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Hurricane Evacuation Modeling Package

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13. Abstract
The Hurricane Evacuation Modeling Package (HEMP) is a computer-based software package that estimates the time-dependent evacuation behavior of households facing an oncoming hurricane. With the exception of the evacuation network, the package operates entirely on data available from official sources and uses models that have been estimated from observed evacuation behavior in past hurricanes. In the package, population is synthesized from census data, storm data is downloaded from the National Hurricane Center, and evacuation behavior is predicted in terms of the number of households evacuating in each 6-hour period, their destination, mode of travel, type of refuge, route, and the resulting traffic flow on the network. A user specifies a past or current storm to be analyzed, the area to be evacuated, if and when evacuation orders and/or contraflow are to be implemented, and the package estimates the consequences of the scenario in terms of average travel time, delay, speed, and degree of migration in each time period.

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Abstract

The Hurricane Evacuation Modeling Package (HEMP) is a computer-based software package that estimates the time-dependent evacuation behavior of households facing an oncoming hurricane. With the exception of the evacuation network, the package operates entirely on data available from official sources and uses models that have been estimated from observed evacuation behavior in past hurricanes. In the package, population is synthesized from census data, storm data is downloaded from the National Hurricane Center, and evacuation behavior is predicted in terms of the number of households evacuating in each 6-hour period, their destination, mode of travel, type of refuge, route, and the resulting traffic flow on the network. A user specifies a past or current storm to be analyzed, the area to be evacuated, if and when evacuation orders and/or contraflow are to be implemented, and the package estimates the consequences of the scenario in terms of average travel time, delay, speed, and degree of migration in each time period.

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The contribution of Jay Baker, Ph.D., in providing the data on which several models in this package were estimated, is gratefully acknowledged. The New York City Emergency Management Department also provided data on Hurricane Sandy that was combined with other data used in the estimation of individual models in this study. Their willingness to share the data is appreciated.

Implementation Statement

The computer package developed in this project must first be tested and validated as providing reliable transportation estimates before it is dispensed to other users. The testing and validation are essential to ensuring the models are functioning correctly and producing plausible results in different situations.

In the initial implementation of the package, it must first be applied to past hurricanes in the New Orleans area because input data from this study is readily available to test how well the model replicates observed behavior when actual management decisions from the past are fed into the package. The initial runs of the package should also measure how long it takes to analyze individual scenarios, whether using computer clusters is feasible, and if internal programming of the package could be streamlined to achieve more rapid turnaround times. When individual scenarios can be analyzed within a few hours, the package should be applied in real time as an actual storm approaches the New Orleans area. Emergency managers and DOTD officials should assess the contribution the package makes in developing sound evacuation decisions.

While the prime role of the modeling package is ultimately as an operational model applied in real time, the package can also be used as a planning tool by entering data on hypothetical storms and testing different management plans and strategies. It can be applied at any time in this manner and will allow the analysis of more management scenarios than is possible in a real-time application. In this role, it can be used to build a repository of preferred management scenarios for different storms while also providing users with a convenient means of becoming familiar with the software and its application.

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Introduction

Emergency managers must make important decisions as a hurricane approaches. Whether to issue an evacuation order, and when to issue it, has been the main concern of emergency managers in the past. However, there are other decisions that they need to make as well, such as if and when to implement contraflow and whether to use staged evacuation, that also can have serious consequences with respect to the safety of the people in their parish. Being able to estimate the consequences of alternative decision strategies in advance would be very helpful to emergency managers. The model described in this report is aimed at ultimately achieving that goal.

In the last 20 years, LTRC has developed time-dependent models that are responsive to discretionary decisions by emergency managers such as those mentioned in the previous paragraph as well as non-discretionary factors influencing evacuation behavior such as the characteristics of the storm, population, land use, and transportation system of the area. As a result, the LTRC models allow factors such as the strength of the storm, its current position and projected path, time of day, land use, population characteristics, network conditions, and management decisions to play a role in estimating evacuation behavior. Emergency managers can test the impact of alternative management decisions amidst all the other influencing factors.

Unfortunately, the LTRC hurricane evacuation models operated entirely independently until the launching of this project to develop the Hurricane Evacuation Modeling Package (HEMP). The objective is to integrate the models in a single, user-friendly package that will facilitate and simplify use of the models.

Literature Review

Research into hurricane evacuation behavior before the 1970s revolved around social issues with primary involvement of sociologists and other behavioral scientists. Transportation engineers first got involved in modeling evacuation traffic following the Three Mile Island nuclear accident in 1973. The emphasis in that case was in modeling evacuation traffic through a network. While there was a flurry of activity in network modeling following the Three Mile Island event, interest waned over the ensuing decades until Hurricane Floyd struck North Carolina in 1999. It generated evacuation travel times of 10-20 hours. As motorists stood stationary on congested highways and observed virtually empty opposing lanes, the obvious benefit of instituting contraflow to harness spare capacity in an emergency was recognized. This initiated greater involvement of engineers in evacuation planning and operation, and their involvement has continued to grow since that period as manifested by the increase in publications, conferences, funding, and committees dedicated to the topic in engineering circles.

One of the areas that transportation engineers began to get involved in was modeling evacuation. As mentioned above, there was a time in the 1970s when engineers concerned themselves with modeling the flow of evacuation traffic through a network, but little effort was given to modeling other aspects of evacuation behavior, particularly evacuation demand. This was probably due to the fact that in a nuclear disaster, which was the emergency considered at the time, all residents can reasonably be expected to evacuate so demand is easily estimated from the population. However, in the case of hurricanes, the threat level varies over time and some households are more vulnerable than others. Thus, the volume and timing of hurricane evacuation demand can vary greatly depending on the perception of personal vulnerability as influenced by announcements from emergency managers, the media, and neighbors. However, current models are generally not sensitive to all these factors, especially in a dynamic sense.

Early work in the area of hurricane evacuation modeling involved following the urban transportation planning four-step paradigm. One of the packages following this approach was ETIS (Evacuation Traffic Information System) developed for the FHWA by the consulting firm Post, Buckley, Schuh, and Jernigan (PBS&J) [1]. ETIS is a web- and GIS-based travel demand forecasting model, estimating major traffic flows and levels of congestion. The model allows a user to input the category of a hurricane, expected participation rate, tourist occupancy, and destination percentages for each parish to produce estimates of congestion levels on major highways, tables of expected vehicles crossing state lines by direction, numbers of vehicles generated by each parish traveling to specific inland locations, and so on. The model operates on a large number of default values based on traffic data from past hurricane evacuation studies and users are not encouraged to change these values without sufficient justification.

Another early evacuation modeling package, DYNEV (Dynamic Network Evacuation), was first developed by KLD Associates, Inc., in the 1980s. In the DYNEV model, the road network is represented as a series of links connected at nodes representing the intersection of these segments. The main inputs to the model include: 1) the topology of the network; 2) the geometry of each link; 3) the trips to be loaded onto each link of the network; and 4) the circulation of traffic through the network. The model produces detailed output in both graphical and tabular form on the operational performance of each link on each route. The type of information provided includes: 1) speed of evacuating vehicles; 2) density of traffic stream; and 3) volume on each link.

I-DYNEV provided improved operational characteristics to DYNEV. I-DYNEV consists of three distinctive models: 1) a macroscopic, deterministic traffic simulation model; 2) an equilibrium traffic assignment model; and 3) an intersection approach traffic capacity model [2]. The models are applicable to a general system of roads including freeways with access control, rural roads, and urban arterials. The types of traffic control used in the model include traffic signals, stop and yield signs, and no control. It estimates evacuation travel time, moving time, delay time, mean speed, and so on. The I-DYNEV model differs from DYNEV in the way it computes the number of vehicles leaving a roadway segment. The improved computational efficiency serves to substantially reduce the computing time and storage. A trip generation model or trip distribution model is not incorporated into DYNEV or I-DYNEV. An assessment of I-DYNEV in estimating evacuation flows has shown that it replicates observed flows adequately [3].

Another model that has been used for hurricane emergencies is the Oak Ridge Evacuation Modeling System (OREMS). This microcomputer-based system was developed by the Center for Transportation Analysis at the Oak Ridge National Laboratory (ORNL) to simulate the traffic conditions over a highway network as evacuation progresses [4]. It is an integrated system consisting of three major components: a data input manager, a traffic simulation model, and an output data display manager. The analytical core of OREMS is a FORTRAN program, ESIM (Evacuation SIMulation), which combines the trip distribution and traffic assignment submodel with a detailed traffic flow simulation submodel. The combined trip distribution and traffic assignment submodel was developed by the researchers at ORNL, and the traffic simulation model was derived primarily from the TRAF simulation system developed by FHWA. Therefore, it has many similarities to that system. The combined algorithm of trip distribution and trip assignment expands the original network by introducing super-destination nodes and adding a set of pseudo-links, which connect the super-destination nodes to the original destination nodes. Each super-destination node is connected to a subset of destination nodes. These subsets of destination nodes are designed in such a way that the flow needs to be assigned from any origin to a single super-destination node. The algorithm then solves the problem by using the assignment model on the expanded network. The flows on the expanded network are converted into flows on the original network by deleting the super-destinations and the pseudo-links.

Given evacuation travel demand, the ESIM program in OREMS determines the destinations selected by evacuees and the routes taken to reach the selected destinations through traffic distribution and assignment. It then performs a detailed simulation of vehicular traffic operations on the evacuation network given these projected flows and routes under prevailing roadway and traffic conditions. The model can identify evacuation routes, estimate service rates in the evacuation network by location and by time, identify traffic operational characteristics and bottlenecks, estimate evacuation times across various categories (link, sector, or region-specific estimates by time), and provide information on other elements of an evacuation plan. It also allows the analyst to experiment with alternative routes and destinations, various alternative traffic control and management strategies, and different evacuee participation rates [4].

The transportation planning package TRANSIMS was developed in the 1990s at Los Alamos National Laboratory to replace urban transportation planning packages based on the four-step process. TRANSIMS is a microsimulation package that simulates the movement of each individual in a study area on a second by second basis. As a result, it requires considerable computer power and is generally not easy to operate. It has not had widespread application, so the FHWA funded a unit within Argonne National Laboratory dedicated to promoting use of the package. The FHWA funded several trial applications of the model package. One such funded effort was at LSU, where the use of TRANSIMS was used to model evacuation traffic in Louisiana. As in other applications, results have been obtained but the use of the package has been shown to be difficult to operate.

A recently-developed emergency evacuation modeling package called the Real Time Evacuation Planning Model (RtePM) was developed for the Department of Homeland Security by the Applied Physics Laboratory at Princeton University. It is a GIS-based system using NavTeq highway information and census population data in a free web-based computer package. It allows a user to draw a polygon around any area and request the clearance time for people in that area. Depending on the size and population of the area, computer simulation runs take between minutes and hours; an area of 1.6 million people in the Galveston/Houston area in which 922,000 people were estimated to evacuate, took just under 2 hours on a computer to complete. The model estimates link flows and illustrates them dynamically using a color thematic on a GIS network. Currently, it estimates private vehicle evacuation flows only and the second phase of its development geared to providing real-time operational assistance to emergency managers was suspended.

A package that is quite unique in that it is aimed at providing operational assistance to emergency managers is HURREVAC. It is a package which all emergency managers are trained to operate and it provides storm information in real time. It provides on-land wind speeds, flooding estimates, storm predictions, and from the transportation component of the package, an estimate of clearance time. It operates on data from the National Hurricane Center and is used in Emergency Operation Centers in real time during the approach of a hurricane. It provides rich weather and storm prediction information but the transportation component provides estimates of clearance time only, making the transportation information the weaker part of the package. A recent version of the software is web based and known as HVX-HURREVAC. HURREVAC use is restricted to emergency personnel.

From the above review the following conclusions are drawn:

1) Most of the computer software models developed so far are focused on the assignment of given traffic demand, the simulation of traffic operations on the road network, and the estimation of evacuation clearance time. The estimation of evacuation demand has received relatively little attention in the evacuation modeling packages developed so far.

2) While most of the more recently developed evacuation modeling packages do accommodate the dynamics of evacuation travel, they assume that dynamic evacuation demand is available from elsewhere. As a result, dynamic evacuation demand must be input to these packages.

3) Most packages are not easy to operate.
4) With the exception of HURREVAC, all other evacuation modeling packages are planning packages that do not provide real-time operational information that can help emergency managers make informed decisions during the onset of a hurricane. That is, most existing evacuation modeling packages allow estimation of evacuation behavior to hypothetical storms under stipulated conditions at any time rather than real-time estimates of an actual storm.

Objective

The overall objective of this study is to incorporate the LTRC hurricane evacuation models and the data on which they operate into a single, user-friendly computer package. The intention is that the program will provide emergency managers with a convenient means of estimating the consequences of alternative management decisions before they need to make them, thereby providing the opportunity to identify and implement the best evacuation decisions.

The specific objectives of this research are to:

1. Integrate the individual models developed by LTRC into a single, automated, user-friendly hurricane evacuation demand estimation package.
2. Translate estimates of hurricane evacuation demand into statistics that emergency managers will find useful in making informed management decisions during the onset of a hurricane.
3. Demonstrate use of the package in an application in the New Orleans metropolitan area.

Scope

The scope of this project is to develop a working software package whose operation is demonstrated in an application to the New Orleans area. The emphasis is on establishing a working version of the package, recognizing that it is likely to require improvement and upgrading as it is run and tested. It is also likely to require extensions to its current capabilities as new requirements are identified.

While applied in the New Orleans area in this study, HEMP can be applied in any area where the model parameters are valid and data on the application area is provided. The default model parameter values in the package are based on data from past hurricanes in Louisiana, South Carolina, and New York. The default values can be altered if required.

Beside the possible need to re-estimate the model parameter values for HEMP as mentioned in the previous paragraph, the application of HEMP does not require survey data; it operates entirely on secondary data from the national census and other official or commercial sources. One of the most demanding input requirements is obtaining detailed information of the evacuation network. All physical, operational, and regulatory features of the network must be provided to allow realistic simulation of traffic flow to be achieved.

Methodology

Background

The first studies into evacuation demand modeling at LTRC involved determining whether the four-step modeling paradigm used in urban transportation modeling would be applicable to evacuation demand modeling. The first study investigated the use of logistic regression and neural networks as trip generation models. This showed that the logistic regression and neural network models estimated the number of evacuees with equal accuracy, and with greater accuracy than that achievable with the use of the participation rate model commonly used in evacuation modeling [5] [6].

Trip distribution of evacuation trips were first modeled using the Gravity Model, the model most commonly used in urban transportation planning to model trip distribution [7]. In a subsequent study, an Intervening Opportunity Model (IOM) was tested [8]. A modification was made to the IOM where the path of the hurricane was allowed to influence destination choice. The IOM performed similarly to the Gravity Model and the modified IOM produced marginally better results than the standard IOM.

On trip assignment, a comparison was made between static and dynamic traffic assignment of evacuating traffic [9]. As expected, dynamic traffic assignment produced realistic results that were close to observed values and showed that errors in clearance time estimates could result from using static traffic assignment in estimating link flows.

Overall, models used in the traditional four-step travel demand estimation process were found to work reasonably well in estimating hurricane evacuation demand, but there were areas of poor compatibility. Areas of poor compatibility were:

1. The dynamic aspect of travel is largely neglected in urban transportation planning models, whereas it is of vital importance in hurricane evacuation modeling. The daily fluctuation in travel demand follows a relatively regular pattern in urban transportation travel so that urban traffic volumes at different times of the day can be inferred from daily flows with relative accuracy. However, evacuation travel is highly dependent on the nature of the incident, the time of day when it occurs, and the public's perception of risk, making traffic flows resulting from each incident different in magnitude and time dispersion.

2. In urban transportation planning, travelers making the same trip each day have the opportunity to identify routes of minimum impedance by experimenting with alternative routes each day. If all travelers seek out their minimum impedance path in this manner, an equilibrium condition is established in which each driver cannot reduce their travel time by taking an alternate route. Thus, user equilibrium is an appropriate paradigm for traffic assignment in a day-to-day urban setting. However, in evacuation, the trip is an irregular event in which there is no opportunity to test alternative routes to determine which one provides the minimum travel time. Thus, user equilibrium trip assignment is not a good paradigm of trip assignment for evacuation trips.
3. The conditions described in 1 and 2 above, namely the static treatment of travel and user equilibrium trip assignment, result in static user equilibrium assignment used in urban transportation planning not being an appropriate trip assignment technique for hurricane evacuation demand modeling. Dynamic trip assignment can be applied to address the need for dynamic traffic conditions, but recognizing that travel time is generally unknown in an evacuation environment, the factors that do influence route choice in an evacuation, need to be incorporated into an evacuation route choice decision.
4. In urban transportation planning, trips are distinguished by trip purpose because they are dependent on different variables and have different trip length frequency distributions. In evacuation modeling there is only purpose (evacuation), but trips differ in their characteristics by destination type (i.e., whether they are evacuating to the home of friends/relatives, to a hotel/motel, public shelter, or another place of refuge). This is because trips to each destination type are dependent on different variables and trip lengths are different for each destination type.
5. With regard to data collection, urban travel in a particular area can be captured through a travel survey at virtually any time. On the other hand, hurricanes are relatively rare events making a travel survey of evacuation behavior at a particular location more difficult to obtain.

These “shortcomings” of conventional demand models in being able to estimate hurricane evacuation demand reliably, prompted development of models that overcame the shortcomings as much as possible. First, the dynamic nature of evacuation demand was addressed by investigating several model forms that allowed the estimation of not only whether a household would evacuate, but when they would do so if they decided to evacuate. First, Survival Analysis was tested as a model form where survival was the period up to the time of departure [10]. Households that did not evacuate at all represented censored observations. After testing this method, it was abandoned in preference to other approaches.

An alternative approach involved the use of a binary logit model to model the decision to evacuate or not in any time period based on prevailing conditions. With the assumption that decisions among time periods are independent of each other, the decision to evacuate in a particular time period is the product of the probability of evacuating in the present time period multiplied by the probability of not evacuating in all earlier time periods. This model was named the sequential logit model and was found to perform better than the Survival Analysis model in predicting "if and when" a household would evacuate [10] [11] [12]. The model is sensitive to time-dependent storm conditions (storm intensity, distance to the storm, forward speed), time of day, household characteristics (whether home is in an area susceptible to storm surge or not, type of home structure), and time-dependent decisions made by emergency managers regarding evacuation (i.e., type and timing of evacuation orders).

In the development of the model, time was discretized into 2-hour or 6-hour periods and the model was made to predict whether a household would evacuate in each time period or not depending on the conditions prevailing at that time. The model has been used by other researchers in urban applications [13] [14] and was also used in the regional simulation of evacuation traffic in the Gulf coast region between New Orleans and Houston as part of a Department of Homeland Security study [15] .

The development of time-dependent demand models require time-dependent data on which they can be calibrated. In general, surveys of hurricane evacuation behavior in the past have not captured time-dependent data. In order to obtain this information, external sources of dynamic information related to the storm and administrative actions were accessed, and added to the data. Dynamic storm information was gathered from NOAA's National Hurricane Center website while information on administrative actions (e.g., issuing of evacuation orders) was gathered either directly from emergency managers or from media reports.

The sequential logit evacuation demand model was later improved by relaxing the assumption of independence of evacuation decisions among time periods. This allows expected future conditions to influence current decisions [16]. This involved development of a nested logit sequential logit model.

The next development that took place in LTRC research on hurricane evacuation modeling was the development of a time-dependent destination choice model which takes time-dependent evacuation trips by destination type and estimates their destination. It operates at individual household level and estimates where each evacuating household will travel to in each time period. In the model, destination choice is made a function of the prevailing congestion on the network, the remaining accommodation in each destination zone, the predicted path of the hurricane, similarity in ethnicity between origin and destination zones, and whether the destination is a major metropolitan area or not [17] [18] [19]. Different models have been estimated for each destination type. Models omitting the variable describing the prevailing congestion on the network, were also estimated [17].

Of the three data sets available to researchers in 2010 (data from Hurricane Floyd in South Carolina, Andrew in south-central Louisiana, and Gustav in south-eastern Louisiana) there was sufficient data to estimate models for friends/relatives and hotel/motel destination types only. All the evacuating trips were assumed to take place by private vehicle and average vehicle occupancy values during evacuation were used to convert household trips to vehicle trips. Trips to family/friends or to hotels/motels were predominantly by private vehicle in the data so this assumption was not expected to result in significant error at the time. However, in 2017 a joint mode/destination type choice model was developed that estimates mode choice and destination type of evacuating trips [20] . The model predicts what destination type each evacuating household will choose and, given the type of destination chosen, what mode will be chosen. The output from the model serves as input to the destination choice model for the friends/relatives and hotel/motel destination types mentioned above, and new destination choice models were developed for shelters and "other" destination types. For shelters, destinations were chosen based on which shelters were closest and availability of space in the shelter. "Other" destination types were distributed equally to all destinations because of their very varied nature.

The preceding three types of models are applied in sequence produce time-dependent origin-destination (O-D) tables of household evacuations by mode. Households evacuating by private vehicle are converted to vehicle trips using standard rates of the number of vehicles used per evacuating household. Those evacuating by transit are converted to equivalent passenger cars by using a standard number of households per transit vehicle. Then, transit vehicles are converted to passenger cars by using the passenger car equivalent of a transit vehicle. The passenger car estimates for each destination type are summed to produce time-dependent passenger car O-D tables. These serve as input to a dynamic traffic assignment procedure to produce estimates of dynamic traffic flows on the evacuation network.

Route choice principles used in dynamic traffic assignment routines typically use minimum travel time as the criterion determining route choice. However, as noted earlier, travel time on alternative evacuation routes is not likely to be known during the evacuation process. In response to this situation, a study was conducted at LTRC where additional factors such as the familiarity of the route to the person making the route decision, the availability of services on the route (e.g., gas stations, rest areas), safety from wind and flooding, and facility class were investigated as playing a role in the evacuation route choice decision. Using data from Hurricane Gustav, it was determined that accessibility to the evacuation route, facility class, travel distance, and "perceived" service availability (product of familiarity with the route and the actual availability of services on it) were significant factors affecting route choice. The research showed that evacuees prefer freeways over other highways to evacuate, and they prefer routes with which they are familiar, have services, are accessible, and provide the shortest distance between origin and destination.

The four models described above collectively provide estimates of dynamic evacuation demand that is sensitive to storm, household, destination, operational, and network conditions. Some of these conditions are beyond human control while others such as the type and timing of evacuation orders, introduction of staged evacuation, initiation and termination of contraflow, and closing of individual links on the network are within the power of emergency managers to alter. Thus, the models can be used to estimate the impact of different hurricanes and other imposed fixed conditions, and then determine what administrative or operational actions could be taken to allow optimum evacuation to occur given the circumstances of the storm. A library of optimal strategies for different storms and local conditions could be compiled to serve as a repository of evacuation plans that could be drawn from as a hurricane approaches and its features are identified.

At this stage it is not known how generalizable the results from these studies are. That is, how accurately can these models estimate evacuation behavior when presented with different storms or in different locations to that in which they were estimated? Models estimated on Floyd data from South Carolina have been applied in Louisiana on Andrew data, and models estimated on Gustav data in New Orleans have been applied to Hurricane Georges data in the same city. The results of the transfer of the Floyd model to Hurricane Andrew data are shown in Figure 1. The transferred model reproduces a similar evacuation pattern but underestimates the number of evacuees by 20 percent (51 evacuating households instead of 64).

