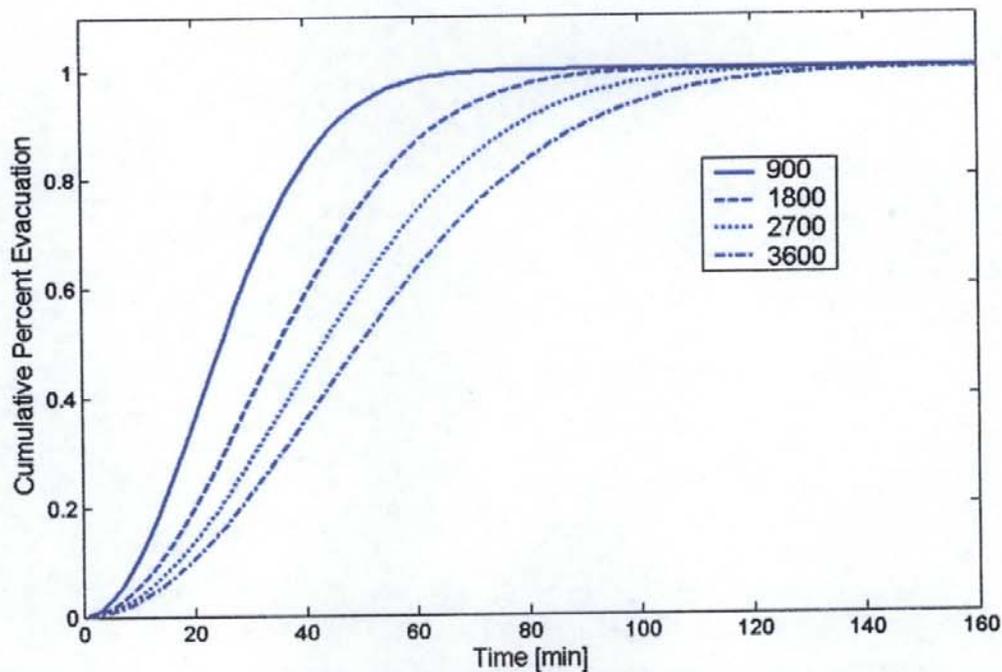
These models were studied further to find the best fit for Cape May County evacuation study. Below the details of the model investigations can be found.

### **Tweedie's Approach**

Tweedie proposes Rayleigh distribution to represent the evacuation loading. The formula for the Rayleigh distribution is given as follows:

$$F(t) = 1 - \exp\left(-t^2/1800\right) \quad (1)$$

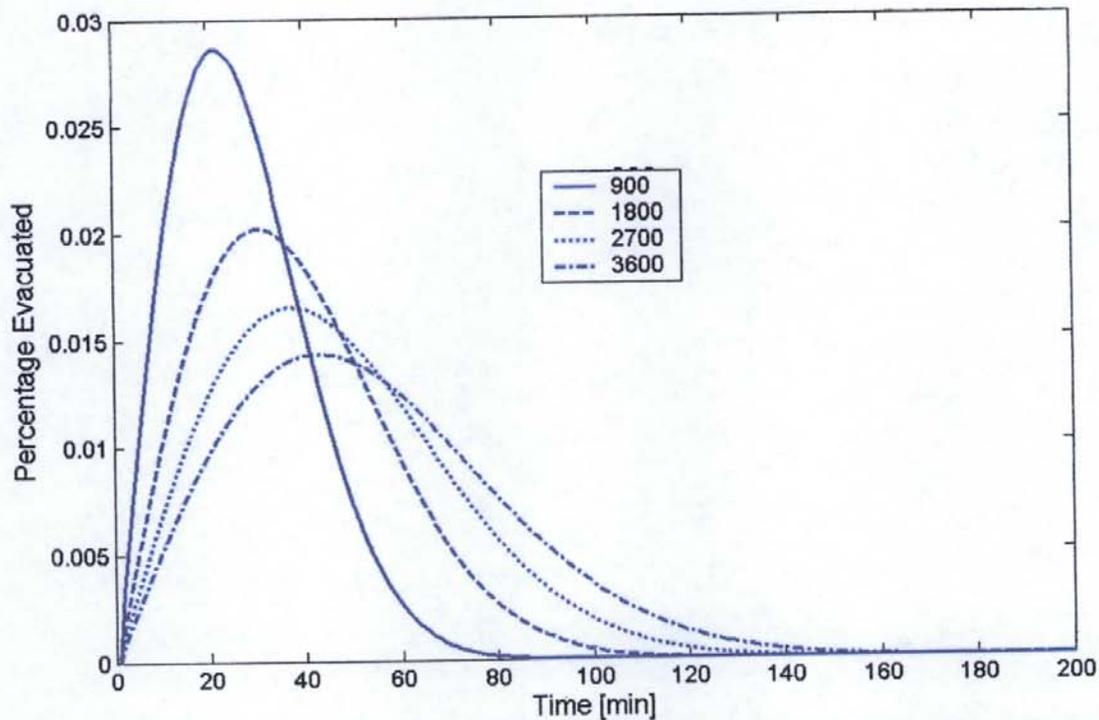
Here, the only parameter to be investigated is the number 1800 that is the maximum mobilization time in minutes. Maximum mobilization time is defined as the time from the issuing of an evacuation order to the time of evacuation departure. Tweedie determined this number with the help of the Civil Defense Office of Oklahoma<sup>(24)</sup>, and naturally, it may not be valid for other locations. The evacuation curves according to different maximum evacuation time values are given in Figure 13 as cumulative percentages and in Figure 14 as percentages loaded at every time step.



**Figure 13. Cumulative percent evacuation with varying maximum evacuation times**

As seen in Figure 13, when Tweedie's approach is employed, the majority of the evacuation demand is observed during the first two hours of the total evacuation period. This is not a very realistic assumption given the empirical evidence obtained from various post-hurricane studies.

In Figure 13, it can be observed that as the maximum evacuation time parameter gets larger, the curves become closer to each other. That can be verified by studying the fact it takes 46, 65, 79, and 92 minutes to complete 90% evacuation for maximum mobilization times of 900, 1800, 2700 and 3600 minutes respectively. Figure 14 shows the loading percentage change over time. Note that, loading values become very close to zero (with a proximity of  $10^{-4}$ ) at 62<sup>th</sup>, 84<sup>th</sup>, 102<sup>th</sup>, 115<sup>th</sup> minutes and maximum loading occurs at the 22<sup>th</sup>, 31<sup>th</sup>, 37<sup>th</sup>, and 43<sup>rd</sup> minutes, for maximum mobilization times of 900, 1800, 2700 and 3600 minutes respectively. Thus, it can be concluded that the time, at which the maximum loading occurs, does not change much with varying maximum mobilization time.