Figure 1. Application of Floyd model to Hurricane Andrew data

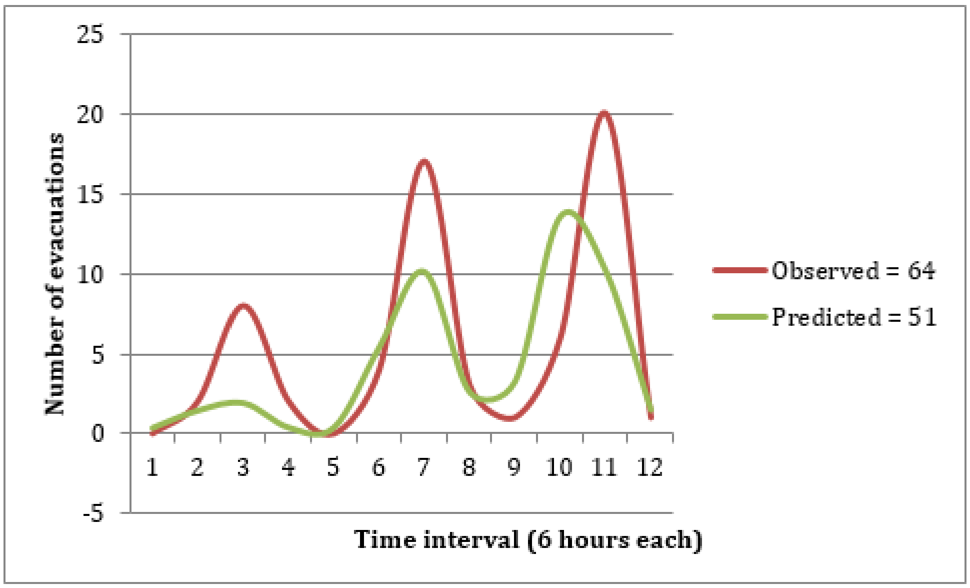
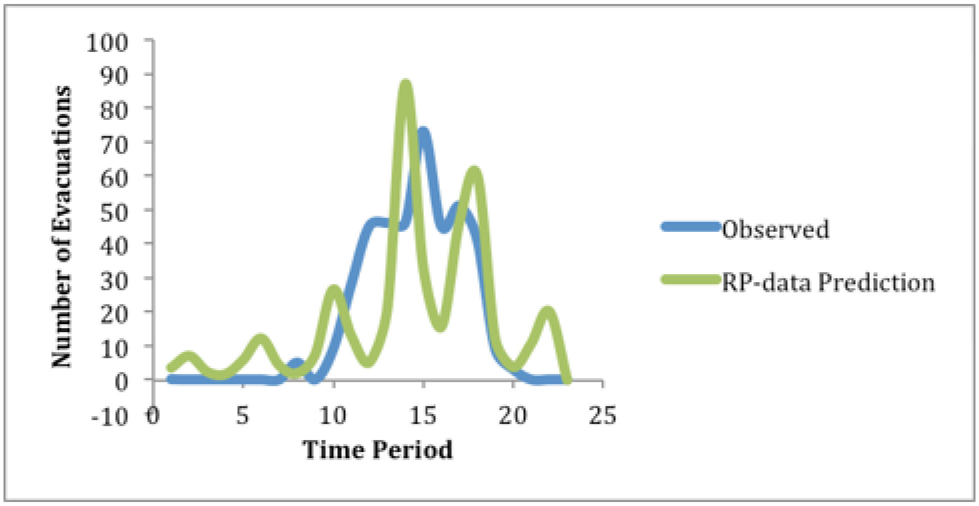


Figure 2. Gustav model applied to Hurricane Georges data



The model estimated on Gustav data in New Orleans and applied to Hurricane Georges data in the same city is shown in Figure 2. The time periods in Figure 2 are 6-hour periods indicating that evacuation occurred over approximately 60 hours between time periods 10 and 20. During this period, a relatively sustained evacuation rate occurred but the model predicted diurnal fluctuations that are typical in most evacuations. The transferred model underestimated evacuation during Hurricane Georges by approximately 14 percent (239 instead of 278).

Taken together, these two cases of model transfer suggest that there is some level of transferability of models between locations, but the transfer is not good. However, these two cases are too few to draw a conclusion on the transferability of the hurricane evacuation demand models tested here.

One of the concerns with urban transportation planning practice as it relates to hurricane evacuation modeling is that travel surveys are typically conducted post-event and rely on recall to collect information. With hurricanes, it is usually months or years after a hurricane has occurred that a survey can be conducted. This makes recall of detail and time-dependent information difficult for survey respondents to perform accurately. As a result, past surveys have not collected much dynamic information. To address this problem, a new method of data collection was developed at LTRC. The method involved the use of stated choice (i.e., where respondents are presented with a hypothetical case and asked what their response would be) applied sequentially to a discrete set of "snapshots" of an approaching hurricane and asked what their behavior would be in each time interval [21] [22]. That is, respondents were presented with a number of hypothetical hurricanes, each presented in a sequence of time-dependent scenarios describing prevailing storm conditions and the administrative decisions made by emergency managers at each time interval as the storm approached. Respondents were presented with the prevailing and forecast conditions in each scenario and then asked whether they would evacuate or not. If they elected to evacuate, information was gathered on when they would elect to leave, where they would go, how they would make the trip, what route they would choose, etc. The time-dependent scenarios were presented audio-visually in a DVD with graphical displays to maximize realism of the scenario.

The time-dependent, audio-visual stated choice survey described above was conducted in 2009 in New Orleans together with a parallel post-event revealed preference survey of evacuation behavior during Hurricane Gustav. One of the 9 hypothetical storms included in the stated choice survey was Hurricane Gustav although this information was not revealed to participants in the survey. This allowed comparison between stated choice and revealed choice on the same storm as one of the ways in which the integrity of the new method was assessed. Another means of assessment was to build models on the stated choice and revealed preference data sets individually and compare the results. The stated choice method produced acceptable results in that the responses between the stated choice and revealed preference surveys were similar but the model estimated on the stated choice data was not as good as that on the revealed preference data. The stated choice data collection effort cost 25 percent more than that of the conventional data collection, although at least part of the reason for the higher cost was due to the fact that the method was new while the revealed preference method was familiar to those conducting the survey.

A study was conducted at LTRC in 2004 to develop a method to delineate hurricane evacuation zones in a systematic, structured manner [23]. It was conducted in response to the absence of guidelines on how to establish hurricane evacuation zones, and the importance of being able to distinguish which residents need to evacuate and which do not. Identifying which households do not need to evacuate is very important since they needlessly add to the congestion on evacuation routes and increase evacuation times.

Eliminating them from the evacuation stream could be one of the most efficient means of improving evacuation performance.

The method developed to establish hurricane evacuation zones distinguishes hurricane evacuation zones on the basis of elevation, flood potential, and recognizable areas (using ZIP codes, major roads, and landmarks). The total area to be divided into hurricane evacuation zones is established by determining maximum flood limits using surge prediction models such as SLOSH or ADCIRC. The area within the flood limits is then subdivided by ZIP code, uninhabited areas are subtracted, and the remaining areas further subdivided by main roads. The elevation of the subdivided areas are then determined using local LIDAR (Light Detection And Ranging) data (if available) or digital elevation data obtainable from USGS for all areas within the continental United States. Small zones of similar elevation are merged and population in each zone established from census data using overlay principles available in GIS. The whole process was automated on a GIS platform (TransCAD) to facilitate application and its use was demonstrated in establishing hurricane evacuation zones for the North Shore of New Orleans [24].

In summary, research conducted on hurricane evacuation modeling at LTRC has involved investigation of the suitability of conventional urban transportation demand estimation models in hurricane evacuation modeling, the development of models that overcome the shortcomings of conventional urban transportation models in modeling hurricane evacuation demand, the development of a new data collection process that allows the collection of time-dependent stated choice data, and a procedure that establishes hurricane evacuation zones which helps prevent unnecessary evacuation by ensuring only those households that need to evacuate are instructed to do so.

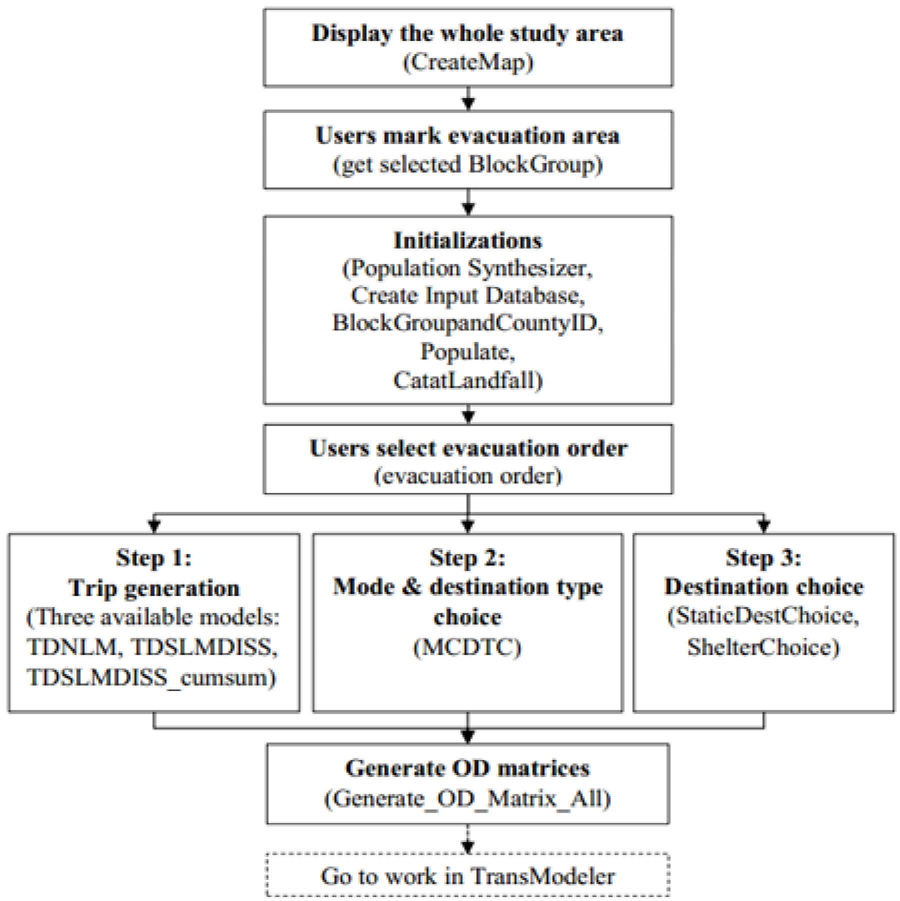
Structure of HEMP

Overall Structure

HEMP is an integrated set of pre-calibrated models that operate in a similar sequence in the four-step urban transportation planning process. It uses the software packages TransCAD and TransModeler as platforms on which the models are applied. Figure 3 and Figure 4 describe the overall structure of HEMP, with Figure 3 showing the operations conducted in TransCAD and Figure 4 showing the operations conducted in TransModeler. TransCAD feeds time-dependent OD matrices to TransModeler for traffic simulation.

Bold text in the two figures describe the function of each module; plain text in parentheses shows the names of associated macros achieving the explained function.

Figure 3. Operations in TransCAD

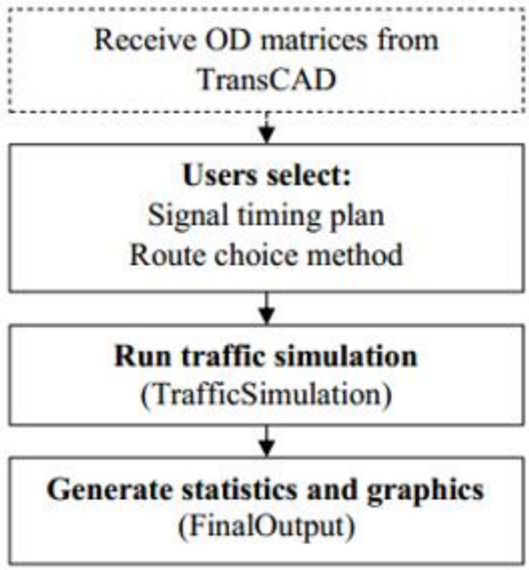


In the first block in Figure 3, the user is introduced to the program and a map of the whole study area is shown on the screen. In the second block, the area to be evacuated is established by the user. Evacuation areas are established by either pointing to individual census block groups, creating a circle of multiple block groups, or creating a polygon by repeated clicks of the mouse to create a closed area in which all block groups within the area are selected. In the third block, a synthetic population is generated for the block groups within the evacuation area(s) and other required data (such as storm data and zonal data) are then also attached to the database - details of how this is accomplished is described in greater detail in the section on Input Data. In the fourth box the user specifies if and when an evacuation order is to be issued in each parish in the selected evacuation area. Thus, staged evacuation is possible by invoking evacuation orders at different times in individual parishes. Selective evacuation is applied by issuing evacuation orders to areas that are at risk and not to those who are not.The next three boxes include activities similar to the first three steps in the classic four-step modeling paradigm: trip generation, mode choice, and trip distribution. These models estimate travel demand for each time interval to produce time-dependent OD matrices to serve as input to traffic simulation in TransModeler.

Figure 4 shows the activities conducted in TransModeler within the HEMP package. Users select a signal timing plan (including current settings or flashing yellow/flashing red) and a route choice method (shortest path or route choice based on multiple factors). Traffic simulation is then run based on the users' specification and the previously generated OD matrices for each time interval. Statistics and graphics are generated after all simulation runs are completed and they are reviewed to assess the performance of the transportation system under the chosen scenario.

HEMP is constructed in modular form with each model or operation in the package forming an individual module. To the extent that the modules are interdependent, information is transmitted between the modules. Therefore, output from some modules serve as input to subsequent modules. The most significant example of this is where a batch of time-dependent OD matrices generated by the modules in TransCAD are fed into TransModeler for traffic simulation.

Figure 4. Operations in TransModeler



Computer Package Platform

The computer package developed in this study was required to provide a user interface, visualization of output, and incorporation of mathematical models that estimate evacuation demand. Furthermore, it was also required that the package perform dynamic traffic simulation. However, because demand estimation and traffic simulation are two fundamentally different operations, no single computer package is available that can accomplish both objectives effectively and seamlessly. Thus, based on the experience of the researchers in using TransCAD, its ability to generate a synthetic population, and prior experience in customizing models in TransCAD, the decision was made to use TransCAD to host the evacuation demand portion of HEMP. However, a clear winner did not emerge for traffic simulation portion of the package and therefore further investigation was conducted with the aim of identifying the most suitable simulation package.

There are a variety of traffic simulation software packages available in the market. A few candidates are Vissim, Paramics, SUMO, AimSUM, Transims, and TransModeler. We evaluated four of the most relevant simulation packages for our purpose on ten characteristics as shown in Table 1.

Table 1. Characteristics of different simulation packages

Characteristics	Software Package			
	Transims	Vissim	Paramics	TransModeler
Open source	yes	no	no	no
Cost	low	medium	medium	high
Technical support	no	yes		yes
Handle large networks	yes	no		yes
Portability	yes	no		no
Documentation	no	yes		yes
Ease of use	no	yes		yes
Ease of creating networks	no	yes		yes
Low processing	yes	yes		yes
Integrate with TransCAD	no	no	no	yes

As can be seen from the table, each simulation package has its own advantages and disadvantages. Transims, an open source and free package, has the advantage of being able to be deployed on high performance computers. However, at the same time, the package lacks technical support and a proper user interface. Vissim, while desirable for most of its features, lacks the ability to integrate well with TransCAD. TransModeler, while not open source or inexpensive, scores high on features such as technical support and its ability to integrate well with TransCAD. After evaluating all the software packages, the decision was made to use TransModeler for traffic simulation purposes.

User Interface

The user interface is an integral part of any stand-alone application. It allows users to interact with the program without the need to know the internal workings of the code. It forms an entryway to the rest of the program. Visual Studio IDE was used to integrate different programming languages, such as C# and GISDK, into a single program. Windows Forms, which uses C# language, was used to create the initial user interface and to display output from the program. This included the welcome page, downloading of storm information, identifying areas to be issued evacuation orders, communicating with TransCAD to generate demand, user input for signal settings and route choice, and running the simulation in TransModeler. The user defines the scenario to be analyzed through the user interface by specifying, for example, the area to be evacuated and the timing of evacuation orders issued to individual parishes. The user interface is also the portal through which output is presented to the user.

Output

Output is generated after all traffic simulation runs are completed in TransModeler. Some output includes statistics of the entire evacuation process while other output reflects conditions in each time interval as evacuation progresses. Some statistics are generated for the whole evacuation area selected by the user while other statistics are generated at block group level and projected to maps for visual presentation. More detail on the output produced by HEMP is described in a later section.

Input

The conceptual design and extent of the data needed as input was dictated by the models required to implement the evacuation demand system developed at LTRC. As outlined previously, the demand system implementation needs input data for four models. The first model that predicts when and if a household evacuates, needs both household characteristics and storm related data. The second model predicts the type of destination (home of friends/relatives, hotel/motel, shelter, or other) and mode choice (car, riding with others, transit, or other) and requires input information on household characteristics as well as the characteristics of the zone in which the household resides. The third model predicts the share of evacuees going to different geographic locations or cities and requires input on the characteristics of potential destination zones and the network that provides access to them. The fourth model predicts the route choice of evacuating households and requires information on the network such as services available, functional class, average daily traffic, and whether individual routes to each destination are in the predicted path of the storm or not.

The application of the first model needs time-dependent data. To accommodate this need, data is organized into rows and columns where each row contains information on a household for a specific time period and each column is information on a characteristic of that household for that time period. Based on the number of time periods used in the model, each household has that number of rows of information. For example, if the demand model is applied over 23 time periods, then each household has 23 rows of data in the database. The number of columns depends on the variables required by all the models. Some variables, such as the household characteristics of a household, are static and remain the same over all time periods. Others, such as the features of the hurricane, are time-dependent and change from one time period to the other. Some variables in the database appear at a disaggregate level (e.g., characteristics of the household), while others are needed at various levels of aggregation (census block group, evacuation area, parish, or metropolitan area) as described later.

Table 2 below shows the variables included in the database necessary to apply the Time-Dependent Sequential Logit Model (TDSLM). The data is obtained from the synthesized population, storm and surge data from the National Hurricane Center, census data for zonal characteristics at the block group level, and information provided by the user on the scenario to be tested in terms of if, when, and where evacuation orders are to be issued. All input data are either synthesized for the area or obtained from official sources thereby eliminating the need for travel surveys in the application of HEMP. More detail on the variables used in other models in HEMP is provided in later sections of this report.

Table 2. Input variables for the TDSLM model

Variable	Description
Household ID	Household identification number
Zone ID	Zone in which household resides
Centroid ID	Centroid number of the zone in which the household resides

Variable	Description
Vehicle ownership	Number of vehicles available to the household
Household weight	Expansion and weighting factor of the household
Time interval	6-hourly time interval under consideration
Hurricane category	Hurricane category on the Saffir-Simpson scale
Evacuation order	Whether an evacuation is in effect or not (1 = yes, 0 = no)
Storm surge	Storm surge >10 foot in home zone (1 = yes, 0 = no)
Distance	Gamma-function of distance from household to eye of storm
Timeofday1	1 when time is between 12 am and 6 am, 0 otherwise
Timeofday2	1 when time is between 6 am and 12 pm, 0 otherwise
Timeofday3	1 when time is between 12 pm and 6 pm, 0 otherwise

Zonal Data for Internal Zones

Zonal data used in applying the mode and destination type joint choice model (MCDTC), is obtained from three different sources as shown below.

Data from the American Community Survey (ACS)

Zonal data is calculated from data published at block group level in the American Community Survey (ACS) database. The following is a list of zonal variables used in the MCDTC model and the process of calculation. All of these variables are unit-free since they are expressed in proportions.

1. ResStab. Residential stability is used as a surrogate for social networking. The premise is, the longer a household remains in an area the more social links they are likely to develop in the surrounding community and the more likely they are to participate in communal activities such as evacuating to the home of friends and relatives, or sharing a ride. Residential stability is measured by the proportion of housing units in a block group that have been occupied by the same household for at least 5 years.
2. CommutebyTransit is the proportion of workers in a block group using transit (excluding taxi) for commuting purposes. This variable is used as a surrogate for transit level of service.
3. PropNoVeh is the proportion of households in a block group that do not own a vehicle.
4. AvgInc is the average annual household income in $1,000 by block group.
5. ComDensity. Community density is the proportion of households in a block group living in multiple dwelling units (i.e., where the number of dwelling units in a structure is 2 or more).
6. PropNonCitizen. The proportion of the population who are not U.S. citizens by block group.
7. PropDisab. The proportion of the population with a disability by block group.
8. PropAge. The proportion of the populations who are less than 18 or over 65 by block group.

Accessibility

Accessibility measures how accessible residents living in one parish are to different destination types in all other parishes considered potential destinations. Accessibility is measured at the parish (or parish) level in this project because some of the variables used in its measurement are only available at that level. Since accessibility is measured at a zonal level, it is assumed all residents in a parish enjoy the same accessibility.

Potential destinations are defined as parishes where over 80% of survey respondents evacuated to in past evacuation surveys. For New Orleans, potential destinations were all parishes in the inland parishes of Louisiana and seven states that are adjacent to or close to Louisiana. The seven states are Mississippi, Florida, Alabama, Tennessee, Texas, Georgia, and Arkansas.

In measuring the attraction of destination parishes, a safety indicator is used to distinguish between parishes experiencing storm conditions or not. A parish is considered safe if it is not within the predicted path of gale force winds of a hurricane. If a parish is marked as safe, the attraction of that parish for evacuation is reflected by its capacity to accommodate people. To quantify the capacity to accommodate evacuees at the homes of friends and relatives (FR) in a parish, the population in that parish is used as a proxy. Data were collected from the ACS to provide this information. To reflect the capacity of a parish to accommodate hotel/motel (HM) guests, the number of hotel employees in that parish was selected as a proxy. The underlying assumption is that there is a direct correlation between the number of hotel employees and the number of guests that can be accommodated. This part of the data was collected from the County Business Pattern (CBP) data from the U.S. Census Bureau. For the capacity of shelters (SH) in a zone, shelter capacities were collected from available online resources. For New Orleans, the capacity of each shelter was collected directly from the government website [25].

Travel impedance is typically measured in terms of distance, time, money, or other forms of travel cost between an origin and a destination. In this study, distance between centroids of parishes was chosen as the measure of impedance because, unlike travel time, it remains fixed and known. If a parish itself is marked as safe, intra-zonal evacuation is also considered possible. The intra-zonal distance within a parish is calculated as half the distance between a parish and its nearest neighboring parish.

The following equations show expressions of accessibility to FR, HM, and SH destinations.

$$accessFR_i = \frac{\sum_{j=1}^{J} \frac{Pop_j \times safety_j}{Distance_{ij}}}{\sum_{j=1}^{J} (safety_j \times Resid_j)} \quad [1]$$

where,

$accessFR_i$ = average accessibility to friends or relatives for residents living in parish i.

Pop_j = number of populations in destination parish j.

$safety_j$ = safety indicator of destination parish j.

$Distance_{ij}$ = distance between origin parish i and destination parish j.

$Resid_j$ = residential indicator of destination parish j; equals 1 if parish j has any residents; 0 otherwise.

$$accessHM_i = \frac{\sum_{j=1}^{J} \frac{HotelEmployee_j \times Safety_j}{Distance_{ij}}}{\sum_{j=1}^{J}(Safety_j \times Hotel_j)} \quad [2]$$

where,

$accessHM_i$ = average accessibility to hotels or motels for residents living in parish i.

$Hotel_j$ = hotel industry indicator of destination parish j; equals 1 if parish j contains any hotels/motels (NAICS industry code 7211: Traveler accommodation); 0 otherwise.

$HotelEmployee_j$ = number of hotel employees in destination parish j.

$$accessSH_i = \frac{\sum_{j=1}^{J} \frac{ShelterCapacity_j \times Safety_j}{Distance_{ij}}}{\sum_{j=1}^{J}(Safety_j \times Shelter_j)} \quad [3]$$

where,

$accessSH_i$ = average accessibility to shelters for residents living in parish i.

$Shelter_j$ = shelter indicator of destination parish j; equals 1 if parish j has any shelter; 0 otherwise.

$ShelterCapacity_j$ = capacity of shelters in destination parish j (number of people).

The calculated accessibilities are not unit-free, which is unlike other zonal variables introduced in the previous section. More specifically, the calculated accessibility is affected by the size of zones and therefore it is important that the use of HEMP involve the same size zones as were used in the calibration of the model.

Data at Zonal Level from Other Sources

Hotel price (HotelPrice) and occupancy rate (HotelOccupy) can have an impact on the choice of hotels and motels by locals depending on the price of a hotel room relative to average local income, and the availability of hotel accommodation when it is sought on short notice. To address this issue, the quarterly average daily rate and monthly occupancy rate of hotels were collected from Statista [26]. Due to the level at which the data is made available, it can only be used at a regional level, (e.g., New Orleans or New York City).