**Figure 14. Percent loading onto the network with varying maximum mobilization times**

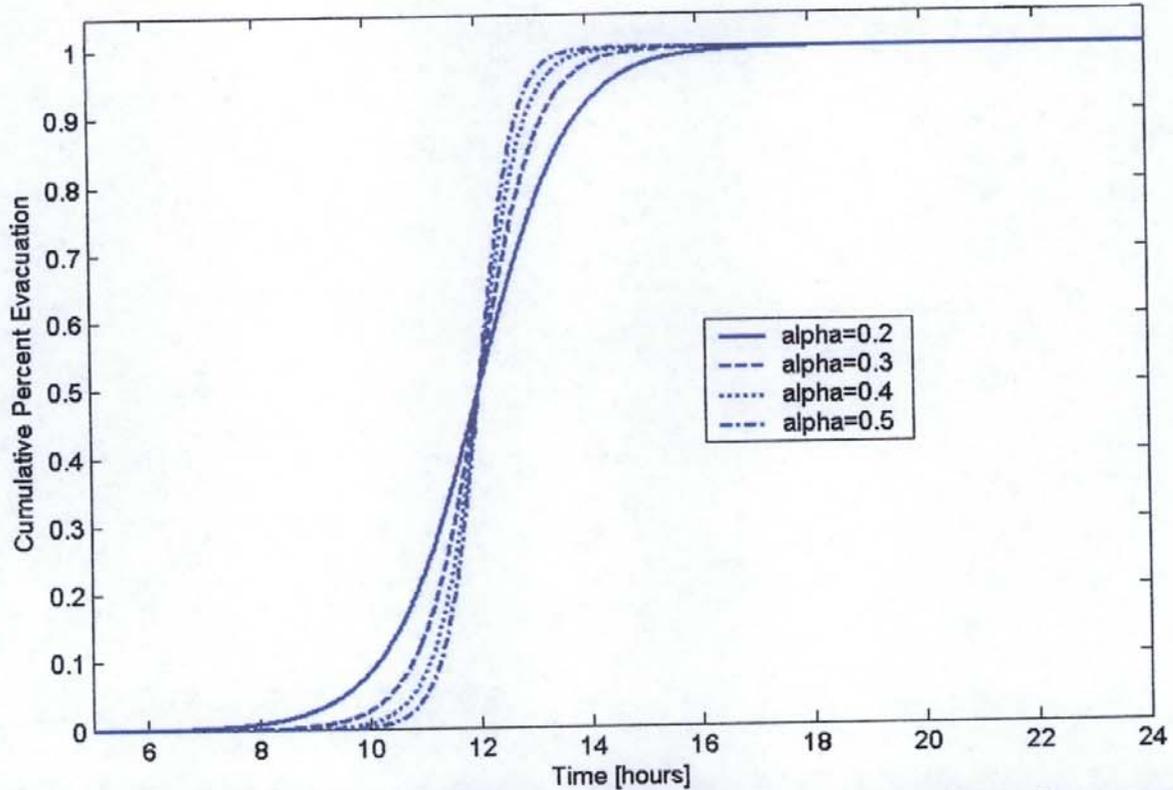
### **Behavioral Response Curves**

Behavioral response curve, or Sigmoid curve, or S-curve that can be mathematically expressed using the equation given in Radwan et. al's<sup>(36)</sup> is used in evacuation software packages such as TEDSS and MASSVAC.

General S curve formula is given as follows:

$$P(t) = \frac{1}{1 + \exp[-\alpha(t - H)]} \quad (2)$$

where  $P(t)$  is the cumulative percentage of the total trips generated at time  $t$ . The " $\alpha$ " parameter represents the response of the public to the disaster and alters the slope of the cumulative traffic loading curve.  $H$  is the half loading time; the time at which half of the vehicles in the system have been loaded onto the highway network.  $H$  defines the midpoint of the loading curve and can be varied by the user according to disaster characteristics. These curves are shown in Figure 15 and 16.



**Figure 15. Sigmoid curves with half loading time=12 hours and varying response rate parameters**

In Figure 15, different S-curves with varying  $\alpha$  parameters are shown. All curves intersect at half loading time, which was kept fixed for all the curves. As the  $\alpha$  parameter increases, the response is more concentrated near the half loading time. Low  $\alpha$  value produces more homogeneous loading percentages. The time it takes for 90% evacuation of all the demand, with half loading time equal to 12 hours, is 12.7, 12.9, 13.2, and 13.8 hours for  $\alpha$  values of 0.2, 0.3, 0.4, and 0.5 respectively. This is an expected result since the  $\alpha$  value determines the response rate and as it increases, the time to reach high loading percentages gets lower and curves become similar.

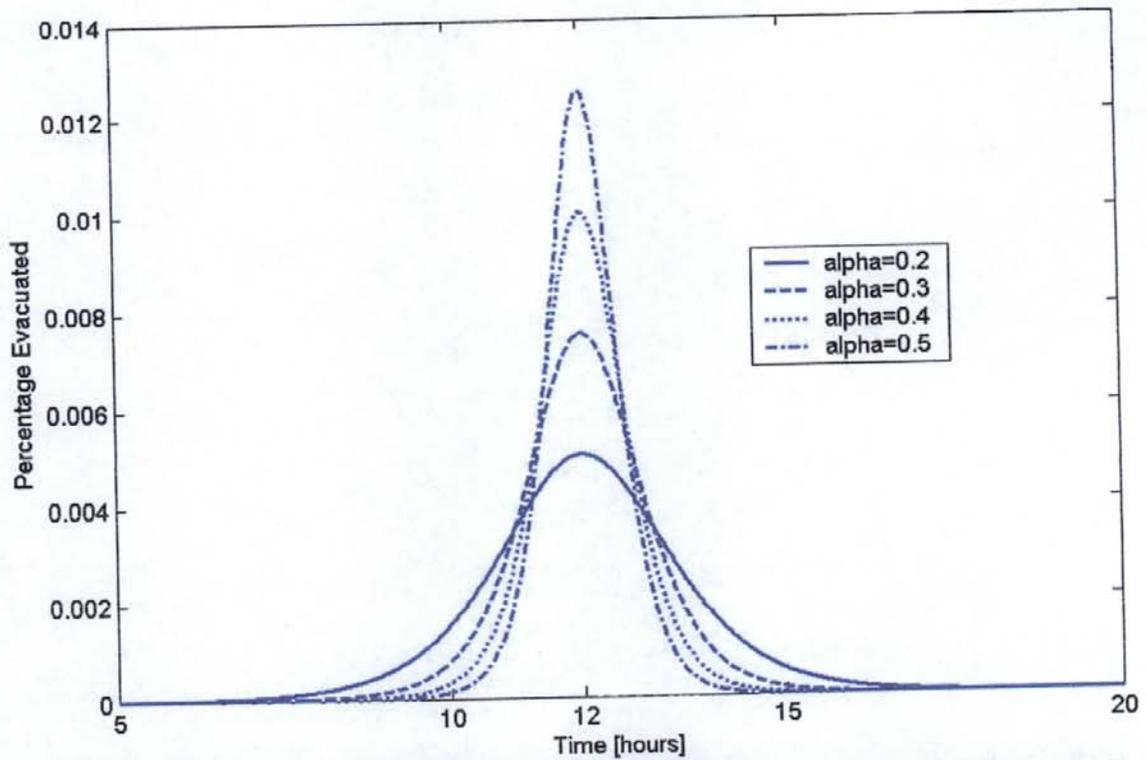


Figure 16. Percent evacuations with half loading time=12 hours and varying response rate parameters