Zonal Data for External Destination Zones

Data for external destination zones are used in applying the static destination choice model estimated by Cheng [17]. Data are collected at parish (parish) level since a parish is considered as a destination for external zones. The following variables are needed in the model:

DIST: travel distance from the origin zone to the destination zone. This is calculated using the shortest path procedure in TransCAD and is expressed as the distance (in miles) on the highway network between all O-D pairs.

POP: destination population. It is used as a surrogate for the likelihood that the home of a friend or relative will be found at that destination.

HOTEL: number of hotels or motels at destination zone. It is used as a surrogate for the likelihood that a hotel or motel will be found at that destination.

DANGER: a risk indicator of a destination's vulnerability due to the path of the hurricane. This variable is entered in the format of a dummy variable indicating whether the destination falls within the region predicted to experience gale force winds or not. It attains the value of 1 when a destination falls within the area predicted to experience gale force winds, and 0 otherwise.

ETHPCT: destination ethnic percentage. This variable describes the White population percentage in the destination zone.

MSA: metropolitan area indicator. MSA is given the value 1 if a destination is a major metropolitan area and 0 otherwise.

INTERSTA: interstate highway proximity indicator. INTERSTA is measured by the number of interstate highways a destination contains.

Synthetic Population

The major input required to apply trip generation models in HEMP is household data at a disaggregate level. Acquiring household data at a disaggregate level using travel surveys is a very expensive and time-consuming task. To avoid costs and to save time, synthetic population can be generated using census data. In HEMP, use is made of the synthetic population generation tool available in TransCAD.

The synthetic population tool in TransCAD requires two types of inputs to generate a synthetic population. The first is a disaggregate database which has rich information on household and personal characteristics. The Public-Use Micro Data Samples (PUMS) available from the U.S. Census Bureau are best suited for this purpose. The second is a zonal database such as that provided by U.S. Census Bureau in their American Community Survey data. This provides aggregate household statistics such as vehicle ownership and number of households by income group or household size at block group level.

To generate a synthetic population, disaggregate data from PUMS are used to produce a seed population in each block group, and then the population in each block group is weighted to match a selected set of socio-economic features from ACS data using iterative proportional fitting. A typical set of socio-economic features used to develop the weights are household vehicle ownership, household size and household income. One must ensure that the socio-economic features by which the weights are established are present in all the cases extracted from PUMS.

Once the input files are prepared, the synthetic population can be generated for the geographical area of interest by running the Population Synthesis tool in TransCAD. The output generated from running the procedure is:

1. A database of households with socio-economic demographics, a weight to adjust and expand the synthetic population, and an ID of the zone of residence
2. A database of persons associated with the synthetic households.

Hurricane Data

In the use of HEMP, storm data is downloaded from the National Hurricane Center website. A Python program that can download storm data was developed and integrated into the overall HEMP package. The program in its current state can download storm data in .csv format and parse the information in the file and extract data fields that are required to apply to the TDSLM/TDNLM models. It can download historic data (past storms) or storm information in real time as it is released at each 6-hour advisory. In the test application of the package in the next chapter, historic data from Hurricane Katrina data was downloaded and processed to fit the format required in the master database used in HEMP.

The program coded into HEMP gathers information such as wind speed, storm location, and time of day at each storm advisory and translates them into the format required by the individual models in the package. For example, to serve the needs of the TDSLM model, wind speeds between 110 and 132 miles per hour are translated into a hurricane category 3 and times between 6 a.m. and 12 p.m. are represented by the Time of Day binary variable with Time of Day 2 = 1 while Time of Day 1 and Time of Day 3 are both = 0. Likewise, storm location information is used to calculate the distance between the centroid of a census block group a household resides in and the storm location. This distance is transformed by a lognormal probability distribution function to provide greater weight to distances in the 200- to 400-mile range where the impact of storm proximity is expected to be the most significant. The reasoning behind this assumption is that when a storm is distant, the danger is not imminent and most people adopt a "wait and see" attitude. On the other hand, when a storm is close there is no longer time to reach safety by evacuating so distance to the storm becomes less important again. In between is where distance has the greatest importance. In HEMP, the lognormal distribution used has a location parameter of 6 and a scale factor of 0.6 [21].

Network

The evacuation network must be established for the area that potentially could be evacuated plus all routes leading to the evacuation destinations. Generally, the evacuation network includes all freeways and arterials beyond the evacuation area and a more detailed representation of the network within the study area although it is entirely up to the analyst to choose the level of detail of the network they consider appropriate for the study. The network must contain the following information on each directional link in the network: number of lanes, shoulder width, AADT, number of hotels/motels per mile, number of gas stations per mile, and whether the link could be used in contraflow mode. At each node, the following information must be provided: traffic control system, traffic signal settings (if appropriate), number of lanes on each approach, turning lanes, and turn prohibitions (if any). The network also needs to establish zone centroids and centroid connectors to load evacuation demand onto the network. This is accomplished using the same principles as in regular urban transportation planning.

Shelters

There are two types of shelters in this project: Red Cross shelters and state shelters. Red Cross shelters are open to the public using non-transit modes during evacuation. Therefore, the number using non-transit modes for evacuation affect the demand for, and subsequently the opening of, Red Cross shelters. In contrast, state shelters are used by those who evacuate using transit service provided by the state and/or local authority. Thus, the number of transit dependents during evacuation affects the opening time of state shelters. Overall, the operation of shelters has an association with the mode choice made by evacuees.

The mechanism to decide which shelter should open first is the same for both types of shelters. The main factor is distance, which means the closest shelter will be opened first and the next closest shelter will be opened after the previous one is filled. However, the definition of "filled" is handled differently in HEMP for the two types of shelters. When a Red Cross shelter reaches 80 percent of its capacity it is tentatively considered full (to accommodate those that are in transit and are not aware the shelter is reaching capacity), and the next nearest shelter is opened. The fill rate of 80 percent is fixed for Red Cross shelters in HEMP since state emergency managers have limited control over their operation. However, while state emergency managers may also choose 80 percent as a fill rate, HEMP allows them to specify any value ranging between 0 (i.e., 0 percent) and 1 (i.e., 100 percent) as the fill rate for state shelters. The next nearest shelter is opened only when the fill rate reaches the specified value.

Management Decisions

HEMP allows a user to make management decisions that can influence the evacuation experience. That is, among all the factors affecting evacuation behavior, those at the discretion of a user of HEMP may be altered to estimate the consequence of alternative management decisions. For example, a user can specify which areas are to be evacuated, and when the order to evacuate should be issued in each area. As mentioned earlier, this allows evaluation of staged evacuation. With respect to the network, a user could test the impact of employing contraflow on different sections, including when to initiate and terminate their use. Road closures and alternative traffic signal settings can also be tested by altering the network and traffic signal settings appropriately.

Models

TDSLM

The time-dependent sequential logit model (TDSLM) is a mathematical model that predicts the probability of a household evacuating in each discrete time step when facing an approaching storm. The model uses input data on the category of the storm, time of day, management decisions by emergency managers, and household characteristics to compute the probability of evacuation of each household in each time period.

The model is applied in three steps to derive time-dependent evacuation probabilities of individual households. In the first step, momentary probabilities are computed based on conditions prevailing in each time interval. It represents the likelihood a household will choose to evacuate at any given moment given existing circumstances and knowledge. A simple binary logit model is used to model this momentary decision and in the TDSLM model each decision is considered to be independent of others. In the second step, sequential probabilities are computed by multiplying the momentary probability to evacuate in each time period by the momentary probability to NOT evacuate in all earlier time periods. It recognizes that in a sequence of decisions by a household, each decision is conditional on the decision to not evacuate in all previous time periods. If each momentary evacuation decision is an independent event, the sequential probabilities are the joint probability of evacuating in a certain time period given the household did not evacuate in all previous time periods. This formulation is consistent with the ordered logistic model first proposed by Amemiya [27] and shown again in Ben-Akiva and Lerman [28]. In the third step, evacuation probabilities are computed taking into account the fact that the population is reduced as households evacuate. In HEMP this is accommodated by withdrawing the predicted number of evacuating households from the population in the database in each time period. The predicted number of evacuating households are estimated by adding the sequential probabilities of evacuation in each time period. The specific households chosen for withdrawal are those with the highest sequential probability. This emulates the situation that occurs during calibration of the model where only the remaining population in each time period feature in the calibration since in the calibration data each household only has lines of data for time periods up to and including the time period in which they decide to evacuate, or the last period is reached without evacuating.

TDNLM

The time-dependent nested logit model (TDNLM) is an improved sequential logit model that adjusts the momentary probability to allow anticipated future conditions to influence the probability of evacuating in the current time interval. That is, it relaxes the assumption that momentary probabilities are independent and allows anticipated future conditions to influence current decisions. The model can be explained mathematically by means of an example. Consider a household that faces the choice of whether to evacuate or stay in time intervals *t1*, *t2*, and *t3*. The momentary probability of staying in time interval 1 can be expressed as:

$$P_{ms1} = \frac{1}{1+e^{-(LS_1 - U_{me1})}} \qquad [4]$$

where,

$$LS_1 = log\left(e^{U_{me2}} + e^{\left(e^{U_{me3}}+e^{U_{ms3}}\right)}\right) \qquad [5]$$

in which,

U_{me1}, U_{me2}, and U_{me3} are utilities of evacuating in time intervals *t1*, *t2*, and *t3*, respectively, and

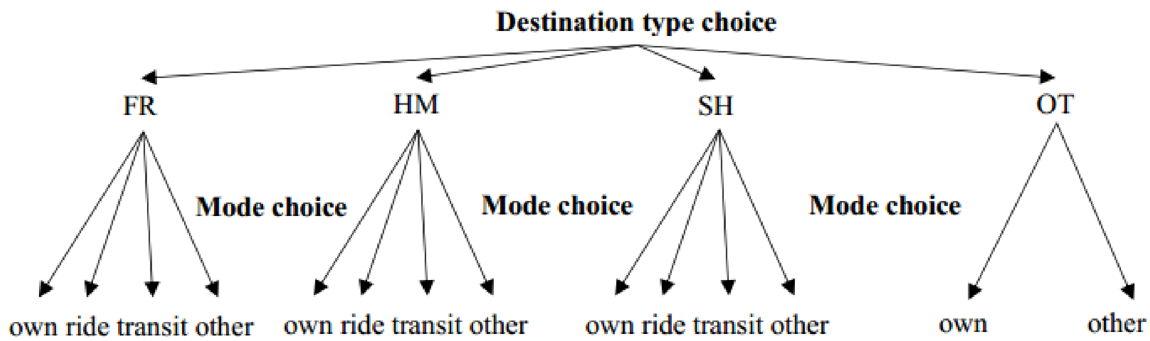
U_{ms3} is utility of staying in time interval 3.

LS_1 is termed the log sum and its function is to incorporate into the utility of time interval *t1* the influence of anticipated conditions in future time intervals *t2* and *t3*. Further description of the TDNLM can be found in Gudishala and Wilmot [22].

Mode and Destination Type Choice

A joint mode and destination type choice model was estimated based on multiple post-storm behavioral surveys from the northeastern seaboard and the gulf coast [20]. The nested logit (NL) structure of the model is shown in Figure 5.

Figure 5. Structure of the joint mode and destination type model



The following equation is a general expression of a NL model of the type used in this study [29] [30] [31].

$$P_{in} = \frac{e^{\left(\frac{V_{in}}{\lambda_k}\right)} \left(\sum_{j \in D_n^k} e^{\left(\frac{V_{in}}{\lambda_k}\right)}\right)^{\lambda_k - 1}}{\sum_{l=1}^{K} \left(\sum_{j \in D_n^l} e^{\left(\frac{V_{jn}}{\lambda_l}\right)}\right)^{\lambda_l}} \qquad [6]$$

where,

P_{in} is the probability decision maker *n* chooses alternative *i* , where *i* belongs in nest k.

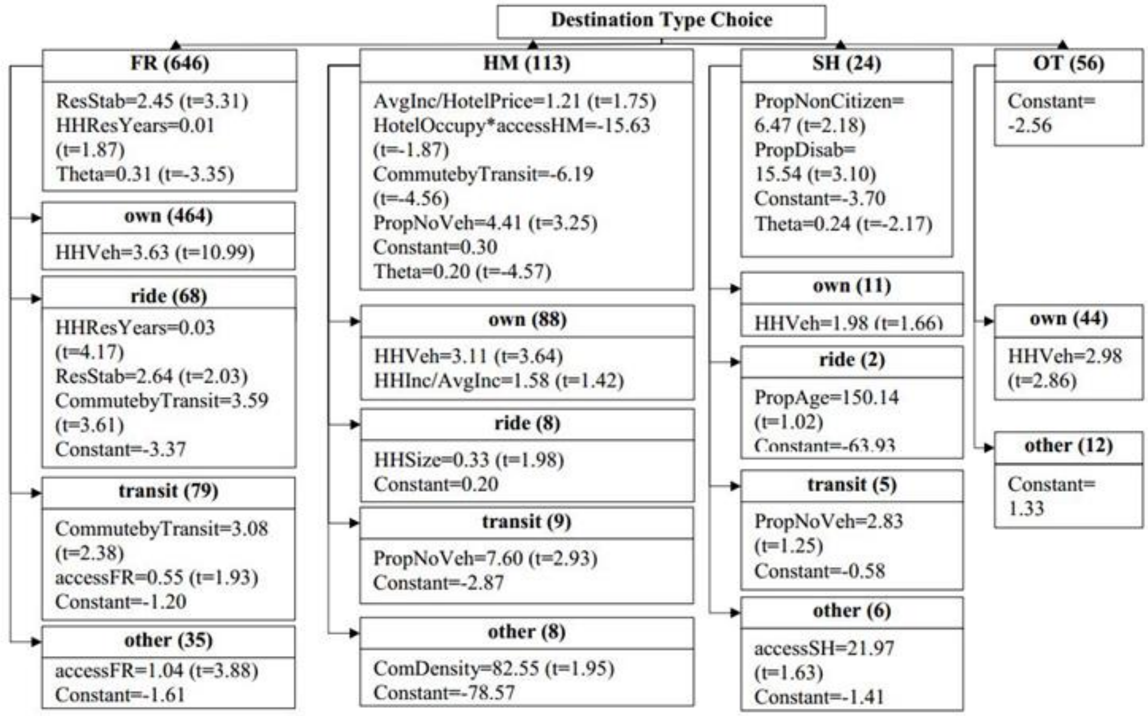
V_{in} is the utility of decision maker *n* choosing alternative *i*.

λ_k is the nesting coefficient or logsum coefficient.

The parameters of the estimated model are presented in Figure 6. As shown, the model specification resulted in a model with a large rho square, which means the estimated model fits the data well. Most of the selected variables presented in Figure 6 have coefficients with t-statistics significant at the 95% level of significance.

Selected variables include both household and zonal characteristics, reflecting the attributes of alternatives (e.g., hotel price and occupancy), the characteristics of households (e.g., residential stability and community density), and the interactions between them (e.g., average accessibility to a destination type). The statistics of variables used in the model estimation can be found in the work of Bian et al. on page 140 [20].

Figure 6. Joint mode and destination choice model estimation results



(Statistics: LL(Zero) = -2214.17; LL(conv..) = -1044.30; Asymptotic rho squared = 0.5284; Adjusted rho squared = 0.5098)

Destination Choice

Separate destination choice models were developed for each type of destination because the factors describing the attraction in each destination type are so different. For example, factors describing the appeal of evacuating to the home of a relative or friend (e.g. number of homes in safe areas, strength of social network) are different to those of going to a hotel or motel (availability of a room, price, income) or a shelter (space, transit service, pet friendly). For Friends/Relatives (FR) and Hotels/Motels (HM) destination types, multinomial logit (MNL) models of destination choice were estimated. A heuristic model was developed for shelters (SH), and an equal probability model was used for "other" destination types (OT).

Origin and destination zones must be established for each application of HEMP. Origin zones are typically smaller than destination zones and destination zones are made progressively larger as the distance from the origin zones increase. Individual cities (and surrounding parishes) usually feature as destination zones within the home state while major metropolitan areas, regions, or even multistate sectors feature as destinations beyond state borders. Destinations are limited to adjoining states. Origin zones are typically parishes or metropolitan areas in the application of the destination choice in HEMP, but the main criterion is that the same level of aggregation of zones (origin and destination) must be used in the application of HEMP as was used in calibrating the model in HEMP. In the destination choice model currently in HEMP, origin zones were three metropolitan areas on the coast of South Carolina, destination zones within the state were parishes, and destination zones in adjoining states were metropolitan regions [17].

Model for Friends/Relatives (FR)

A multinomial logit destination choice model estimated using Hurricane Floyd data for those choosing the homes of friends and relatives as their destination type is included in HEMP. Table 3 shows the parameters of the estimated model [17]. The variable DIST is the distance between the origin zone and destination zone on the network in miles. The parameter estimated shows that distance is a significant disincentive in the choice of a destination. POP is the population of the destination zone. Its positive significant value shows as the population of a destination zone increases, the probability of finding the home of a friend or relative in that destination is increased. DANGER is a binary variable that attains the value of 1 when the destination falls within the cone of predicted cone gale force (>38 mph) winds, and is zero otherwise. Its negative value reflects the population's tendency to evacuate away from a storm. The MSA variable attains the value of 1 when the destination zone includes a major metropolitan area. The variable ETHPCT is the percentage white population in the destination zone; it measures the tendency of friends and relatives to be of the same ethnicity and is positive because the majority of the residents in the origin zones in South Carolina are white.

Table 3. Parameter estimates of destination choice model for friends and relatives

Independent Variables	Parameter description	Parameter estimate	Standard error	t-value
DIST	O-D Distance	-0.00456	0.000875	-5.22
POP	Destination population	2.09E-07	4.27E-08	4.89
DANGER	Risk Indicator	-0.5057	0.1769	-2.86
MSA	Metropolitan Area	1.3717	0.1869	7.34
ETHPCT	White Percentage	1.5546	0.5514	2.82
ASC	Alternative specific constant	0.3888	0.2074	1.87
			Estrella	0.6854
			McFadden's LRI	0.1593

Model for Hotels/Motels (HM)

Cheng also estimated a multinomial logit model for hotels/motels in the same study [17]. The following table of estimated parameters is presented on Page 75 in Cheng's dissertation [17]. The INTERSTA variable measures the number of interstate highways in the destination zone.

Table 4. Parameter estimates of destination choice model for hotels/motels

Independent Variables	Parameter description	Parameter estimate	Standard error	t-value
DIST	O-D Distance	-0.00761	0.001195	-6.36
HOTEL	Destination # of hotels	0.002104	0.000442	4.76
DANGER	Risk Indicator	-1.4279	0.2664	-5.36
INTERSTA	Interstate Proximity	0.216	0.0628	3.44
ETHPCT	White Percentage	4.0091	0.7386	5.43
ASC	Alternative specific constant	0.5009	0.2593	1.93
			Estrella	0.7271
			McFadden's LRI	0.1770

Shelters (SH)

A previous section described the mechanism of shelter opening adopted in HEMP. In general, it is assumed that evacuees go to the closest shelter first, but when the number of occupants approaches a certain upper level of the capacity of the shelter (typically 80%), evacuees are directed to the next closest shelter. From discussions with emergency managers, this is a common tactic adopted in practice. The rationale is that the remaining 20% at each shelter accounts for those still en route to the shelter, the uncertainty of not knowing exactly how many people are at the shelter, and the desire to not turn people away.

As an illustration of the process, consider the example shown in Table 5 below. Say 50 shelter users are evacuating from a zone in a particular time period. The closest shelter to the zone, shelter A, has a capacity of 100 users but has already accommodated 70. The next closest shelter, shelter B, has a capacity of 500 and has no occupants. If the assumed saturation rate at which users are directed to the next closest shelter is 80 percent in both shelters, the usable capacity is 80 for shelter A and 400 for shelter B. However, since there are already 70 in shelter A, only 10 of the new evacuees can be added to shelter A, and the remaining 40 are assigned to shelter B. Since shelter B can accommodate all 40, the calculated probability assigning the evacuees is as shown in the last column in Table 5.

Table 5. Procedure to calculate shelter choice probability

Shelter	Distance (Miles)	Total capacity	Usable capacity	Accumulative occupancy from previous time intervals	Expected occupancy in the current time interval	Probability
A	60	100	100*0.8=80	70	80-70=10	10/50=0.2
B	150	500	500*0.8=400	0	50-10=40	40/50=0.8

Usable capacity is equal to the total capacity multiplied by the saturation rate. Expected occupied capacity in the current time interval is equal to the usable capacity minus the cumulative occupancy from previous time intervals if the shelter is not the furthest among all opened shelters; is equal to the total number of shelter users minus the sum of expected occupancy of all other shelters in the current time interval if the shelter is the furthest among all opened shelters. Probability is equal to the expected occupied capacity in the current time interval divided by the total number of shelter users in the current time interval.

Other Destination Types (OT)

In HEMP it is assumed that there is an equal probability of choosing each destination in the case of trips to OT destination types. This is because the wide variety of destination types in this category (e.g., workplace, club, vacation home, camp, recreational vehicle) make it difficult to capture any significant characteristics that influence choice probability. Equal probability means the probability of assignment to each destination depends on the number of destinations.

Time-Dependent O-D Tables

Time-dependent Origin-Destination (OD) matrices describe the number of vehicles traveling from each origin (O) to each destination (D) in each time interval. However, the output from the destination choice model is a table of time-dependent household destination choice probabilities. Therefore, an additional step is needed to convert the table of household destination choice probabilities into OD matrices of traffic volumes.

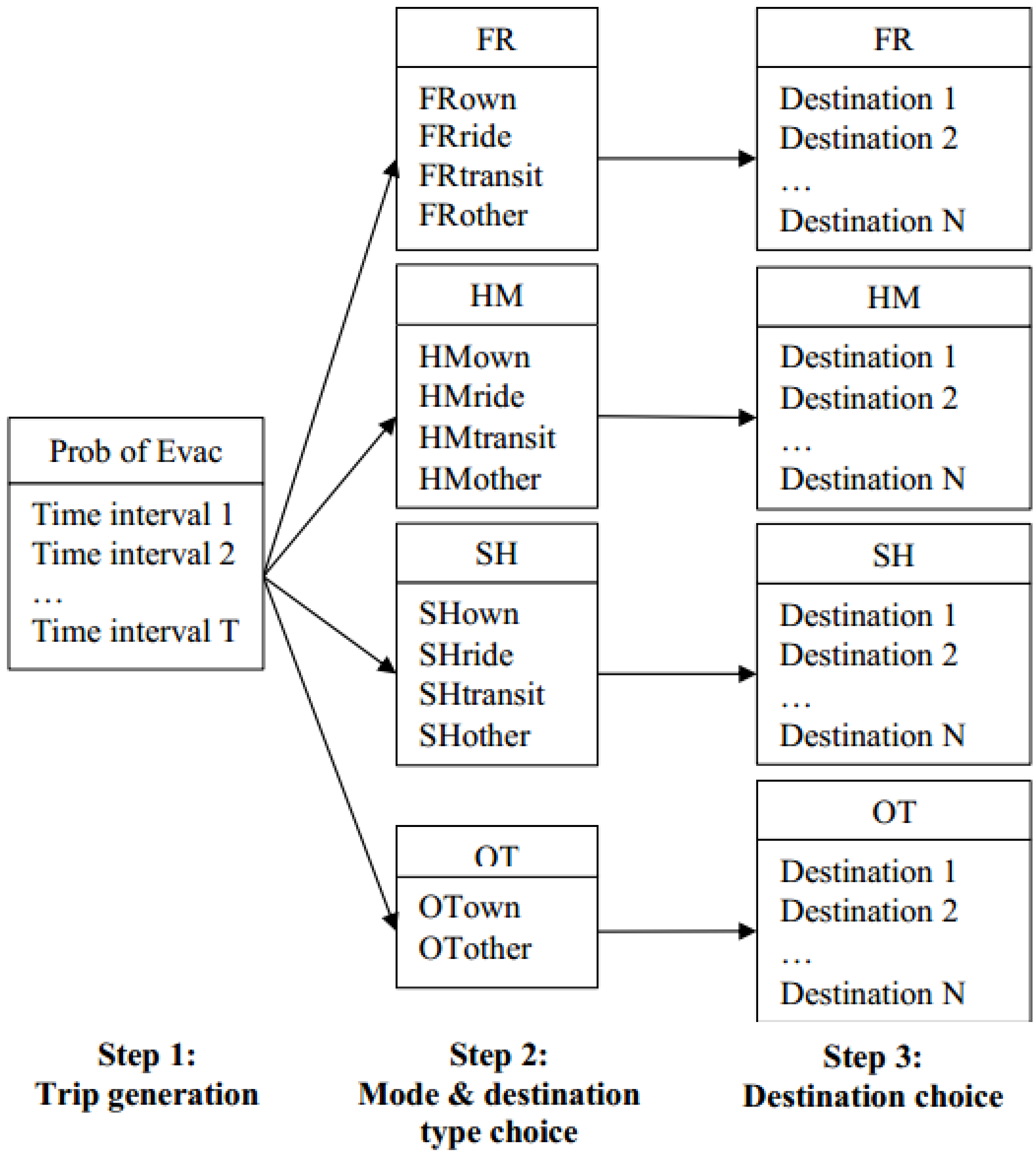
The household destination choice probabilities from the previous steps are automatically recorded in the master data file on which the entire package operates. In this file, each record (or row) stands for a synthesized household in a particular time interval. Therefore, the total number of records equals the number of synthesized households multiplied by the number of time intervals. A field (or column) in the data file contains information such as the characteristics of the household, its surrounding environment, management decisions affecting the household, and the household destination choice probabilities from the previous steps in each time interval.