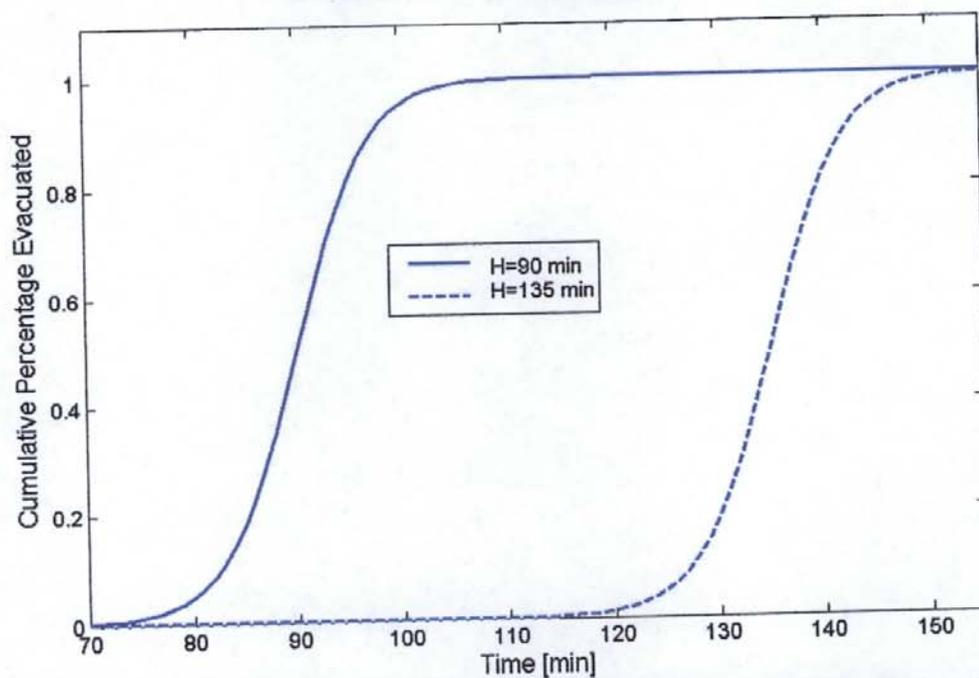


Figure 17. S-curves with fixed  $\alpha = 0.3$ , and varying half loading times

Half loading time for S-curves is a very important factor since it determines the time at which the maximum loading will occur. As shown in Figure 17 the half loading time

shifts the S curve in the horizontal direction. It also changes the time of the maximum loading onto the network. Half loading time parameter changes the timing of the evacuation, without changing the behavior of the evacuees.

### Sequential Logit Model

This relatively new loading model proposed by Fu et al <sup>(38)</sup> is shown to capture the underlying relationships between the dependent variable, which is the probability of evacuation for each time interval, and the independent variables with the major variables that have been proven to play important roles in studying hurricane evacuation.

The theory and actual implementation of logit model are both quite complex. Moreover, logit model is a disaggregate model that determines the likelihood of each households to evacuate. This makes it even more difficult to implement it for a large population since a separate Monte Carlo simulation is needed to generate evacuation probabilities for each household. Thus, the mathematical description of the logit mode is not given here to ensure simplicity but interested reader is referred to Fu et al <sup>(38)</sup> and Ozbay et al <sup>(39)</sup>. On the other hand, a brief description of the covariates used in the sequential logit model are given below:

- dist: Distance, a function of distance to the storm at time t
- TOD: Time of the day, periods used – night, morning, afternoon
- speed: Hurricane speed; forward speed of the hurricane at time t
- orderper: Perceived evacuation order; determines if evacuation order was received or not (0,1)
- flood: Flood risk; determines if the residence is likely to be flooded or not (0,1)
- mobile: Mobile home; determines if a mobile home or not (0,1)

After studying 26 hurricane evacuations, Baker <sup>(37)</sup> identified the five most important variables in hurricane evacuation. These are some of the major factors that are agreed by most of the researchers in this area to affect the evacuation behavior <sup>(24)</sup>. The variables used in the sequential model are listed along with these major factors determined by Baker <sup>(37)</sup> for comparison purposes.