The first step in estimating the time-dependent matrices is to calculate the joint probabilities. Figure 7 illustrates the process of calculation. The probabilities of choosing to evacuate in each time interval are used in Step 1, the probabilities of choosing each mode and destination type is used in Step 2, and the probabilities of choosing each destination is used in Step 3. The three steps are considered independent of each other so their joint probability is the product of their individual probabilities. Thus, the arrows in the figure represent a multiplication operation.

The joint probabilities are stored as new fields in the master data file. The number of new fields for each household (i.e., each row) is T*14*N, where T is the number of time intervals, 14 is the number of alternatives in mode and destination type joint choice, and N is the number of destinations. As an example, one of the fields would stand for the probability that, in a specific time interval, a household would drive their own vehicle to the home of a friend or relative, located in a specific destination zone.

In the next step, the T*14*N new columns are merged to produce probabilities regarding non-transit modes (sumprob non-transit) and probabilities regarding transit (sumprob_transit). Note that the merging process is completed by fields, not by records. Therefore, the joint probabilities are now distinguished by T time intervals, 2 modes, and N destinations. Thus, the number of new fields is reduced to T*2*N for each household. The new fields of information are needed for 1) shelter assignment and 2) converting transit trips into equivalent cars for traffic simulation.

Figure 7. Calculating joint evacuation probabilities



Converting the choice probabilities to traffic volumes is slightly different for the two modes (i.e., transit and non-transit). For non-transit, the conversion is completed by multiplying the merged probability by the average number of cars used by each household to evacuate (assumed as 1.56 based from past studies). Regarding transit, the conversion is completed by multiplying the merged probability by the associated household size (which is recorded in HHSize) to get the number of passengers, divided by the average capacity of transit vehicles (assumed as 50 passengers per transit vehicle) to get the number of transit vehicles, and multiplying by the car-equivalent factor of a bus (which is 1.76 from the Highway Capacity Manual) to get the number of equivalent passenger vehicles.

The next step is to expand the synthesized households to cover all households in the selected area by using the household associated value of weight (recorded as WEIGHT in the master data file). This is the expansion factor to account for the fact that only a sample of households are generated in the synthetic population. It also incorporates the weight assigned to individual households to allow the sample to match census block group totals in the synthetic population generation process.

Sum the above-calculated values to get the number of cars each record stands for. This process of summing is still completed by fields, not by records. Therefore, the table still distinguishes by T time intervals and N destinations but not by modes. That is, the number of new fields is reduced to T*N.

The following equation shows the process of generating the T*N fields from the T*2*N fields:

$$VALUE = (sumprob\_non\text{-}transit * 1.56 + sumprob\_transit * HHSize / 50 * 1.76) * WEIGHT \quad [7]$$

The next step combines records by zones to complete the conversion from choice probabilities to traffic volumes. Each record in the table is associated with an origin block group ID. Assume households are from M block groups. Combining the calculated VALUE by origin block group ID and destination ID for each time interval will give the number of cars traveling between origins and destinations in that time interval. That is, if households evacuate from M block groups to N destinations, T O-D matrices are formed, each of which estimate traffic volumes from each of the M origins to each of the N destinations in a specific time interval.

Reducing 6-hour Demand Values to Hourly Values

The time-dependent O-D matrices generated above list the estimated evacuation traffic volumes in each 6-hour time interval. That is, a cell value in one matrix is the demand (i.e., traffic volume) between an O-D pair in a time period of 6 hours. However, TransModeler requires time-dependent O-D demand in hourly intervals. Therefore, the 6-hour demands from above must be distributed to each hour. The process adopted in this study to distribute demand from 6-hour intervals to each hour is described below in Figure 8.

Figure 8. Procedure to reduce 6-hour demands to 1-hour demands

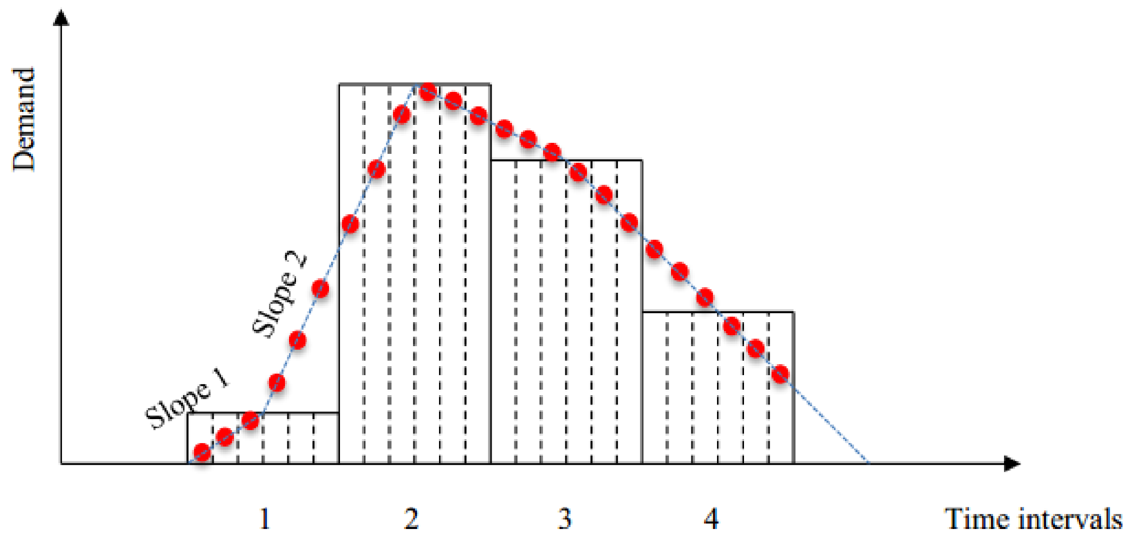


Figure 8 illustrates how demand in 4 intervals of 6 hours each are converted to 24 hourly intervals. Overall, it is a process of linear distribution where the hourly values are derived as follows:

- Connect the mid-point of each bar in the 6-hour histogram to the mid-point of adjoining bars. The connecting lines are drawn in blue dash lines in Figure 8.
- Calculate the slopes of the connecting lines. There are two slopes for each time interval: a preceding and succeeding slope. The preceding slope is named slope1 and the succeeding slope is named slope2 in all cases.
- For starting and ending intervals, slope1 and slope2 are assumed to be the same (as in time interval 4) except when this assumption would distribute the demand to a negative value, (as in time interval 1). To remedy this, slope1 in time interval 1 is altered to (demand in time interval 1 minus zero)/3 while slope2 is (demand in time interval 2 minus demand in time interval 1)/6.

If the total demand in a 6-hour time interval i is depicted as Di, then it is broken into 1-hour demand as follows:

Di=(Di*2.5*slope1)+(Di*1.5*slope1)+(Di*0.5*slope1)+(Di+0.5*slope2)+(Di+1.5* slope2)+(Di+2.5*slope2).

That is, the proportion of the total demand in each consecutive hour in a 6-hour interval i is:

Proportion 1 = (Di*2.5*slope1)/Di

Proportion 2 = (Di*1.5*slope1)/Di

Proportion 3 = (Di*0.5*slope1)/Di

Proportion 4 = (Di+0.5*slope2)/Di

Proportion 5 = (Di+1.5*slope2)/Di

Proportion 6 = (Di+2.5*slope2)/Di

The red dots in Figure 8 represent the distributed hourly demand derived by the method described above.

TransModeler has the capability of accepting time-dependent O-D information at hourly intervals and converting it to smaller time intervals (0.1 second time steps are typically recommended for micro simulation). The distribution can be assigned in a number of ways but a uniform distribution was chosen for use in HEMP. Due to the long computation time taken when simulating traffic conditions over several days, macro simulation is recommended in HEMP. In TransModeler, macrosimulation is achieved by increasing the time step in which the speed and location of each vehicle in the network is calculated. The time step can be increased up to 10 seconds.

Route Choice

Route choice in HEMP can be conducted in two possible ways. The first is to use the shortest path alternative in TransModeler. The second is to use the probabilistic route choice model developed by Akbarzadeh [32]. Akbarzadeh's model assigns evacuation traffic to routes based on four characteristics of the route: distance, accessibility, perceived level of service, and facility class of the route. Each of the route choice characteristics in Akbarzadeh’s probabilistic model are described in greater detail below.

Distance in the probabilistic route choice model is the shortest distance between each origin and destination on the network in miles. Distance was chosen over travel time because it does not change over time and is more likely to be known by evacuees. In HEMP, the shortest path distance is computed within TransModeler from the evacuation network.

Accessibility is defined as the straight-line distance in miles from the origin zone to the closest point on a potential evacuation route. This variable represents how easy it is for evacuees to access each major route in their choice set. It is computed by taking the straight-line distance from the centroid of the origin to the nearest point on the major evacuation route. Therefore, each origin zone has a unique value of accessibility for each route. To compute these values, the position of the zone centroids and network links are exported from TransCAD to Excel. A Visual Basic program calculates the Euclidean distance from an origin to each point on a route and saves the smallest value.

Perceived service is the combined influence of two variables – familiarity with a route— and the services such as gas stations and hotels on the route. Familiarity is represented by the number of vehicles that travel the path every day (i.e., the AADT), based on the notion that travelers are more likely to choose routes they know. Services include amenities that evacuees are likely to need along the route such as fuel, food, accommodation, and restroom facilities. Service levels are represented by the number of amenities per mile of each evacuation route for the first 100 miles from the origin. However, because businesses tend to locate along routes which have high levels of traffic, a strong correlation was found to exist between variables representing service and familiarity of a route. In order to retain the influence of both while not generating multicollinearity in the utility function of the model, they were combined by multiplying them together to form a single variable labeled "perceived service."

Facility Class is modeled as a dummy variable in HEMP. It attains the value of 1 when the route chosen is a freeway and 0 otherwise. It captures the preference travelers have for freeways over other types of roads for evacuation.

TransModeler does not normally support simulations longer than 24 hours, so an additional macro had to be written to stitch the three 24-hour periods together by saving the end of each 6-hour time period as an initial state to be loaded in the beginning of the next simulation.

Output

Numeric Output

TransModeler reports trips in an output table, where each record stands for a trip. However, some statistics reported in HEMP relate to persons so a factor of average vehicle occupancy is needed in the conversion. It was assumed earlier in generating OD matrices that the number of vehicles used by each household in evacuation is 1.56. The average household size can be estimated for an evacuation area from the census data for that area. Therefore, average vehicle occupancy equals average household size divided by 1.56. Then the population each trip stands for can be roughly estimated by multiplying it by this factor of average vehicle occupancy.

The set of statistics listed in the output table, together with a description of each statistic, is listed below:

- TimeToLandfall: Time to hurricane landfall (in hours), reported every 6 hours corresponding to the storm advisories issued by the National Hurricane Center.
- Total_Pop: The population of the area(s) marked for evacuation before any evacuation occurs.
- Evacuated_Pop: The population choosing to evacuate in a particular time interval.
- Arrived_Pop: The population who have arrived at their destinations by a particular time interval.
- Enroute_Pop: The population who are enroute to their destination in a particular time interval.
- Remaining_Pop: the population remaining at an origin by a particular time interval.
- VMT: vehicle miles traveled. It is the total travel distance (in miles) of vehicle trips completed in a particular time interval.
- Avg_Travel_Dist: average travel distance (in miles) of evacuation trips completed in a particular time interval. It equals VMT divided by the number of completed trips in a particular time interval.

- Max_Travel_Dist: The maximum travel distance (in miles) of any trip reaching its destination in a particular time interval. It is generated to observe the maximum travel distance traveled in each time interval.
- VHT: vehicle hours traveled. It is the total travel time (in hours) of vehicle trips completed in a particular time interval.
- Avg_Travel_Time: average travel time. It equals VHT divided by the number of completed trips in a time interval.
- Max_Travel_Time: The maximum travel time (in hours) of any trip reaching its destination in a particular time interval. It is generated to observe the maximum travel time in each time interval.
- Avg_Travel_Speed: Average travel speed (in mph). It equals Avg_Travel_Dist divided by Avg_Travel_Time
- Total Delay: The difference in total travel time and the free flow travel time plus departure delay of all trips completed in a particular time interval (in veh-hrs).
- Total Delay per trip: The total delay of all the trips completed in a particular time interval divided by the total number of trips completed in that interval.

The statistics above are based on completed trips only; incomplete trips are not considered in the calculation. This is because if a vehicle does not complete its trip within one time interval in TransModeler, the trip is marked as "enroute" in that time interval and fed into the next simulation time interval. The trip is marked "completed" as soon as it is completed in a time interval. Information, such as trip starting/ending time and travel distance associated with that trip, is only recorded in the time interval when the trip is completed. Therefore, it is not appropriate to consider data associated with incomplete trips since it would result in double counting. It is possible that some trips may still be incomplete in the last simulation interval as some vehicles may still be on road when the traffic simulation is completed. These trips will not be counted in the statistics above and, therefore, the total population choosing evacuation may not match the population who have arrived at their destination.

Graphic Output

HEMP is constructed to also provide graphic output of several of the statistics above. In particular, it generates a color-coded thematic map of the levels of congestion on individual links of the network over time. It also uses a thematic map to show the migration of the population as they depart the evacuation area and fill the destination zones over time.

Integration

Purpose

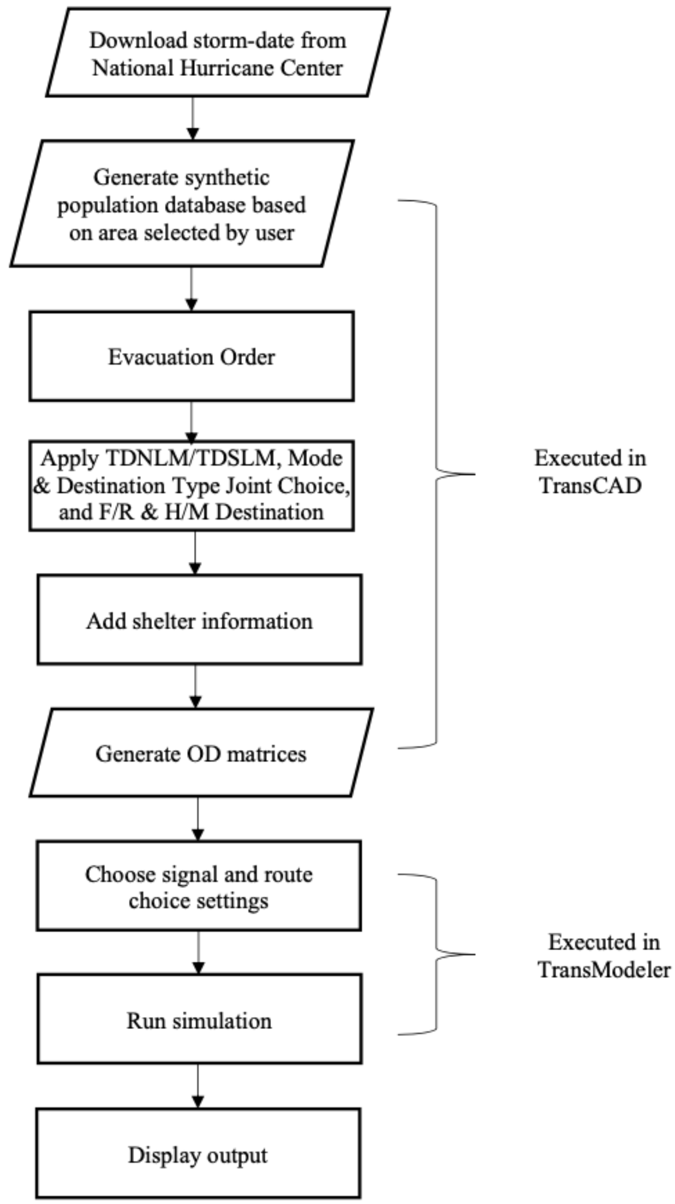
The purpose of integrating hurricane evacuation models into a single package is to facilitate their application and allow easy formulation and testing of alternative management decisions. The models access data and feed information among the models automatically to produce estimates of time-dependent evacuation behavior. The focus has been on getting a working package with the possibility of refining it later as improvements become evident.

The package uses TransCAD and TransModeler from Caliper Corporation as platforms on which to conduct different operations and present the results. The user interface uses .NET to provide menu-driven operations of the package. The general features of the package are described below.

Structure of HEMP

A user can choose historic or current storm data as input, generate a synthetic population for the area to be evacuated, and run simulation based on evacuation management decisions (e.g. evacuation orders, shelter choice, signal settings and route choice). The flowchart in Figure 9 shows the basic structure of the package.

Figure 9. Structure of HEMP



Once the program is started, the first thing a user needs to select is the storm that will form part of the scenario to be analyzed. For past storms, the program retrieves storm information from the National Hurricane Center (NHC) archives. These files contain the position, intensity, forward speed, and projected path of the hurricane at each 6-hour advisory. As currently constructed, a user can select one of eight major past storms (Hurricane Andrew, Hurricane Georges, Hurricane Ivan, Hurricane Katrina, Hurricane Rita, Hurricane Gustav, Hurricane Isaac, and Hurricane Harvey) or they can choose a current developing storm. Information on a current storm is automatically downloaded at each storm advisory from the NHC website.

In the next step, the program opens TransCAD and a map is displayed with state, block group, and ZIP code layers of the parishes in Louisiana. The user selects the area to evacuate on the map based on predictions of the path of the storm, the expected storm surge, and the resulting flooding potential. Based on the selection, a synthetic population for the evacuation area is generated within HEMP and added to the master database. The storm information retrieved from the National Hurricane Center is parsed to include only the relevant variables and merged into the master database at this time. After this, the user is asked to select the areas to receive an evacuation order, the type of evacuation order to be issued, and the time interval in which it is first applied. In the demand models currently in use in HEMP, no distinction is made between voluntary and mandatory evacuation orders so only two kinds of evacuation order can be given; no evacuation order or a voluntary/mandatory evacuation order. The database is updated with this information once it is provided by the user.

Next, all the demand models (TDSLM / TDNLM, Mode and Destination Type, and Destination Choice models) together with the shelter assignment procedure described earlier, run automatically based on information in the master database. The process produces an estimate of the probability of each household evacuating in each time interval by mode. Average vehicle occupancies are used to convert household evacuations to movement of equivalent passenger car units. The probabilities of evacuation of these passenger car units are summed by time interval to produce origin-destination matrices of vehicle movements for each 6-hour time interval before hurricane landfall. These time-dependent OD matrices are used as inputs to the traffic simulation in TransModeler.

Before applying TransModeler, the user is asked to choose the signal settings that will be in operation during evacuation and the route choice option that will be in effect. Three types of signal timing plans can be tested. The first option is to have no traffic signals at any of the intersections. Vehicles are allowed to pass through the intersection without stopping or slowing down on any approach, provided another vehicle is not in their path. This option provides the most favorable, but most unrealistic, traffic flow because in reality motorists cannot negotiate intersections safely or practically in this manner. The second option is to select the traffic signal control plans that are in operation under normal circumstances. The third option is flashing yellow signals on the main routes and flashing red on cross streets. With the two evacuation order options and three signal settings, six options are generated and their data included in the master datafile. The user is also asked what route choice model will be used at this point of time. The user can choose either the shortest path option or use the multiple criteria probabilistic model developed by Akbarzadeh [32]. TransModeler is applied using the information above and the effectiveness of each evacuation plan is evaluated using statistics of evacuation performance.

Platform(.NET)

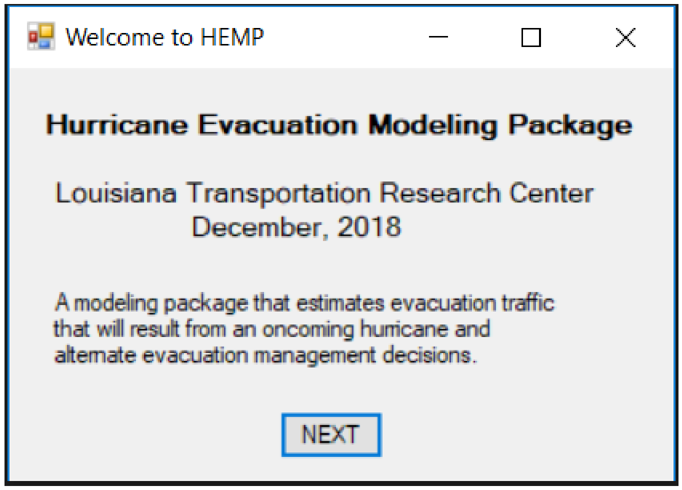
To allow the application to communicate with TransCAD and TransModeler, Visual Studio 2017 version was used. Visual Studio is free software from Microsoft which supports many programming languages and provides the means to automate the operation of the package. It provides numerous extensions and has a simple code editor and debugger. Windows Forms was used to build the user interface applications which are linked with the code using an event-driven model. In event-driven models, the program flow is determined by user actions (events) such as a mouse click, pressing a key, etc.

For the user interface to communicate with TransCAD and TransModeler, a CaliperForm.dll file was needed. The CaliperForm.Connection class establishes a connection to the GISDK environment and includes methods to convert data types between GISDK and .NET environments. When the connection is opened, GISDK functions and macros can be accessed via the connection GISDK dynamic object. To execute the macro written in GISDK (.rsc file), the file needed to be converted to a .dbd file which then could be called from .NET with the function WithAlternateInterface(\program.dbd)".

User Interface

The HEMP package opens with a title page and a brief description of what the package does (see Figure 10). It is followed with prompts to formulate the scenario to be tested.

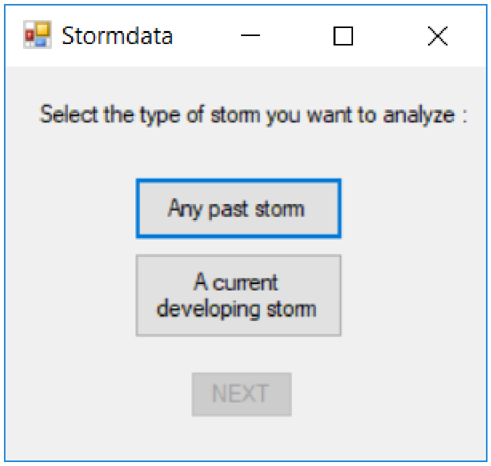
Figure 10. HEMP opening window

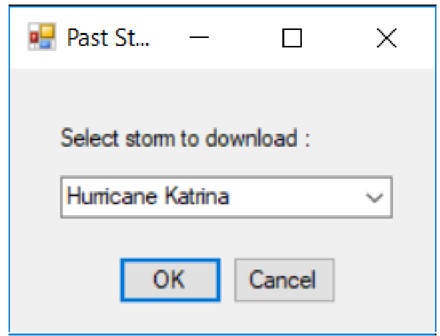


The first information sought, is the storm to be analyzed. As shown in Figure 11, the user has two options for downloading storm data. If they choose the first option, which is "any past storm," another form opens which allows the user to select from 8 storms listed from the drop-down menu. Based on the user's choice, connection is established with the National Hurricane Center website and data scraping is performed to find and download the relevant .dat file that contains all the storm information. All the required features (i.e., year, month, day, time, forecast technique, latitude, longitude, wind speed, radius, eye, direction) of the storm are extracted and written in comma-separated value format into the master datafile.

If the user selects the button for "a current developing storm," a regular expression is used to perform data scraping and navigate to the last storm added to the NHC website. Relevant information is then downloaded in csv format as it becomes available with each storm advisory from the National Hurricane Center.

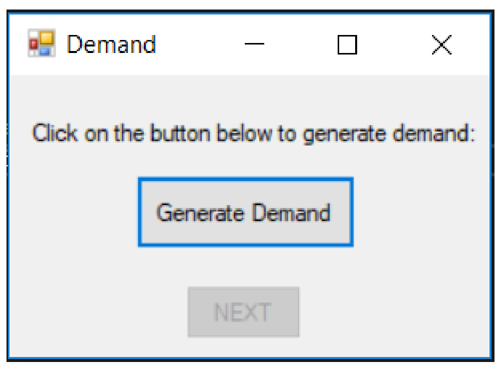
Figure 11. Initial input windows





Once the storm-data is downloaded, the application opens the interface which allows the user to estimate demand as shown in Figure 12. In generating demand, the user interface establishes a connection with TransCAD and executes the GISDK program that initiates and controls execution of the demand estimation models.

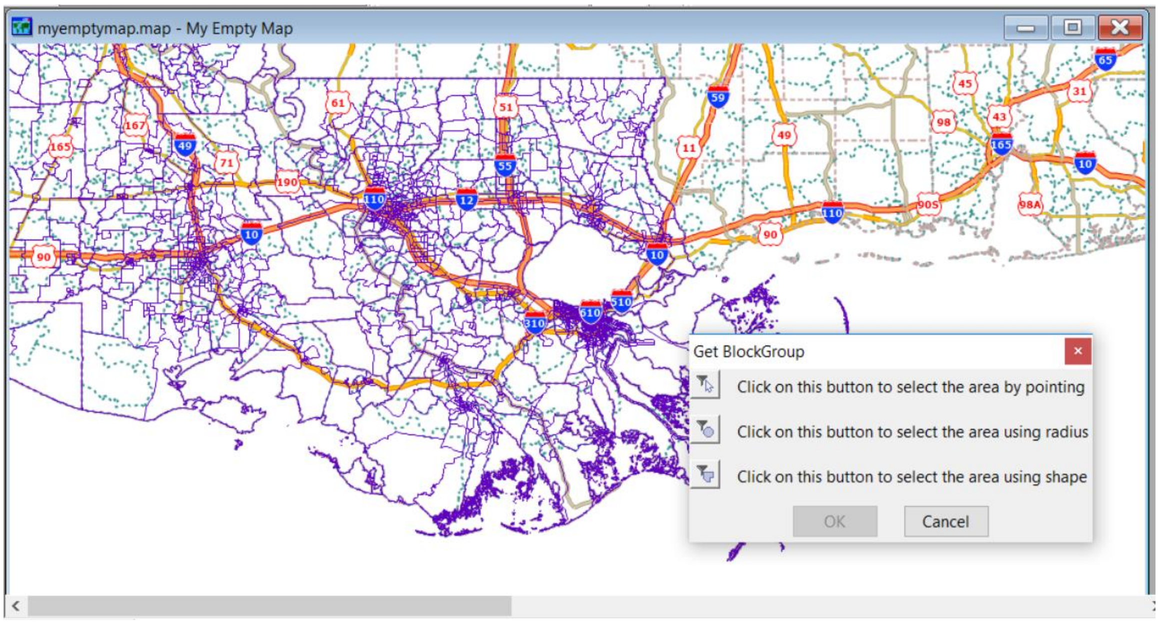
Figure 12. Initiating demand estimation



The GISDK code starts by creating a map of the study area. The user interface provides three options to select the area of evacuation. As shown in Figure 13, the user may select individual census block groups by pointing and clicking on them, select an area based on a stated radius, or designate a polygon of any shape and size by progressively clicking boundary points until the position of the last point is the same as the first and an enclosed area is established.

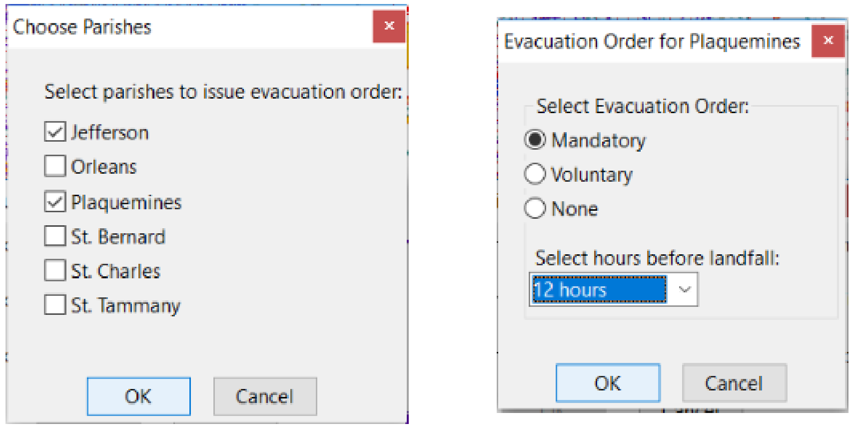
Purple lines in Figure 13 designate census block group boundaries and the green dotted lines ZIP code boundaries. The area selected by the user is stored in the form of an array of census block group IDs. The synthetic population is generated for these selected block groups only.

Figure 13. Establishing an evacuation area



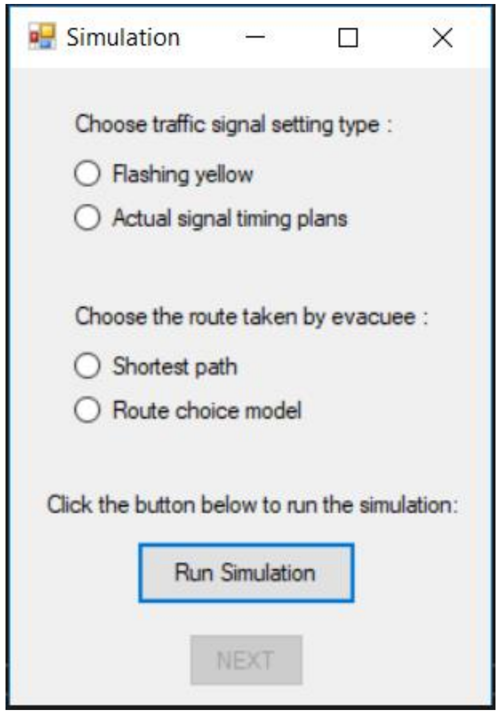
The next step is for the user to select the parishes for which an evacuation order is to be issued, the type, and the time the evacuation order is to come into effect (see Figure 14). If the user selects no evacuation order, no changes are made to the database. If the user selects a voluntary/mandatory evacuation order, the program opens the database created in the previous step and changes the values for the field `evacuation order' from 0 to 1 for households in the relevant parishes for all time periods following introduction of the evacuation order. After choosing the evacuation order, the program goes through the remaining macros for implementing the demand models. The final step is to generate the origin-destination matrices for each time interval.

Figure 14. Specifying evacuation orders



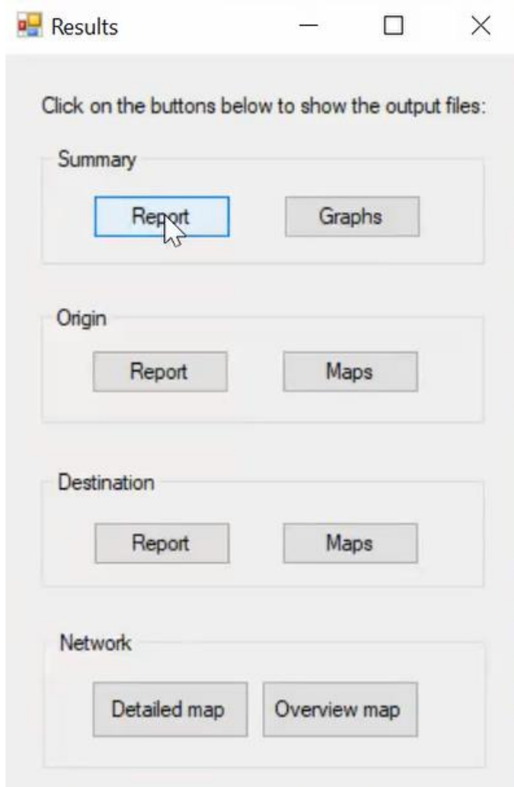
The OD matrices generated are the input for the simulation process conducted in TransModeler. Once the OD matrices are read into TransModeler and the user clicks the button "NEXT," it opens the interface which allows the user to choose the signal settings and route choice options (see Figure 15). The user selection of signal settings and route choice is stored in a variable and passed to the GISDK macro written to run the simulation. Following this, the network is opened and simulation in TransModeler commences.

Figure 15. Traffic signal and route choice options



Once the simulation is complete and the user clicks “NEXT” on the user interface, the results of the simulation are compiled into numeric and graphic files displayed in a window as shown in Figure 16. The numeric files consist of csv files containing the summary report, information about the remaining population at the origin, information on the vehicles on the network, and the population that have arrived at their destination in each time period. The thematic maps show the population and network changes over time. The output produced in an actual application of the entire package is presented in the next chapter.

Figure 16. Output file selection



Discussion of Results

Trial Application of HEMP in New Orleans Metropolitan Area

Test Site

New Orleans metropolitan area was chosen as the site, and Hurricane Katrina as the storm, to demonstrate the use of HEMP. They were chosen because of the vulnerability of New Orleans to hurricanes, its importance to the state of Louisiana, and interest in testing alternative evacuation management decisions to those employed in Hurricane Katrina. In this study, the only scenario investigated was Hurricane Katrina with the same management decisions as those that actually adopted in the storm. This was done to be able to compare HEMP's predictions with observed evacuation results. Six parishes were considered part of the New Orleans metropolitan area in this application: Jefferson, Orleans, St. Charles, St. Bernard, Plaquemines, and St. Tammany as these were affected by Hurricane Katrina. Further application of HEMP will investigate alternative strategies.

Synthetic Population

A synthetic population was generated for the six-parish study area. To expedite the generation process only 10 percent of the population was simulated at the census block group level but the households were weighted to expand the sample to the population.

The PUMS dataset used in the generation of the synthetic population was obtained from the U.S. Census Bureau website for year 2013; whereas, the zonal database, which is a database compiled at census block group level for the state of Louisiana, was obtained from Caliper Corporation for the same year. Once the two required inputs were acquired and verified for integrity and compatibility, they were used to generate a synthetic population.

Zone and Network Information

The simulation network that was input into traffic simulation package was prepared from scratch using the network editing tools available within TransModeler. Freeways, arterials, and major evacuation routes in the New Orleans area were coded into the simulation network. In the initial stages of the project, Caliper Corporation provided assistance in coding freeways and major arterials. The research team coded minor arterials, major evacuation routes, traffic signal timing plans, contraflow lanes, centroids, and centroid connectors into the network.

Centroids of census block groups were imported into the network using tools provided by TransCAD and TransModeler. Centroid connectors were manually added from each centroid to the nearest viable entry and exit point in the network. A database that linked centroid ids to census block groups was also generated at this point for later use in the OD matrix generation process.

The centroid of each census block group in the New Orleans area was used as an origin for evacuation trips estimated by the demand estimation model. These are shown as red dots in Figure 17. Destination centroids, shown as blue dots in Figure 17, were grouped into 8 metropolitan areas in Louisiana, and 6 external regions in bordering states as described later in Table 10. While Figure 17 shows the major evacuation routes outside the greater New Orleans area, Figure 18 shows the detailed evacuation network within New Orleans. It includes all interstates, national and state highways, and major and minor arterials which are important during an evacuation. Each link in the network is defined in terms of number of lanes, lane width, direction, type of road, medians if any, etc.

Figure 17. Origin and destinations of evacuation trips

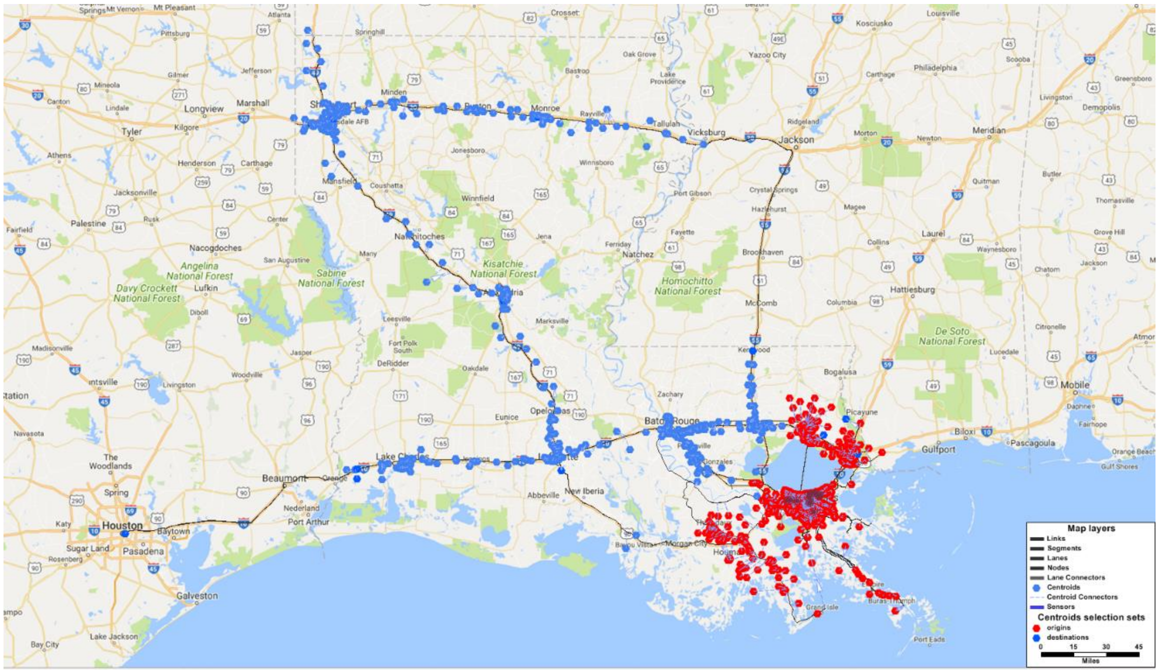
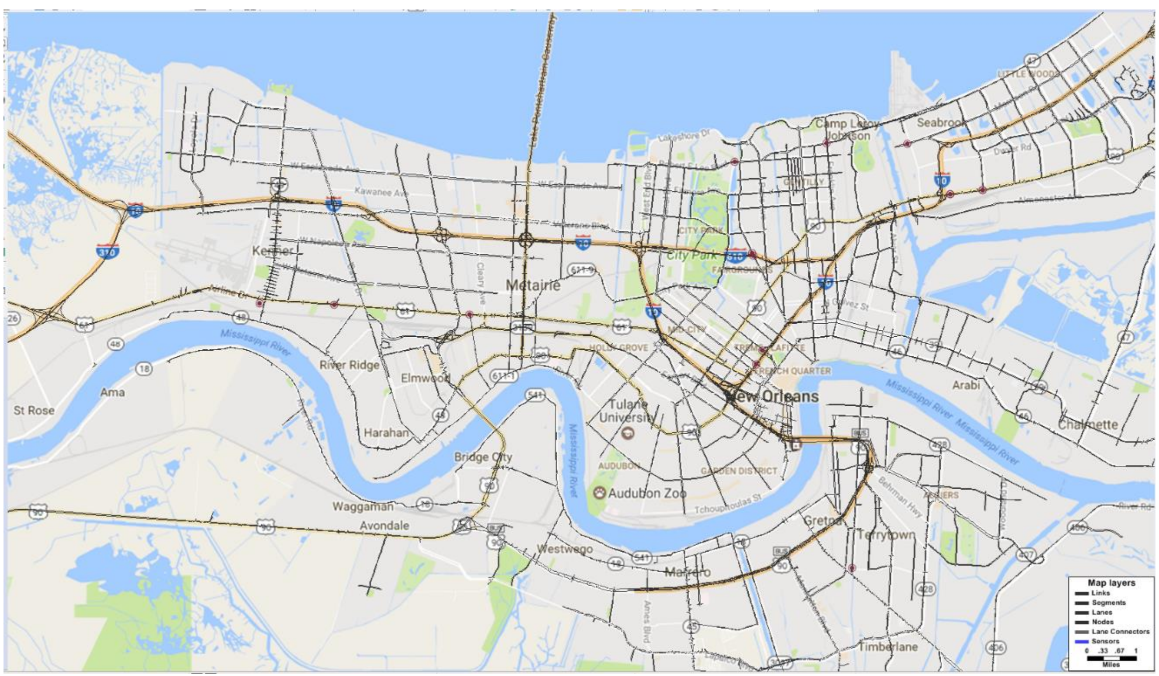


Figure 18. Evacuation network within the New Orleans area



To represent contraflow, the network was altered to allow vehicles to travel west on both the westbound and eastbound carriageways of I-10 from 12 p.m. August 27 to 12 p.m. August 28th. This involved reversal of relevant lane connectors and activation of a macro to command a switch to the contraflow network, and switch back to the old network, at the appropriate time.

Internal Zones

The joint mode and destination type choice model is a prime user of zonal data. For this model, zonal data at block group level were obtained from the American Community Survey (ACS). A complete dataset for all zonal variables at block group level are only available for 2000, 2013, and 2014. The most recent block group data (2014) were used in this project. Parish level data (needed to calculate accessibility) were also retrieved for 2014 to maintain consistency. The following sections describe zonal data collected by different geographic units.

Zonal Variables at Block Group Level

There are 1,062 block groups within the six parishes of Jefferson, Orleans, Plaquemines, St. Bernard, St. Charles, and St. Tammany in the New Orleans metropolitan area. Table 6 shows the statistics of all zonal variables at block group level by parish. The statistic on the first line of each cell is the average value of that variable. The second line of each cell shows the minimum and maximum values of that variable. Some block groups do not have any household, which makes the minimum value of some variables zero.

Table 6. Block group data in New Orleans MSA

Variables	Jefferson	Orleans	Plaquemines	St. Bernard	St. Charles	St. Tammany	All
Number of block groups	331	497	24	50	34	126	1062
AvgInc (Average household income in $1,000)	66.802 [0, 358.788]	58.375 [0, 386.031]	59.047 [0, 106.905]	54.927 [0, 92.608]	70.179 [0, 130.637]	79.398 [0, 171.781]	63.726 [0, 386.031]
ResStab (Residential stability: proportion of households who lived in their current home in 2000 or earlier, so that they occupied the housing unit for at least 4 years prior to Hurricane Katrina)	0.701 [0, 0.979]	0.514 [0, 1]	0.667 [0, 0.938]	0.563 [0, 0.896]	0.779 [0, 0.977]	0.710 [0, 0.974]	0.610 [0,1]
CommutebyTransit (Proportion of workers using transit (excluding taxi) for commuting purposes)	0.014 [0, 0.361]	0.091 [0, 0.567]	0.002 [0, 0.040]	0.013 [0, 0.105]	0.001 [0, 0.015]	0.002 [0, 0.054]	0.048 [0, 0.567]
PropNoVeh (Proportion of households that do not own a vehicle)	0.080 [0, 0.549]	0.204 [0, 1]	0.052 [0, 0.486]	0.056 [0, 0.222]	0.059 [0, 0.600]	0.042 [0, 0.243]	0.131 [0, 1]
ComDensity (Community density: proportion of households living in multiple dwelling units, i.e., number of units in structure is greater than 2)	0.244 [0, 1]	0.359 [0, 1]	0.076 [0, 0.433]	0.134 [0, 0.622]	0.093 [0, 0.573]	0.109 [0, 0.761]	0.268 [0, 1]
PropNonCitizen (Proportion of people who are not U.S. citizens)	0.106 [0, 0.443]	0.053 [0, 0.614]	0.043 [0, 0.126]	0.045 [0, 0.224]	0.031 [0, 0.246]	0.036 [0, 0.265]	0.066 [0, 0.614]
PropDisab (Proportion of people with a disability)	0.259 [0, 0.659]	0.260 [0, 1]	0.230 [0, 0.439]	0.236 [0, 0.520]	0.282 [0.109, 0.656]	0.303 [0, 0.662]	0.264 [0, 1]
PropAge (Proportion of people who are less than 18 or over 65)	0.364 [0, 0.704]	0.316 [0, 0.602]	0.364 [0, 0.541]	0.334 [0, 0.499]	0.371 [0.242, 0.539]	0.387 [0, 0.567]	0.343 [0, 0.704]

Zonal Variables at Parish Level

As mentioned earlier, 8 internal and 6 external destinations were considered for evacuation from New Orleans. As defined earlier, accessibility used in the mode and destination type joint choice model is not unit-free since it is affected by the size and number of zones. The estimated mode and destination type joint choice model used accessibilities calculated at ZIP code level [20]. Therefore, accessibilities of this project were adjusted to account for the difference in ZIP code areas and the destinations used in this application to keep them in the same range as those used in the original estimated model. Table 7 shows statistics of those adjusted accessibilities.

Table 7. Adjusted accessibility measures for MCDTC model

Variables	min	max	mean
accessFR	1.8e-5	1.328	0.029
accessHM	0	0.014	1.9e-4
accessSH	0	1.0e-6	3.5e-9

Zonal Variables at Regional Level

Two variables in joint mode destination type choice (MCDTC) model are used at regional level: hotel price and hotel occupancy rate. They were collected from Statista for Year 2014 to keep consistency with other data used in the MCDTC model. Table 8 shows the quarterly average daily rate of hotels in New Orleans.

Table 8. Quarterly average daily rate of hotels ($/night)

	Q1	Q2	Q3	Q4
New Orleans	187	167	153	186

Table 9 shows the monthly average occupancy rate of hotels in the U.S., because it is not available for New Orleans specifically. Therefore, the statistics for the whole U.S. was used as a substitute in this project.

Table 9. Monthly average occupancy rate of hotels

Area	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
U.S.	0.52	0.60	0.65	0.66	0.67	0.72	0.74	0.72	0.66	0.68	0.59	0.53

HEMP retrieves values based on the clock time of the computer system. For example, if a user runs HEMP in October, hotel price will be $186 and hotel occupancy rate will be 0.68.

External Zones

Destinations are grouped into 14 areas as shown in Table 10. The first 8 are metropolitan areas in Louisiana and the remaining 6 are regional destinations in neighboring states. Hinds County in Mississippi includes the state capital Jackson and represents the destination of those evacuating north from New Orleans up the I-55. Forrest County in Mississippi includes Hattiesburg and captures those evacuating northeast from New Orleans up the I-59. Mobile, Alabama, is east of New Orleans and is the representative destination of those that evacuate east on the I-10. Jefferson and Harris counties in southern Texas, housing Beaumont and Houston cities respectively, represent the destination of those that evacuate west beyond the border of Louisiana on the I-10.

As described in documentation on the static destination choice model by Cheng [17] , the variable "POP" is the population of the parishes forming the destination area, "DANGER" is a dummy variable that attains the value of 1 if the destination is on the projected path of the hurricane and is zero otherwise, "MSA" is a dummy variable that attains the value of 1 if the destination area contains a Metropolitan Statistical Area and is zero otherwise, "ETHPCT" is the White population percentage in the destination zone, "HOTEL" is the number of hotels or motels in the destination area, "INTERSTA" is the number of interstate highways in the destination area, and "DIST" is the distance in miles from New Orleans to each destination area.