**Table 9. Sequential logit model variables compared with Baker’s findings**

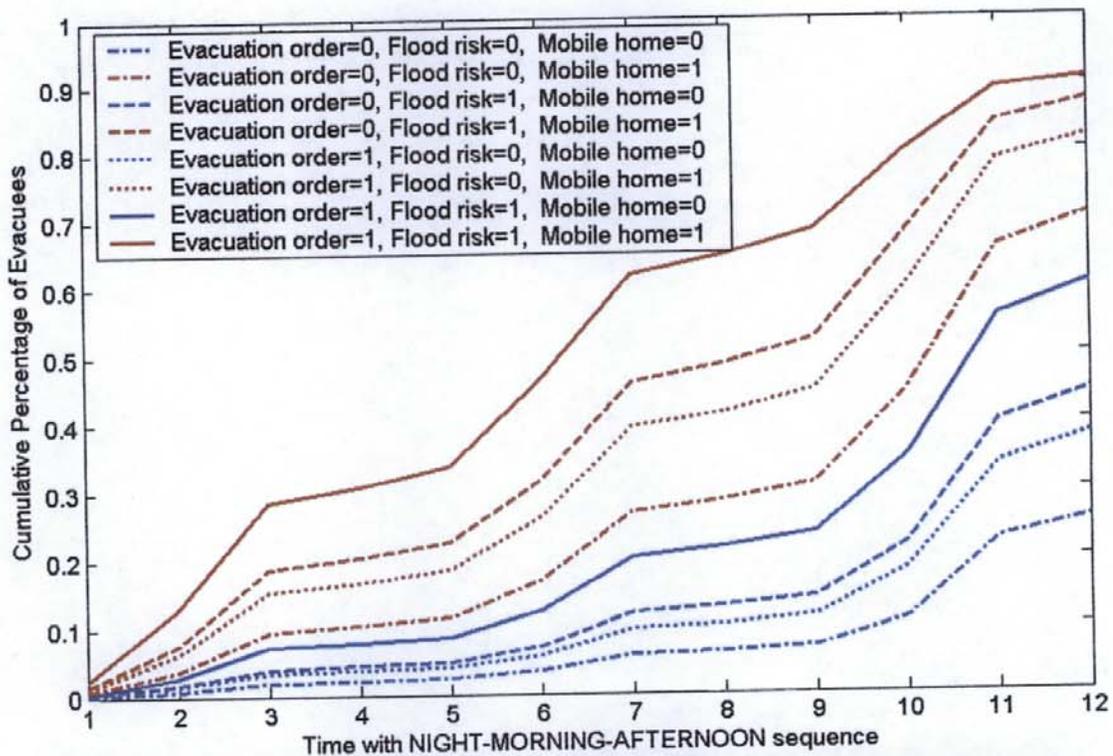
<b>VARIABLES IDENTIFIED BY BAKER’S STUDY <sup>(37)</sup></b>	<b>VARIABLES USED IN THE SEQUENTIAL LOGIT MODEL <sup>(24)</sup></b>
Risk Level (Hazardousness) of the area	Flood (0 or 1)
Actions by public authorities	Evacuation order (0 or 1)
Housing	Mobile (0 or 1)
Prior perception of personal risk	Hurt risk, protection <sup>1</sup>
Storm specific threat factor	Distance, wind speed, time of the day

1: Excluded from the sequential logit model

Although the names of the variables used by various studies are different, the variables used in sequential logit model cover almost all the important factors identified by the

Baker study<sup>(37)</sup>. According to post hurricane surveys analyzed for the development of the sequential logit model, the variables representing prior perception of personal risk were also found significant, but they were later excluded because data for such personal perceptions are deemed to be difficult to obtain. The last variable, the storm-specific threat factors also mentioned by the Baker study<sup>(37)</sup>, are also included in the sequential logit model as distance from the storm, hurricane speed, and time of day<sup>(24)</sup>.

In the utility model, the signs of the covariates are found to be as expected. Increasing distance will decrease the probability of evacuation, where increase in all other covariates will increase the evacuation probability. Among all the covariates, Time of Day (*TOD*) has the largest absolute value, and it affects the household evacuation decision considerably. Second important parameter is the type of housing captured as the mobile home or regular home by the variable "*mobile*". According to this variable, people living in mobile homes are about 5.2 times ( $e^{1.6496}$ ) more likely to evacuate than people not living in mobile homes. "*Flood*" is the third important parameter in the sequential model. This variable states that household with the flooding risk is twice ( $e^{0.7809}$ ) likely to evacuate, than a household with no flooding risk. The parameter *orderper* is treated as a static variable, although a time dependent treatment could have been more appropriate. However, the lack of information about the evacuation order timing in the survey data made it impossible for the authors to include it as a dynamic variable into the model. The covariate "*dist*" is a dynamic continuous variable and the negative coefficient means that the nearer the storm, the more likely a household would evacuate. From the data set used for model estimation, the values of "*dist*" ranges between 0 and 7 and there is a 270 times difference in magnitude between the two extreme values of *dist*, making *dist* the most influential covariate in the model<sup>(13)</sup>.