Table 10. Destination areas and their characteristics

Destination	POP	DANGER	MSA	ETHPCT	HOTEL	INTERSTA	DIST
Shreveport	200,000	0	1	0.43	65	2	327
Monroe	172,000	0	1	0.36	36	1	267
Alexandria	150,000	0	1	0.31	24	1	203
Lake Charles	200,000	0	1	0.26	35	1	207
Lafayette	290,000	0	1	0.29	44	1	136

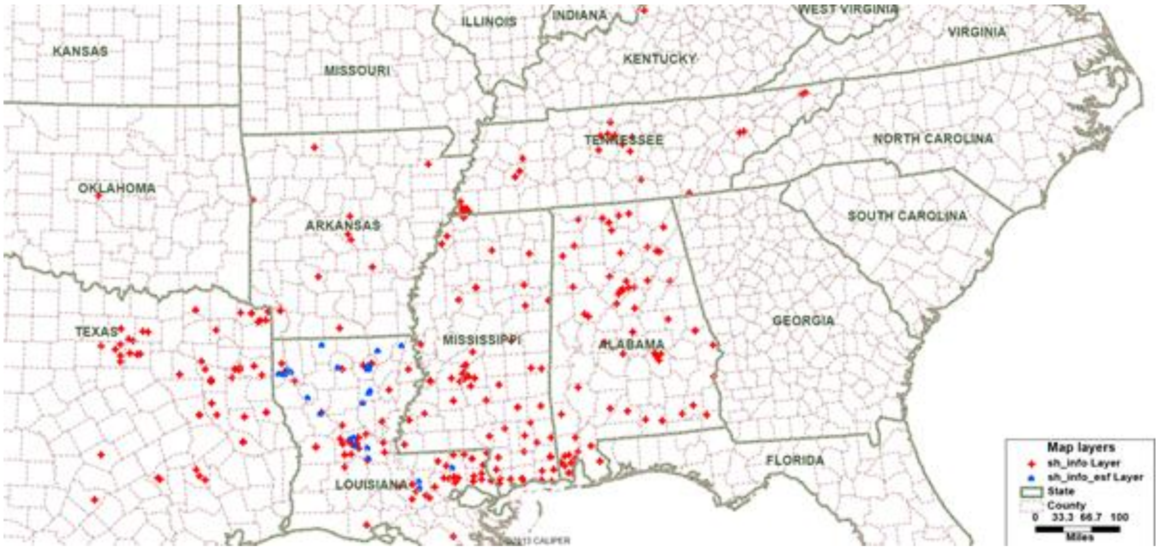
Destination	POP	DANGER	MSA	ETHPCT	HOTEL	INTERSTA	DIST
Baton Rouge	800,000	0	1	0.37	83	2	82
Northshore	64,750	1	1	0.3	19	1	33
Houma	76,395	0	1	0.22	34	1	58
SE Texas	5,273,000	0	1	0.34	668	4	348
NE Texas	5,812,000	0	1	0.31	812	4	506
Arkansas	650,000	0	1	0.26	119	2	424
S.W. Mississippi	530,000	0	1	0.49	107	1	188
S.C. Mississippi	140,000	0	1	0.3	24	1	112
S.E. Mississippi	1,086,000	0	1	0.29	208	2	144

Shelters

There are two types of shelters: Red Cross shelters and state shelters. Red Cross shelters are for those who evacuate by non-transit modes. State shelters are managed by the state and transit service is provided to transport people from the affected area to a state shelter. Figure 19 shows the location of shelters serving Louisiana. Red Cross shelters are shown with a red dot and state shelters with a blue dot. There are 379 Red Cross shelters and their average capacity is 425. The Red Cross shelter with the largest capacity is located in Oklahoma City with a capacity of 12,500 people and is approximately 700 miles from New Orleans. The largest Red Cross shelter in Louisiana is in Alexandria with a capacity of 7,000 people and is about 200 miles away from New Orleans. There are 32 state shelters located within Louisiana. The average capacity of these shelters is 763 people. The state shelter with the largest capacity is located in Alexandria with a capacity of 2,500 people and is about 200 miles from New Orleans. The nearest state shelter to New

Orleans is in Amite with a capacity of 400 people and is at a distance of 80 miles. The shelter information was added to the master data file.

Figure 19. Shelters



Demand Estimation

Table 11 shows the TDSLM model parameters used in implementing the model in HEMP. The model estimation and additional details about the model can be found in the following reference [21].

Table 11. TDSLM parameter values

Variable	Estimated parameter	Standard error	t-statistic
Evacuation Order	0.66	0.22	2.99
Hurricane Category	0.47	0.07	6.57
Time of day 1(TOD1)	1.23	0.29	4.19
Time of day 2 (TOD2)	1.92	0.29	6.63

Variable	Estimated parameter	Standard error	t-statistic
Time of day 3 (TOD3)	0.83	0.3	2.71
Time dependent distance	760.15	179.84	4.22
Storm surge	0.91	0.377	2.41
Constant	-5.91	0.32	-18.01

The input data required to apply the model was compiled from a combination of data sources. For instance, the information about type and timing of evacuation orders issued by each parish was gathered from newspaper archives and Wikipedia. Information on the time-dependent characteristics of Hurricane Katrina were extracted from the archive on the National Hurricane Center website. Storm surge data was gathered using the SLOSH Display Program (SDP), a tool provided by National Hurricane Center to aid emergency managers in visualizing storm surge vulnerability. There are five main inputs that should be selected in SDP to extract potential storm surge heights for the geographical region of interest—the SLOSH basin, storm conditions being accommodated (Historical, MEOW—maximum envelope of water, or MOM – maximum of maximums), category of storm, and direction of storm. The New Orleans basin (labeled MS2), north west direction, and MOM were used in combination with the storm category of Hurricane Katrina in each time interval. The output generated by SDP is a shapefile with predicted inundation levels above ground for the New Orleans basin. The shapefiles for different categories of storm were overlaid on a census block group shapefile to join predicted storm surge to each census block group.

Hurricane Katrina made landfall at 6:10 am Monday, August 29, 2005. Demand was estimated for 3 days prior to landfall and presented in 12 consecutive OD matrices, each representing demand over a period of 6 hours. Demand was estimated when a voluntary/mandatory evacuation order was issued 48 hours before landfall, and when no evacuation order was issued at all. In Hurricane Katrina, evacuation was ordered in most parishes 48 hours prior to landfall and 30 hours prior to landfall in Orleans parish, so the predictions closely relate to the conditions during Hurricane Katrina. The predicted demand estimates are summarized for both conditions in Table 12, and the variation of demand is depicted graphically in Figure 20.

Figure 20. Predicted evacuation demand for different types of evacuation orders

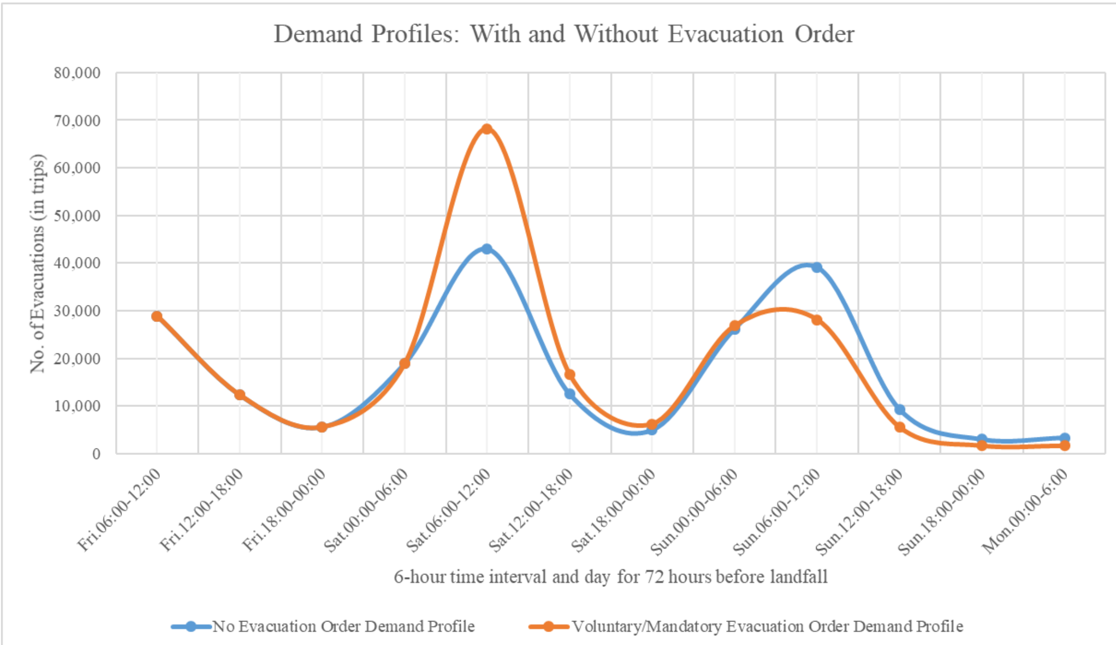


Table 12. Predicted time-dependent demand for 72 hours prior to landfall

Day and time	Time inter-val	Demand -no evac. order (trips)	Demand - evac. order 48 hours before landfall (trips)	Time period before landfall (hrs.)	Abscissa joining points for hourly demand estimation(X)
		(Y1)	(Y2)		
Fri.06:00-12:00	1	28,899	28,899	72 - 66	69

Day and time	Time inter-val	Demand -no evac. order (trips)	Demand - evac. order 48 hours before landfall (trips)	Time period before landfall (hrs.)	Abscissa joining points for hourly demand estimation(X)
Fri.12:00-18:00	2	12,315	12,315	66 - 60	63
Fri.18:00-00:00	3	5,573	5,573	60 - 54	57
Sat.00:00-06:00	4	18,897	18,897	54 - 48	51
Sat.06:00-12:00	5	42,965	68,228	48 - 42	45
Sat.12:00-18:00	6	12,504	16,622	42 - 36	39
Sat.18:00-00:00	7	4,960	6,204	36 - 30	33
Sun.00:00-06:00	8	26,176	26,864	30 - 24	27
Sun.06:00-12:00	9	39,138	28,150	24 -18	21
Sun.12:00-18:00	10	9,320	5,543	18 -12	15
Sun.18:00-00:00	11	3,005	1,647	12-6	9

Day and time	Time inter-val	Demand -no evac. order (trips)	Demand - evac. order 48 hours before landfall (trips)	Time period before landfall (hrs.)	Abscissa joining points for hourly demand estimation(X)
Mon.00:00-06:00	12	3,348	1,642	6-0	3

Joint Mode and Destination Type Choice Model

Table 13 shows the predicted mode and destination type joint choice for the whole study area. It is predicted that 58.4 percent of the households will evacuate to the homes of friends or relatives, 32.7 percent to hotels and motels, 2.2 percent to shelters, and 6.7 percent to other destination types. A study conducted by Dewberry and the Stephenson Disaster Management Center at LSU in 2017 for the Corps of Engineers, found that among those that evacuated from Hurricane Katrina, 54 percent evacuated to friends and relatives, 30 percent to hotels and motels, 6 percent to shelters, and 9 percent to other destination types [33]. The same study found that 96 percent of the respondents who reported evacuating from Hurricane Katrina, evacuated in either their own private vehicle or that of a friend or relative. This compares closely with the 94.6 percent of households predicted to evacuate driving their own private vehicle or riding with others in Table 13.

Table 13. Predicted mode and destination type choices for Hurricane Katrina

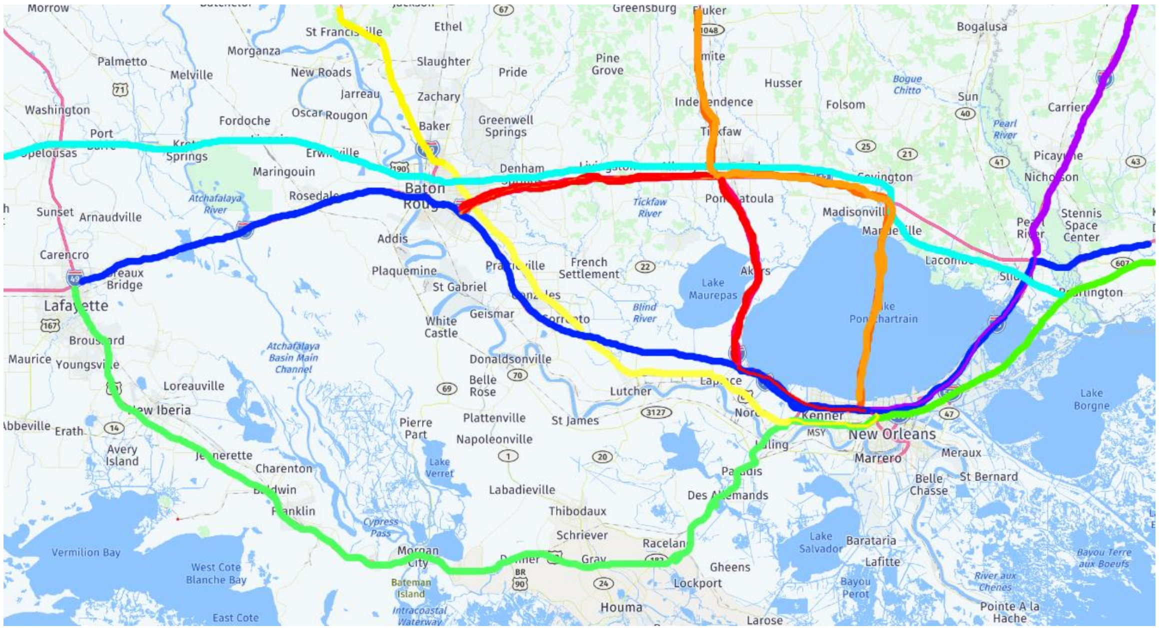
Destination type choice	Mode choice	Percentage
FR (friends/relatives' home)	own (driving own vehicle)	54.2
	ride (riding with others)	1.5
	transit (taking transit)	1.8

Destination type choice	Mode choice	Percentage
	other (using other modes)	1
HM (hotels/motels)	own (driving own vehicle)	28.3
	ride (riding with others)	3.7
	transit (taking transit)	0.7
	other (using other modes)	0
SH (shelters)	own (driving own vehicle)	1.6
	ride (riding with others)	0
	transit (taking transit)	0.5
	other (using other modes)	0.1
OT (other types of destinations)	own (driving own vehicle)	5.3
	other (using other modes)	1.4

Evacuation Routes

The major evacuation routes are shown below in Figure 21. US-90 is shown in green, US-61 in yellow, US-190 in turquoise, I-10 in dark blue, I-55 to I-12 and I-12 to I-10 in Baton Rouge in red, Causeway to I-12 and I-55 in brown, and I-10 to I-59 in purple. For probabilistic assignment of traffic to these routes, each link on these routes must be characterized in terms of distance, accessibility, perceived level of service, and facility class.

Figure 21. Major evacuation routes from New Orleans



Accessibility is the straight-line distance in miles from the origin to the major route. This variable represents how easy it is for evacuees to access each major route in their choice set. This value was computed by taking the straight-line distance from the origin to the nearest point on the major evacuation route. Therefore, it is as much a function of the relationship between the origin and the route as it is a property of the link itself. To compute these values, the centroid dataview containing information such as latitude and longitude plus the link dataview containing the route tag, as well as latitude and longitude, were exported to Excel. A Visual Basic program was used to calculate the Euclidean distance from an origin to each point on a route and save the smallest value. The assumption was made that distance is only two dimensional (i.e., elevation was ignored), and that, in the Greater New Orleans area, 1 degree of latitude is 68.88 miles and one degree of longitude is 59.953 miles. This process was repeated for each route and each origin. The values were saved in a table for later use.

As mentioned in the methodology chapter, perceived level of service is the impact of two variables, familiarity and level of service. In keeping with the manner in which familiarity was calculated in the model developed by [32] , familiarity is measured in terms of a familiarity factor defined as:

$$FF_p = \frac{\sum_{i=1}^{n_p} l_{ip} \cdot x_{ip}}{\sum_{p \in C} \sum_{i=1}^{n_p} l_{ip} \cdot x_{ip}} \quad [8]$$

where,

FF_p = Familiarity factor for route p.

l_{ip} = length of link i on route p.

x_{ip} = AADT on link i on route p under normal conditions

n_p = number of links on route p.

The variable service, on the other hand, was measured by the total number of gas stations and hotels that could be seen from the road divided by the length of the route. For routes that were longer than 100 miles, only the first 100 miles were considered since they were more likely to be subject to congestion and unpredictable delay than later portions of the route.

The product of the familiarity factor and service for each route made up the new variable perceived level of service. The values of perceived level of service originally calculated by Akbarzadeh [32] were used to better coincide with the model derived by that work.

Facility Class is a dummy variable between 0 and 1 that captures travelers stated preference for freeways over other types of roads. The values of Facility Class originally calculated by Akbarzadeh [32] were used to better coincide with the model derived by that work.

Traffic Signal Settings

Two types of traffic signal settings were considered in the application of HEMP in New Orleans: the existing daily traffic signal control plans, and flashing yellow on major routes with flashing red on cross-streets. From the 1300 intersections in the network, 525 important intersections were identified along major evacuation routes. Among these 525 intersections, 253 had traffic signal inventory plans that were obtained from DOTD in

New Orleans, 150 had Synchro coded network plans obtained from Urban Systems and Neil Schaffer, and the remaining 122 signal timing plans were manually coded as pre-timed concurrent signals using the following rationale. First, an intersection of similar geometry (number of approaches, number of lanes, turning lanes) was sought from among the intersections with known signal plans. If a similar intersection was found, its signal settings were adopted. If no resemblance was found, cycle lengths of 120 seconds or 90 seconds were used for intersections with or without auxiliary turning lanes, respectively. Within a cycle length, green times were allotted proportional to the number of lanes on each approach. Yellow time of 4 seconds, and red clearance times of 0 seconds were used in all cases. Pedestrian phases were neglected due to low or no pedestrian traffic during hurricane evacuations.

The 525 signal timing plans were coded into TransModeler using a control plan file with an extension ".tms." This file contains all signal timing parameters and settings that a controller requires in order to operate one or more signals. The signal timing input file was added to the road network layer using the Intersection Toolbox in TransModeler. Controller configuration and the signal parameters were edited for each intersection based on the traffic signal inventory plans.

For the Flashing Yellow/ Red (FYR) signal timing scenario, the same 525 intersections were coded into a different ".tms" file to represent flashing yellow on major streets and flashing red on minor streets. Functional classification and the number of lanes on each approach were considered the major criteria in distinguishing major streets over minor streets at an intersection. Each FYR signal is coded as a simple one phase "Pretimed Sequential Phasing" control type with respective signal heads of the major and minor streets set to flashing yellow or flashing red as required.

Evacuation Scenarios

A total of four scenarios were developed based on the type of evacuation order issued (none or voluntary/mandatory) and the traffic signal plan employed (existing traffic signal plans or flashing yellow/red). Each traffic signal plan was paired with each evacuation order to produce the four scenarios shown in Table 14.

Table 14. Evacuation scenarios

	Evacuation order	
Traffic control system	None	Voluntary/Mandatory
Flashing yellow/red	Scenario 1	Scenario 2
Existing traffic signal plans	Scenario 3	Scenario 4

Simulation was conducted for the final 72 hours before the storm. The 72 hours of simulated time was conducted in 3.5 hours on a regular laptop computer using macrosimulation in TransModeler. Nine simulations were run for each scenario and the average taken to generate a set of representative results for each scenario. To assess the performance of the scenarios, 4 measures of effectiveness (MOEs) were used:

- Vehicle Hours Travelled per Trip
- Vehicle Miles Travelled per Trip
- Total Delay per Trip
- Average Speed

The estimated performance of the system in terms of the above MOEs is shown in Figure 22 to Figure 29. In Figure 22, the estimated average vehicle hours traveled per trip with different traffic signal settings is shown for demand generated when no evacuation order was issued. Figure 23 is performance on the same MOE but for the demand generated when an evacuation order was issued 48 hours before hurricane landfall. What is evident in both figures is that flashing yellow/red is equal to, or below, the average travel time with existing traffic signal plans throughout the analysis period. Flashing yellow/red is of particular value as a traffic signal control mechanism as demand peaks on Saturday and Sunday (see Figure 20 for demand peaks).

Figure 22. VHT/trip with different traffic signal settings, no evacuation order

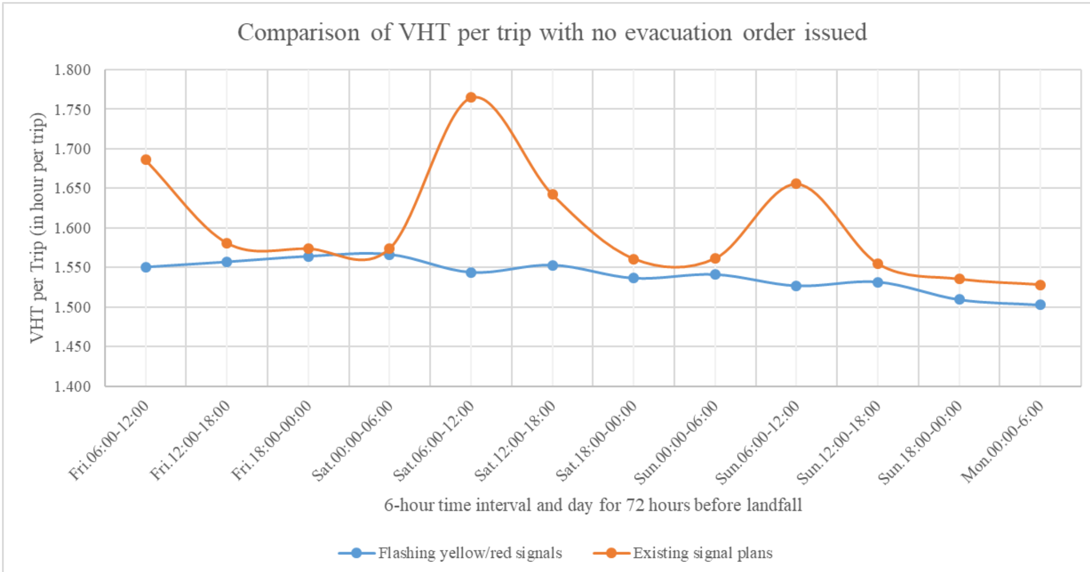
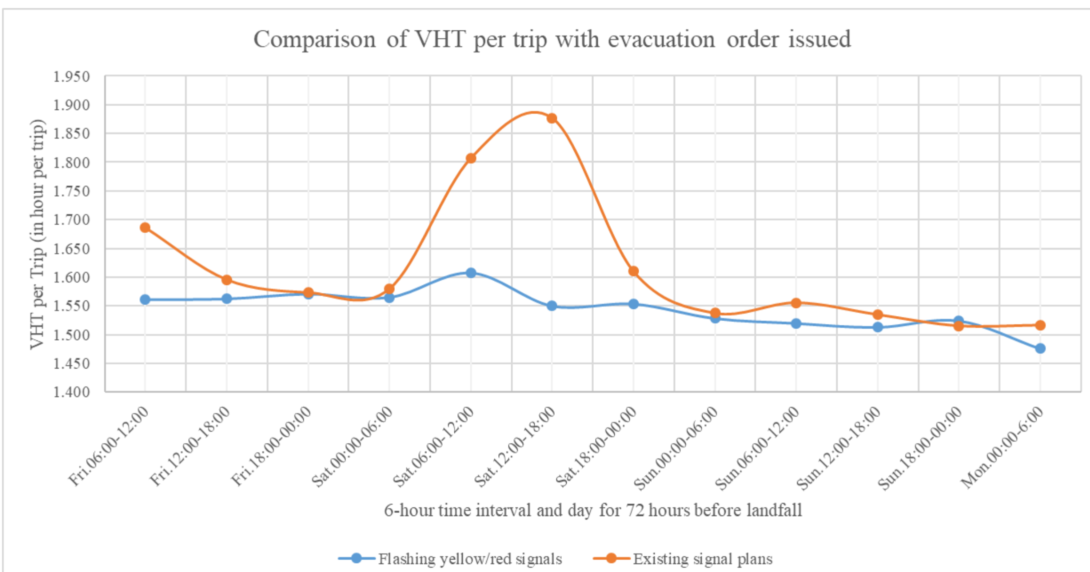


Figure 23. VHT/trip for different signal settings with evacuation order issued



With respect to the MOE of Vehicle Miles Travelled (VMT), Figure 24 and Figure 25 show the estimated miles traveled per trip when no evacuation order was issued, and when an evacuation order was issued, respectively. Both diagrams show that VMT decreased during periods of high demand with flashing yellow/red but remained relatively stable when the existing traffic signal plans were kept in effect. The decrease in travel with flashing yellow/red can be understood by the effect of congestion resulting in reduced speed and, although the same effect would be present for existing traffic signal plans, this was possibly countered by some vehicles deviating onto longer but less congested paths. However, overall VMT is affected little by the change in traffic control measures.