**Figure 18. Evacuation curves of households with different attributes**

The evacuation percentage outputs of sequential logit model for various participation rates are shown in Figure 18. Figure 18 is a comparison used to determine the evacuation demand from various evacuation zones with different characteristics. Sequential logit model produces about 90% participation rate for mobile households with flood risk that also receive evacuation order. According to the behavioral studies conducted by Federal Emergency Management Agency & Army Corps of Engineers <sup>(40)</sup>, these participation rates for high-risk households are reasonable. However for low risk households, without any evacuation order, the 25% participation rate predicted by this model is higher than the 10-15% rates assumed by most of the behavioral studies conducted in the past. Although the model estimate is higher than the assumed rates used in past studies, it still gives a value that lies on the safe side. It should also be noted that these participation rates are also assumptions, so it may be misleading to decide about a model's accuracy only relying on those assumptions.

Overall, sequential logit model captures the general evacuation behavior process successfully, because it:

- has a behavioral basis and employs random utility theory for evacuation decisions,
- can accommodate dynamic variables: including, hurricane speed and distance, TOD, evacuation order etc.
- gives consistent results with respect to assumed or observed participation rates
- can be applied to different situations if the data for re-estimation of the location specific parameters is available

### **Recommended Evacuation Loading Model for Cape May Study**

Among the alternatives briefly discussed above, Tweedie's model was eliminated due to its dependence on the hurricane experiences of local officials and the public. A lack of hurricane evacuation experience in New Jersey prevents the use of this method. Detailed analysis<sup>(39)</sup> shows that the sequential model does not give realistic results for short time evacuations less than 24 hours because the model proposed by Fu<sup>(24)</sup> is originally constructed to represent a 3 days long evacuation. The sequential model also needs detailed household specific data such as flood risk, being mobile home or not etc., because the evacuation decision for each household is treated individually according to the household characteristics. Moreover, the model estimation is based on revealed preference and post hurricane survey data that can only be collected among people who have actually experienced a hurricane evacuation. This type of data was not available for New Jersey for model validation and calibration. Thus, the estimation of the sequential logit model for New Jersey specific conditions is not a feasible option.

Following the recent state-of-the-practice behavioral response curves (S-curves) are recommended as the loading model to be employed in Cape May Evacuation study, because they:

1. Are mathematically simple to use and implement,
2. Require considerably less site-specific data compared to sequential logit model,
3. Can reproduce realistic evacuation behavior with the loading rate and half loading time constants determined based on past evacuation data
4. Are extensively mentioned in literature and employed in a number of official studies (See references,3,4,5,6,7, and 8) thus they are considered as a credible modeling approach that is widely used by other studies,
5. Were employed in the Delmarva evacuation study which is a location similar to Cape May both in terms of geographical conditions and hurricane experience.

Thus, behavioral response curves are the most reasonable recommendation for the Cape May study too due to the aforementioned reasons.