Figure 24. VMT/trip for different signal settings with no evacuation order

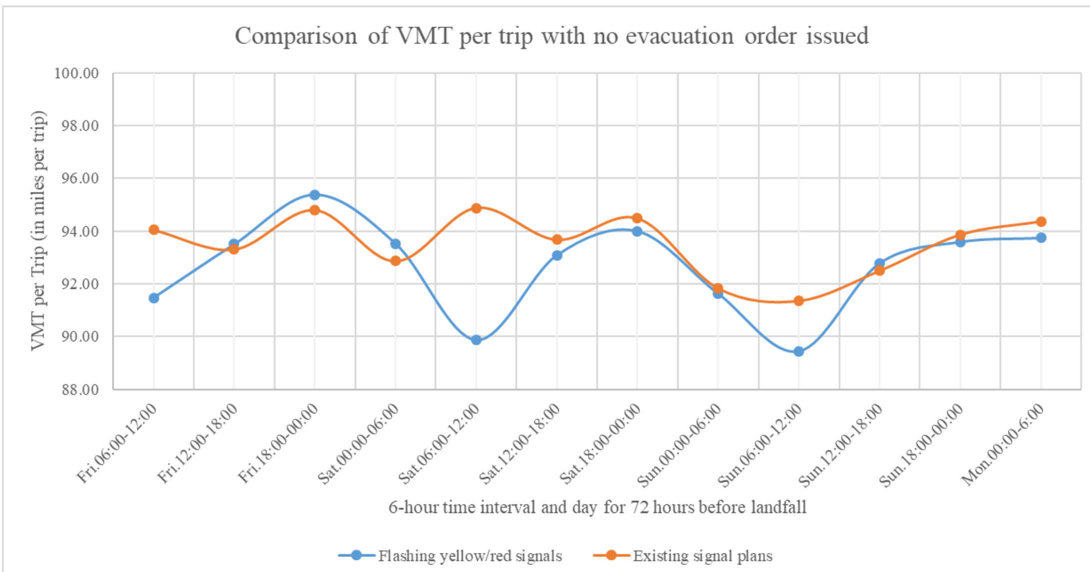


Figure 25. VMT/trip for different signal settings with evacuation order issued

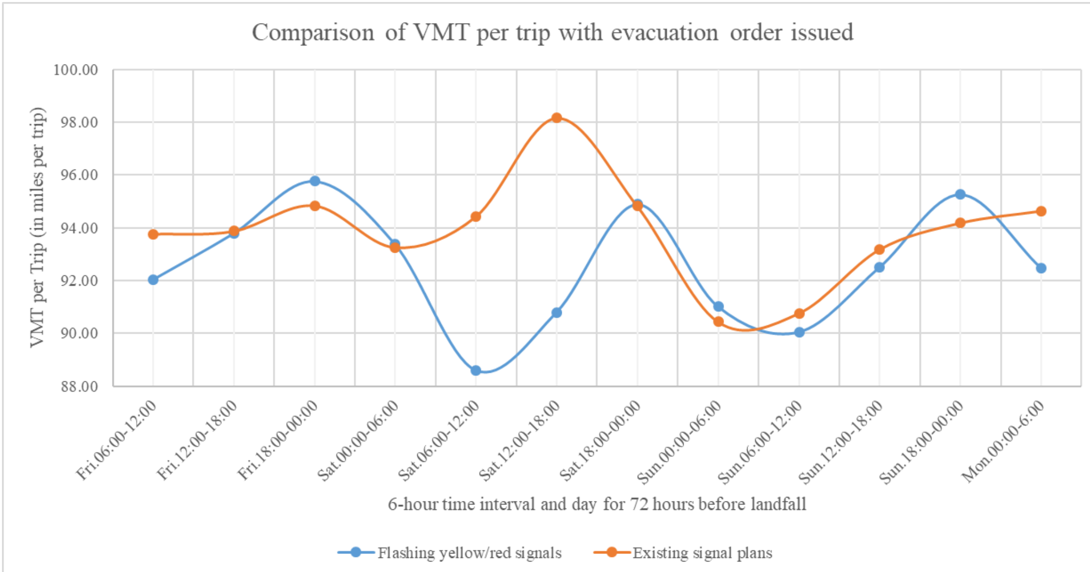


Figure 26 and Figure 27 show the estimated average delay per trip in the system with flashing yellow/red and existing traffic signal plans, respectively. Clearly, there is a significant difference in estimated delay between the two traffic control systems during periods of peak demand, with the delay using existing traffic plans being almost double that with flashing yellow/red in use in certain circumstances.

Figure 26. Total delay per trip for different signal setting with no evacuation order

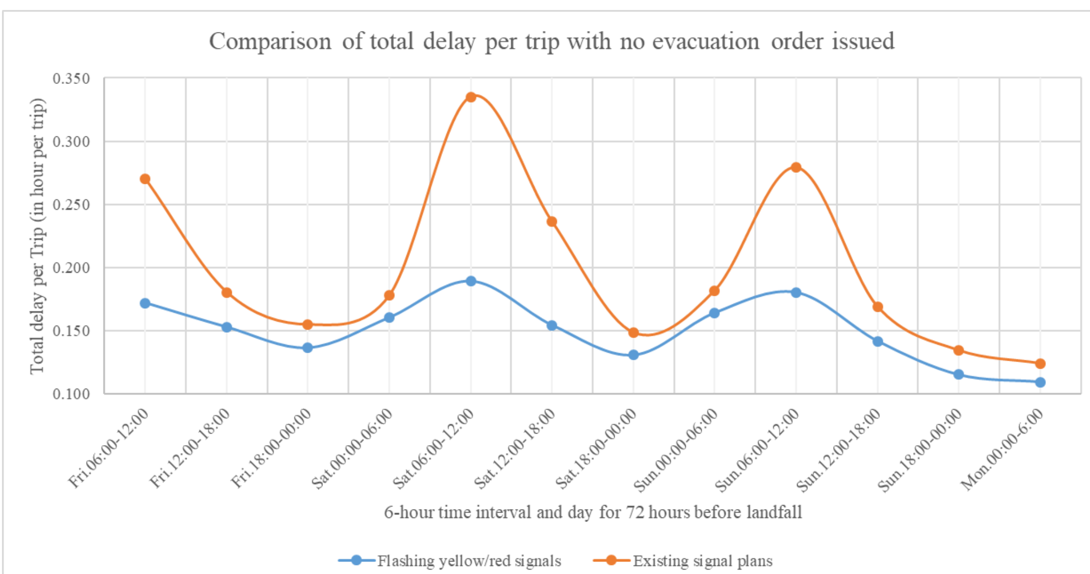
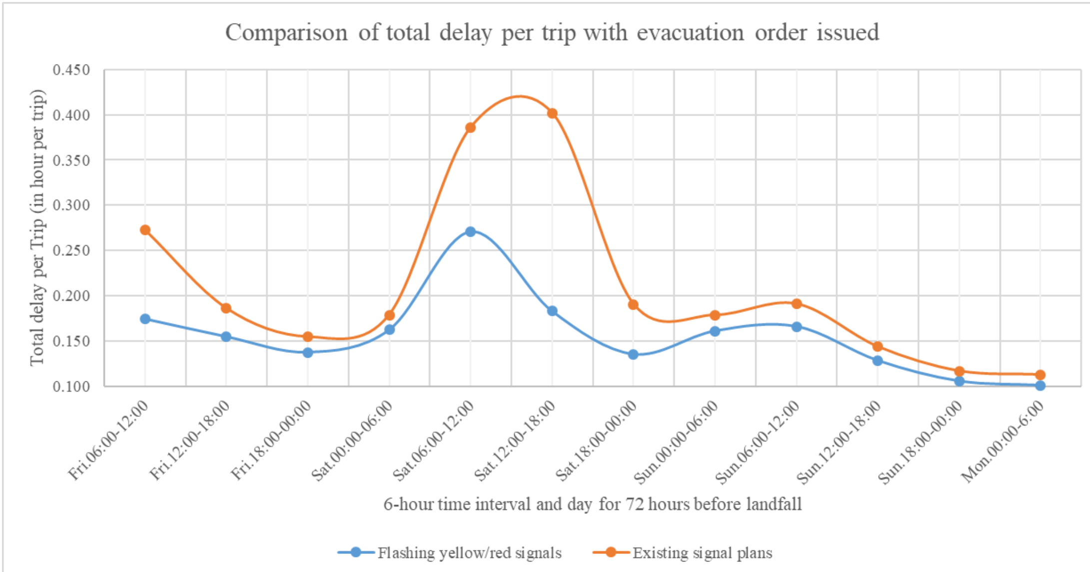


Figure 27. Total delay per trip for different signal settings with evacuation order issued



Average speed in miles per hour with different traffic signal control systems are shown in Figure 28 and Figure 29. Speed is reduced during peak periods with both traffic control systems, but the reduction is greater when the existing traffic signal plans are kept in place. The reduction in average travel speed is less than 5 miles per hour, but it must be kept in mind that this is a system-wide average and that speed reductions on individual links in the network could be much higher.

Figure 28. Average speed for different signal settings with no evacuation order

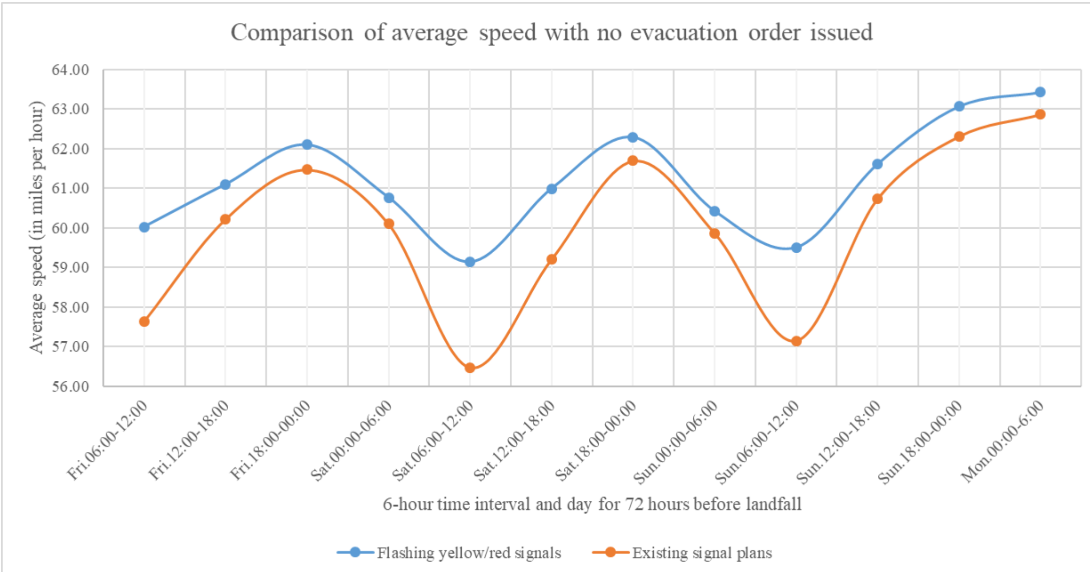
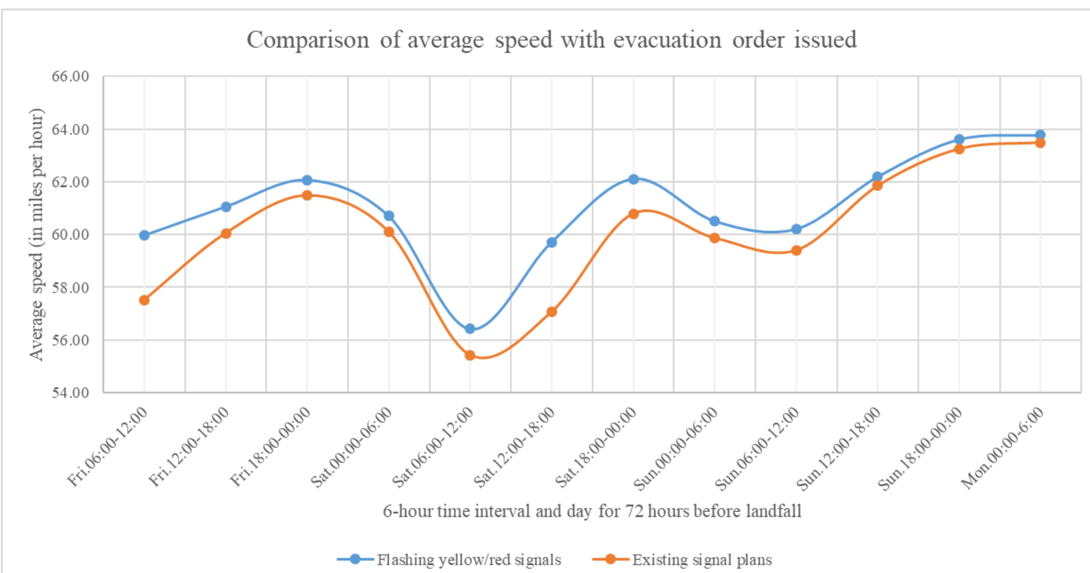


Figure 29. Average speed for different signal settings with evacuation order issued



Route Choice Parameters

Because of the nature of the route choice model developed by [32] Akbarzadeh and the variables included in it, TransModeler was unable to implement the model directly. A path file listing all the potential paths between the origins and destinations had to be developed independently. An initial set of paths was established by intentionally overloading the network to force TransModeler to produce a path file that contained all possible paths. There were 64,389 paths between 8,462 OD pairs generated by this process. A series of Excel spreadsheets using Visual Basic macros removed paths which were determined to not be meaningfully different, leaving 12,192 distinct paths. For the remaining paths, the relevant input data corresponding to the route choice parameters was aggregated. Then the spreadsheets produced a table of the computed probability that a vehicle would take a path for each path between each OD pair using the parameters outlined by the model. That probability table was then formatted as a path flow table in a .bin file and attached to the OD demand matrices for 12 time windows so that TransModeler would send the appropriate number of vehicles on each path in each time period.

Shortest Path Assignment

To properly determine the strength of the route choice logit model, it was compared against a baseline shortest path assignment from TransModeler. The same time-dependent OD demand matrices were fed as inputs to TransModeler, minus the path flow tables. TransModeler developed its own path flow table based on shortest path.

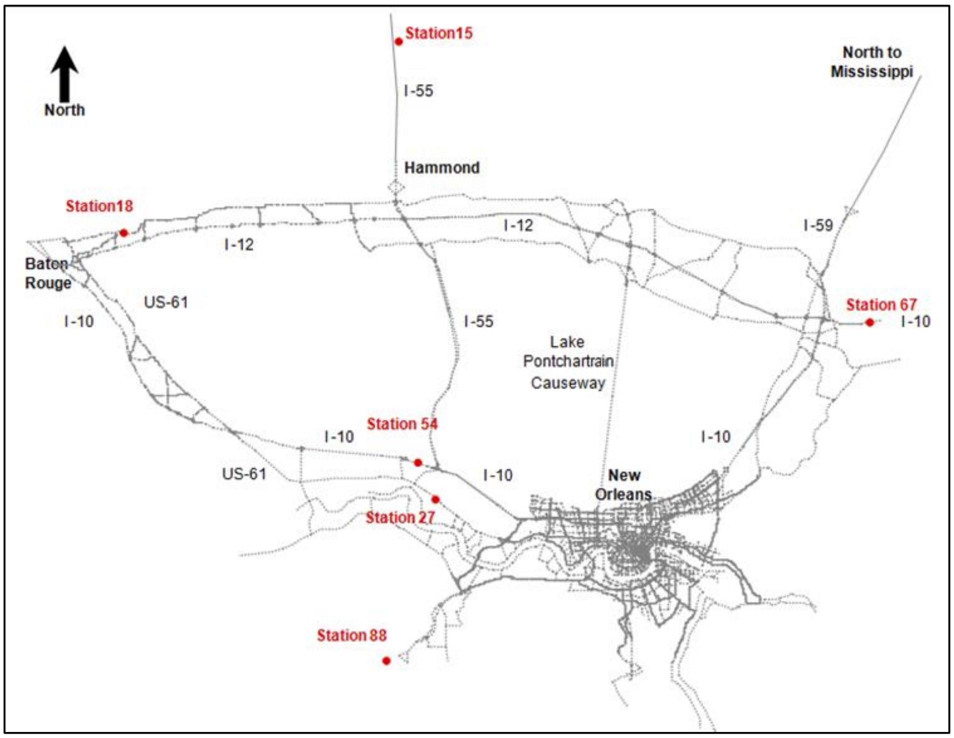
TransModeler does not normally support simulations longer than 24 hours, so an additional macro had to be written to stitch the three 24-hour periods together by saving the end of each 6-hour time period as an initial state to be loaded in the beginning of the next simulation. This macro also contained the hourly distribution values for each OD matrix.

Comparison with Traffic Counts

Vehicle counts observed during the evacuation of Hurricane Katrina were obtained from the Louisiana Department of Transportation and Development for 48 hours from 12 AM August 27, 2005 to 12 AM August 29, 2005. Counts from five permanent traffic counting stations on the major evacuation routes from New Orleans were used: I-10E in Slidell

(Station 67), I10-W in Laplace (Station 54), I55-N near Hammond (Station 15), US 61N in Laplace (Station 27), and US 90 in Raceland (Station 88). Model predictions of traffic counts were made at the same locations in the network as those from the permanent traffic counters. In line with Dixit et al. [34], the counts from Station 18 on US 190 were not analyzed because they did not differ statistically from standard traffic patterns in that area. Figure 30 below displays the traffic count locations.

Figure 30. Traffic count locations



The predicted hourly volumes from HEMP using the logit route choice model and the shortest path, together with the actual traffic counts at individual traffic count locations, are shown in Figure 31 to Figure 35.