### **More on Behavioral Response Curves**

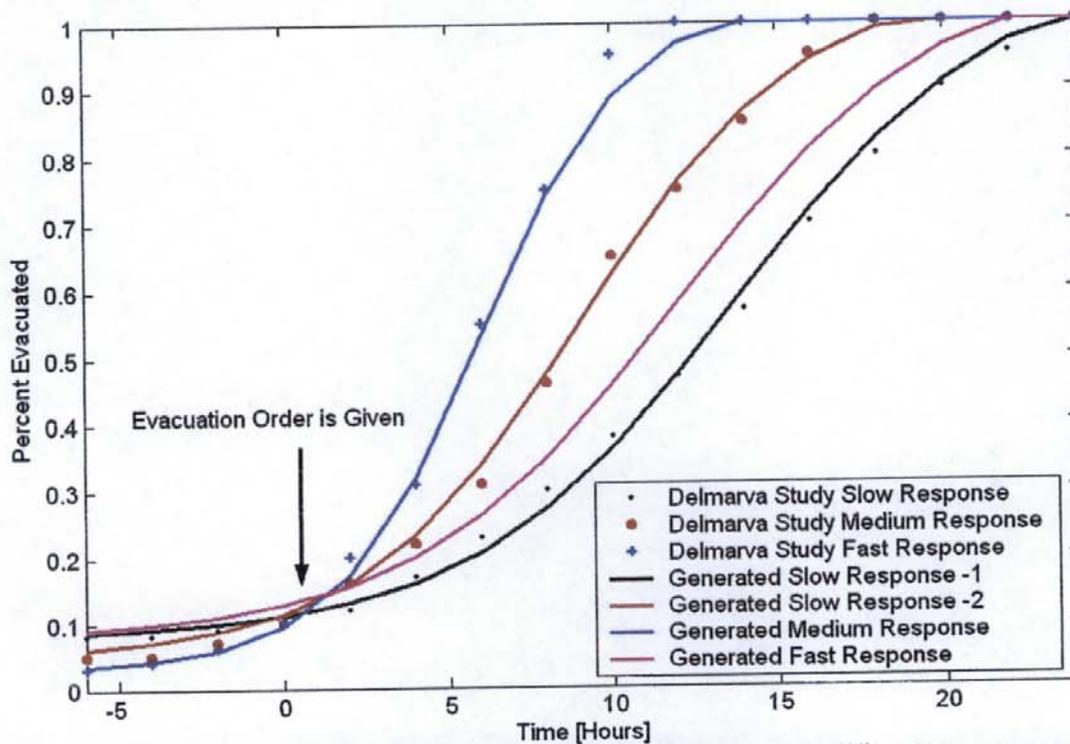
For the Cape May study, Delmarva study<sup>(41)</sup> curves obtained from the surveys are reproduced by substituting different " $\alpha$ " and "H" values in the S-curve formula. As mentioned before, among other studies, Delmarva study is the most relevant one for Cape May because of similarity of the two regions. Table 10 shows the values that can be used for demand generation curves. Figure 199 shows the similarity between Delmarva survey based data and S curve reproduction of the data. H value for slow response data is given with 2 alternatives. H value of 12 hours is theoretically more valid since it gives 24 hours of total evacuation time. However, H value of 13.7 hours gives better fit for Delmarva study. H value of 12 hours is recommended for the Cape May study since Cape May does not have to have a one-to-one correspondence with Delmarva study. Besides 12 hours of half loading time is more reasonable in terms of the project requirements.

Regarding the shadow traffic, assuming an initial value of zero is also possible. However for this study, state-of-practice is followed and use of shadow traffic is recommended for the Cape May study. Consequently, about 10% of demand is already loaded onto the network before the evacuation order is given, which is also a widely used assumption in all other previous studies <sup>(See references,3,4,5,6,7 and 8)</sup> Although there is no consensus about tourist behavior during evacuations, these curves are assumed to be valid for tourist or vacationer evacuations as well. This follows the assumptions made in Delvarma study.

**Table 10. S-curve parameters for network loading**

PARAMETERS	Slow	Medium	Fast
INITIAL VALUE	0.08	0.05	0.03
$\alpha$	0.25	0.3	0.45
H	12 (13.7*)	9	6

This H value fits Delmarva Study better but theoretically gives total evacuation time more than 24 hours



**Figure 19. Approximate Delmarva evacuation study <sup>(41)</sup> values and generated s-Curve values**

# APPENDIX C: HURRICANE EVACUATION STUDY (HES) MAP OF CAPE MAY COUNTY, NEW JERSEY