Figure 31. Predicted and observed traffic counts on I-10W in LaPlace

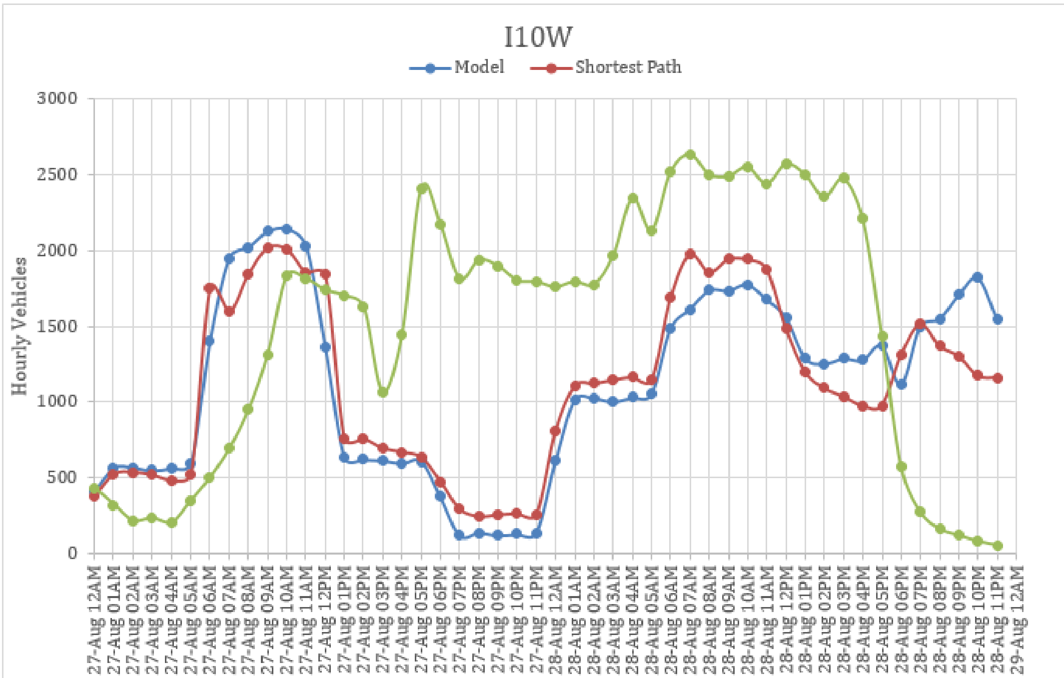


Figure 32. Predicted and observed traffic counts on I-10E in Slidell

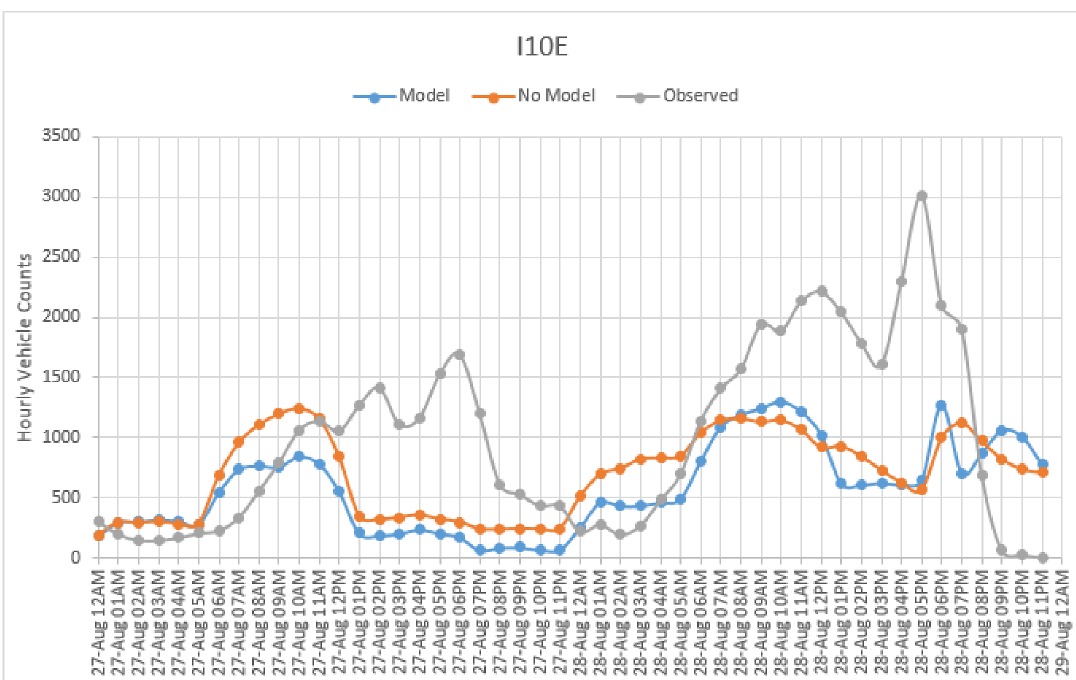


Figure 33. Predicted and observed traffic counts on I-55N in Hammond

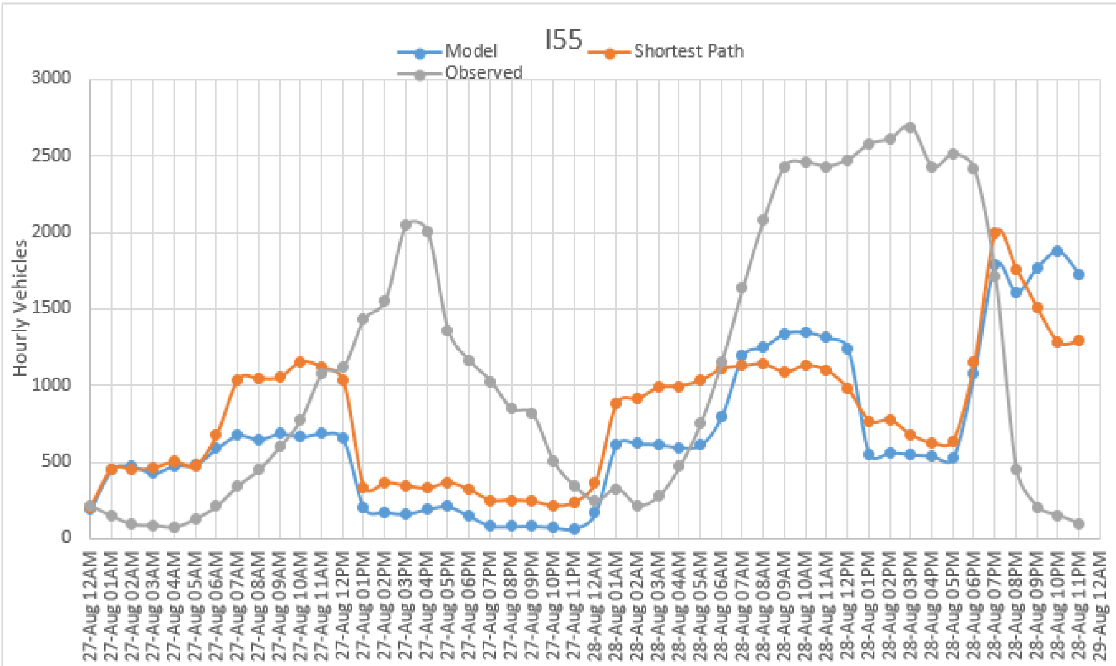


Figure 34. Predicted and observed traffic counts on US 61N in LaPlace

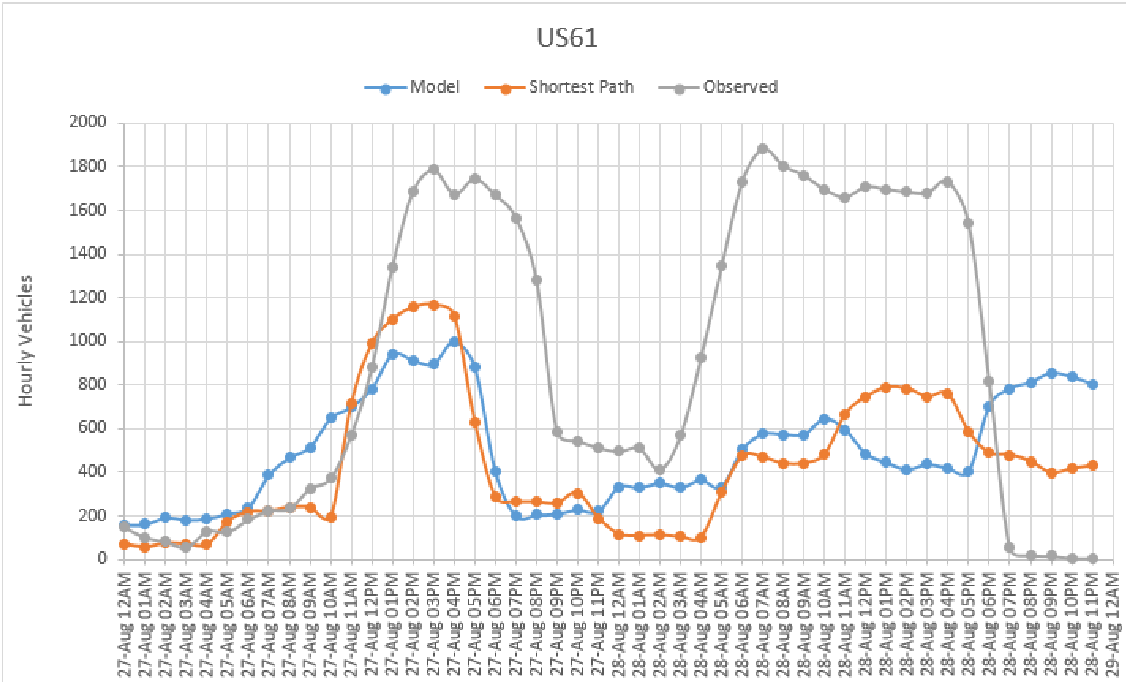
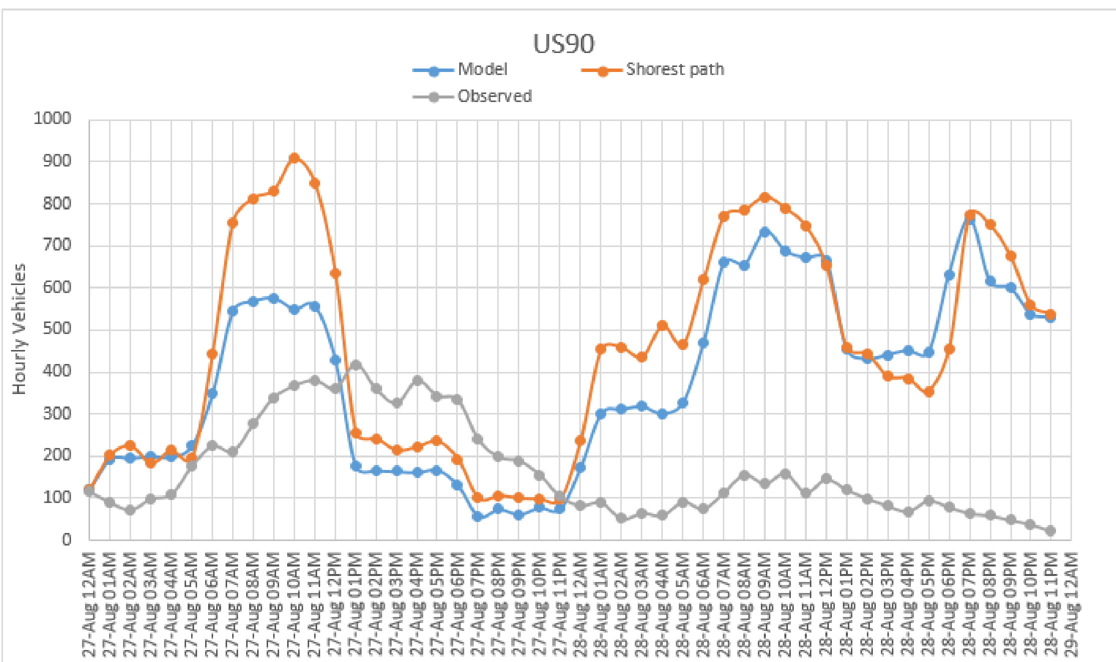


Figure 35. Predicted and observed counts on US90W in Raceland



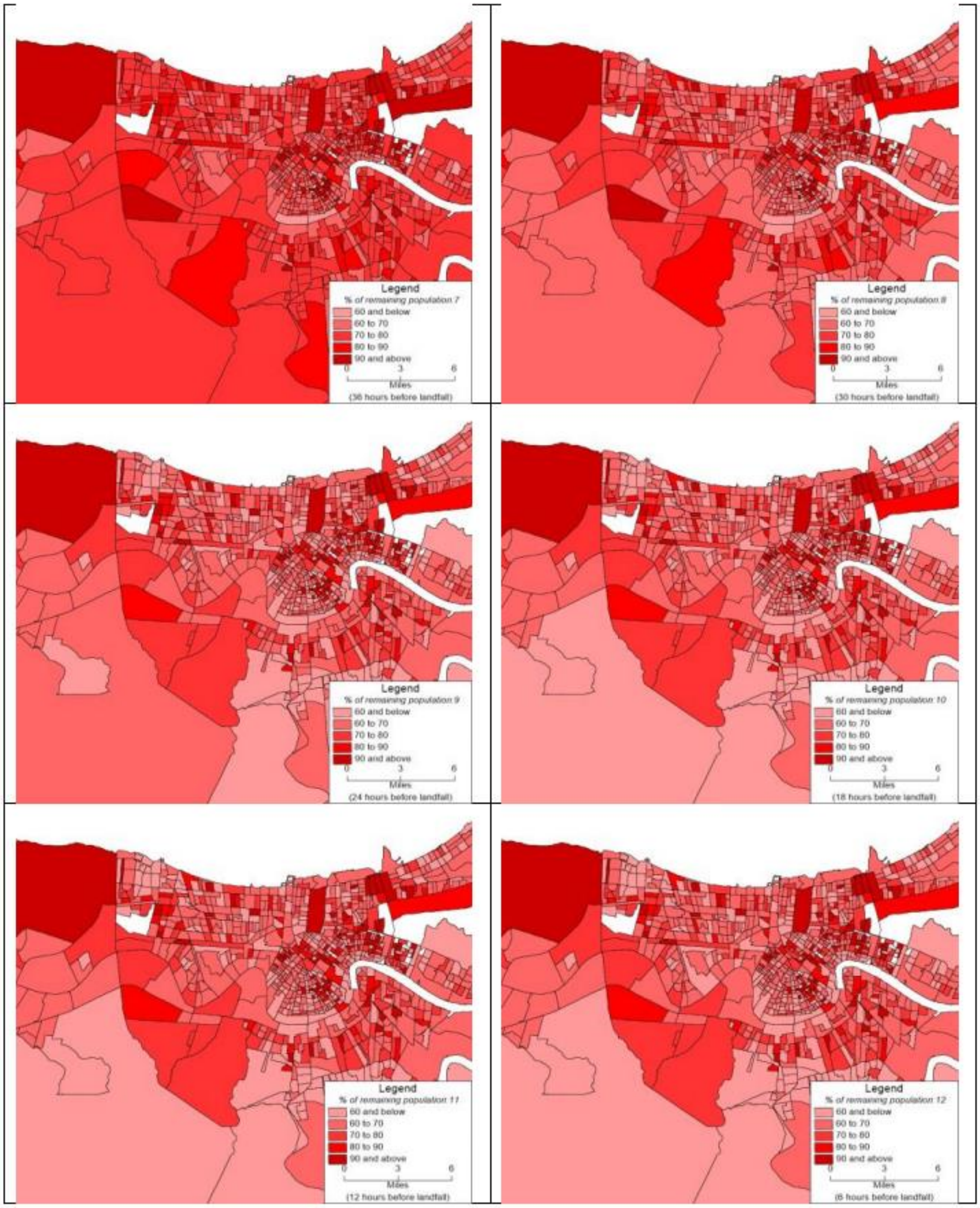
Both simulated methods of assigning vehicles to the evacuation network have similar shapes. Both have day and night cycles which are not as clearly apparent among the observed values, and both methods underestimated the total number of observed vehicles by at least 10,000 on the 4 highest volume routes. The lack of a clear diurnal pattern among the observed values is put down to the fact that increasingly severe warnings were issued during the day on Saturday, August 27, 2005, resulting in a large number of households uncharacteristically evacuating at night on Saturday. The demand models in HEMP are only sensitive to if and when an evacuation order is issued and not on the strength of the evacuation message or to its repeated mention. The average difference between the cumulative totals of the two models was only 2,374 vehicles; whereas, the average difference between the models and the observed were 13,727 vehicles and 11,353 vehicles. There are several reasons why the demand was underestimated. First, the population data set used was based on 2013 New Orleans which had not quite recovered to the 2005 New Orleans levels. Second, modeling the demand for the last 48 hours neglected the fact that some traffic was still on the network from earlier departures.

One prediction that was dramatically different to the observed value was US 90, the highway from New Orleans to Lafayette, where evacuation traffic was overestimated. Interestingly, Dixit et al. [34] also overestimated the demand on US 90 in a similar fashion suggesting that an additional factor is needed to better explain this lower volume route. Anecdotally, US 90 is known locally to flood easily, making it an uncertain path for evacuation among those familiar with the route.

Graphic Output of Evacuation Migration

Thematic maps are generated for visual presentation of spatial information at a disaggregate level. One of these maps reflects the percentage of the population remaining in each block group over time as the population evacuates. Figure 36 shows a series of these maps in 6-hour intervals showing the remaining population in New Orleans as households leave their homes in the face of Hurricane Katrina. As shown in the legend, dark red stands for a high percentage of the residential population still in their zone of residence, and at 72 hours prior to hurricane landfall, the diagram is almost universally dark red. At 66 hours prior to landfall, some areas are beginning to evacuate as shown by the light red areas in the map. As time progresses, the areas experiencing evacuation expands from, primarily, Orleans and Jefferson parishes to areas further afield. At 6 hours prior to landfall, many areas have 60 percent or less of their normal population.

Figure 36 Graphic representation of time-dependent evacuation


Legend
% of remaining population 7
60 and below
60 to 70
70 to 80
80 to 90
90 and above
0 3 6
Miles
(36 hours before landfall)
Legend
% of remaining population 8
60 and below
60 to 70
70 to 80
80 to 90
90 and above
0 3 6
Miles
(30 hours before landfall)
Legend
% of remaining population 9
60 and below
60 to 70
70 to 80
80 to 90
90 and above
0 3 6
Miles
(24 hours before landfall)
Legend
% of remaining population 10
60 and below
60 to 70
70 to 80
80 to 90
90 and above
0 3 6
Miles
(18 hours before landfall)
Legend
% of remaining population 11
60 and below
60 to 70
70 to 80
80 to 90
90 and above
0 3 6
Miles
(12 hours before landfall)
Legend
% of remaining population 12
60 and below
60 to 70
70 to 80
80 to 90
90 and above
0 3 6
Miles
(6 hours before landfall)

Conclusions

The objective of this project was to establish an integrated set of hurricane evacuation demand models in a user-friendly package, and demonstrate its use in an application to the New Orleans metropolitan area. Both objectives were met.

One of the conclusions drawn from the development of this package and its application in New Orleans is that care must be taken to apply the models in the package in exactly the same manner as that in which they were estimated. Specifically, the level of aggregation, units, and time to which each variable applies, must be consistent between the estimation and application environments. For example, the Time Dependent Sequential Logit Model in HEMP operates on households, describes distance to the storm in terms of a gamma function, and uses discrete time periods of 6 hours to describe the change in conditions over time. When using this model in HEMP, the input data must use households as the sampling unit, transform distance to the storm in terms of the gamma function, and use 6-hour time intervals. Similarly, the destination choice model uses zonal information at different levels of aggregation depending on the distance from the point of evacuation, and measures distance as the shortest path distance on the evacuation network between origin and destination in miles. In applying the model, the same range of zone sizes must be used and distance must be measured in miles. All models in HEMP must be applied in the same manner in which they were estimated. Failure to do will result in false model estimates.

A second conclusion is that coding a network for application can take a large amount of time and effort if the network is to be coded accurately and provide all the network features needed by the models in HEMP. Specifically, current traffic signal settings must be accurately coded if TransModeler is to simulate traffic on the evacuation network realistically. If intersections are left without traffic control in TransModeler, vehicles are assumed to pass through intersections unhindered if another vehicle is not crossing their path, leading to unrealistically favorable traffic conditions. The probabilistic route choice model in HEMP requires data on AADT and the number of gas stations and hotels on each route. This data is needed as a proxy for the familiarity evacuees have with a route and as a means to measure the perceived level of service on each route, respectively.

A further finding of this study is that traffic control involving flashing yellow on main routes and flashing red on minor routes, was consistently better than keeping existing traffic signal settings in operation during evacuation, particularly during periods of peak traffic. In the application reported in this study, flashing yellow/red resulted in less delay, higher speeds, shorter travel times, and less total travel than with current traffic signal settings.

Traffic assignment using the route choice method included in HEMP resulted in similar traffic flow estimates to that achieved using shortest path assignment in TransModeler. This may indicate that travel time is the most important consideration in route choice even in evacuation. However, the two methods do produce results that are up to 450 vehicles per hour different at certain times in certain locations. Further research into the application of the route choice method in TransModeler is needed to verify the integrity of the method.

Further work is needed to streamline the application of HEMP, ensure input data is correctly submitted, and verify the package is operating correctly. Repeated runs of individual components, testing the sequential operation of models, and assessing the plausibility of alternative scenarios is needed to verify the integrity of the package. Besides this "debugging" operation, attention should be given to improving the output generated by the package. In particular, the statistic "clearance time" should be added since emergency managers use it to determine the latest they can issue an evacuation order without having evacuees exposed to gale force winds as they evacuate.

Recommendations

The following recommendations are made based on the conclusions of this study:

1. Test HEMP to identify any bugs in the package.
2. Incorporate instructions in the running of HEMP that will ensure input data is correctly specified.
3. Review the application of the route choice method in TransModeler.

Acronyms, Abbreviations, and Symbols

Term	Description
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACS	American Community Survey
CBP	County Business Pattern
cm	centimeter(s)
DOTD	Louisiana Department of Transportation and Development
FHWA	Federal Highway Administration
FR	Friends/Relatives
ft.	foot (feet)
FYR	Flashing yellow/red (traffic signal)
HEMP	Hurricane Evacuation Modeling Package
HM	Hotel/Motel
IOM	Intervening Opportunity Model
in.	inch(es)
LTRC	Louisiana Transportation Research Center
lb.	pound(s)
LIDAR	Light Detection and Ranging
m	meter(s)
MCDTC	Joint Mode and Destination Type Choice model
MEOW	Maximum Envelope of Water
MOE	Measure of Effectiveness
MOM	Maximum of Maximums
MNL	Multinomial Logit
PUMS	Public Utility Microdata Samples
NHC	National Hurricane Center
NL	Nested Logit
OD	Origin-Destination
OT	Other

Term	Description
SH	Shelter
TDSLM	Time-Dependent Sequential Logit Model
TDNLM	Time-Dependent Nested Logit Model
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled

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Appendix

Predicted and Observed Volumes

	I10W			I10E		
Time	Model	Shortest Path	Observed	Model	Shortest Path	Observed
27-Aug 12AM	415	383	433	182	189	306
27-Aug 01AM	569	526	323	299	296	202
27-Aug 02AM	569	538	217	304	291	151
27-Aug 03AM	549	519	235	322	302	149
27-Aug 04AM	566	483	206	309	284	171
27-Aug 05AM	596	521	350	281	285	208
27-Aug 06AM	1402	1,756	502	543	684	230
27-Aug 07AM	1951	1,596	693	736	959	338
27-Aug 08AM	2024	1,847	950	766	1,112	559
27-Aug 09AM	2127	2,020	1317	756	1,203	793
27-Aug 10AM	2145	2,010	1838	843	1,248	1062
27-Aug 11AM	2034	1,858	1816	784	1,164	1143
27-Aug 12PM	1368	1,844	1743	556	843	1059
27-Aug 01PM	635	758	1704	209	346	1271
27-Aug 02PM	621	757	1630	189	320	1418
27-Aug 03PM	615	697	1064	204	338	1112

27-Aug 04PM	596	670	1446	238	355	1168
27-Aug 05PM	610	636	2412	206	323	1526
27-Aug 06PM	375	477	2174	175	299	1694
27-Aug 07PM	121	294	1815	67	240	1200
27-Aug 08PM	139	245	1939	87	238	612
27-Aug 09PM	121	255	1901	90	243	532
27-Aug 10PM	129	263	1805	70	240	438
27-Aug 11PM	138	257	1795	73	245	434
28-Aug 12AM	614	812	1761	256	514	222
28-Aug 01AM	1018	1,107	1797	464	697	282
28-Aug 02AM	1026	1,123	1778	434	746	197
28-Aug 03AM	1004	1,146	1968	436	824	272
28-Aug 04AM	1031	1,164	2349	463	835	485
28-Aug 05AM	1053	1,145	2134	494	851	700
28-Aug 06AM	1490	1,693	2525	803	1,044	1138
28-Aug 07AM	1614	1,977	2637	1090	1,147	1409

	I-10W in LaPlace			I-10E in Slidell		
Time	Model	Shortest Path	Observed	Model	Shortest Path	Observed
28-Aug 08AM	1739	1,858	2505	1188	1,163	1571
28-Aug 09AM	1737	1,944	2493	1242	1,136	1943
28-Aug 10AM	1777	1,943	2554	1298	1,150	1887
28-Aug 11AM	1679	1,877	2442	1216	1,070	2134
28-Aug 12PM	1559	1,488	2574	1024	920	2212
28-Aug 01PM	1293	1,201	2504	621	932	2043
28-Aug 02PM	1254	1,093	2353	609	847	1789
28-Aug 03PM	1288	1,037	2477	626	731	1609
28-Aug 04PM	1278	976	2210	612	627	2303
28-Aug 05PM	1376	979	1432	646	567	3009
28-Aug 06PM	1117	1,313	573	1272	1,003	2097
28-Aug 07PM	1501	1,515	275	707	1,124	1901
28-Aug 08PM	1550	1,372	163	873	972	682
28-Aug 09PM	1707	1,303	119	1061	824	64
28-Aug 10PM	1821	1,175	81	1010	738	28
28-Aug 11PM	1550	1,161	54	779	711	8
Total Counts	53491	53612	72066	27513	33220	47761

	I55			US61		
Time	Model	Shortest Path	Observed	Model	Shortest Path	Observed
27-Aug 12AM	191	210	215	159	69	146
27-Aug 01AM	448	456	146	162	56	102
27-Aug 02AM	473	451	93	193	74	81
27-Aug 03AM	429	464	86	182	70	57
27-Aug 04AM	480	503	76	188	67	130
27-Aug 05AM	486	478	129	211	174	127
27-Aug 06AM	591	682	212	238	217	183
27-Aug 07AM	676	1041	343	388	221	225
27-Aug 08AM	650	1045	448	466	238	234
27-Aug 09AM	686	1055	599	515	237	326
27-Aug 10AM	667	1157	777	647	194	374
27-Aug 11AM	687	1120	1077	697	713	571
27-Aug 12PM	653	1033	1117	783	988	881
27-Aug 01PM	201	334	1432	938	1,098	1342
27-Aug 02PM	177	367	1553	911	1,154	1686
27-Aug 03PM	164	347	2046	894	1,166	1785
27-Aug 04PM	196	330	2007	998	1,116	1675
27-Aug 05PM	212	368	1357	881	630	1743
27-Aug 06PM	149	320	1161	404	285	1670
27-Aug 07PM	88	252	1030	201	264	1565

	I55-N in Hammond			US 61N in LaPlace		
Time	Model	Shortest Path	Observed	Model	Shortest Path	Observed
27-Aug 08PM	83	253	848	205	262	1279
27-Aug 09PM	86	244	815	210	257	583
27-Aug 10PM	77	217	503	228	305	544
27-Aug 11PM	69	239	344	221	189	513
28-Aug 12AM	170	372	244	333	116	496
28-Aug 01AM	617	887	326	330	109	511
28-Aug 02AM	622	915	217	350	112	413
28-Aug 03AM	617	989	277	331	103	567
28-Aug 04AM	598	998	470	364	102	927
28-Aug 05AM	613	1035	753	334	307	1344
28-Aug 06AM	800	1110	1151	504	473	1731
28-Aug 07AM	1197	1129	1637	575	467	1881
28-Aug 08AM	1251	1141	2082	573	439	1804
28-Aug 09AM	1340	1088	2433	573	441	1760
28-Aug 10AM	1348	1133	2455	645	481	1695
28-Aug 11AM	1311	1098	2430	595	664	1660
28-Aug 12PM	1243	978	2474	486	744	1708

28-Aug 01PM	552	771	2575	445	787	1696
28-Aug 02PM	565	776	2610	414	782	1684
28-Aug 03PM	551	678	2690	436	745	1680
28-Aug 04PM	542	626	2428	419	757	1733
28-Aug 05PM	527	641	2512	403	583	1540
28-Aug 06PM	1082	1151	2412	704	488	816
28-Aug 07PM	1786	1996	1714	783	479	52
28-Aug 08PM	1609	1762	451	811	449	22
28-Aug 09PM	1773	1506	210	854	397	17
28-Aug 10PM	1875	1282	153	837	415	7
28-Aug 11PM	1729	1290	99	805	429	6
Total Counts	32937	38318	53217	23824	20913	43572

US90

Time	Model	Shortest Path	Observed
27-Aug 12AM	121	121	116
27-Aug 01AM	193	202	90
27-Aug 02AM	195	224	73
27-Aug 03AM	200	183	99
27-Aug 04AM	198	214	110
27-Aug 05AM	225	194	177

27-Aug 06AM	348	444	224
27-Aug 07AM	544	757	212

US90 in Raceland

Time	Model	Shortest Path	Observed
27-Aug 08AM	568	813	277
27-Aug 09AM	575	832	339
27-Aug 10AM	549	908	367
27-Aug 11AM	557	850	380
27-Aug 12PM	429	636	361
27-Aug 01PM	176	256	418
27-Aug 02PM	166	242	359
27-Aug 03PM	164	214	326
27-Aug 04PM	161	222	379
27-Aug 05PM	167	235	343
27-Aug 06PM	131	193	333
27-Aug 07PM	58	100	239
27-Aug 08PM	74	106	198
27-Aug 09PM	62	100	189
27-Aug 10PM	78	98	156
27-Aug 11PM	75	97	104

28-Aug 12AM	174	238	83
28-Aug 01AM	302	454	90
28-Aug 02AM	311	458	51
28-Aug 03AM	318	436	65
28-Aug 04AM	301	510	59
28-Aug 05AM	328	466	92
28-Aug 06AM	470	619	75
28-Aug 07AM	660	770	114
28-Aug 08AM	655	784	156
28-Aug 09AM	734	817	134
28-Aug 10AM	687	789	159
28-Aug 11AM	671	747	114
28-Aug 12PM	666	652	145
28-Aug 01PM	453	459	120
28-Aug 02PM	432	444	99
28-Aug 03PM	441	390	82
28-Aug 04PM	452	385	69
28-Aug 05PM	447	355	94
28-Aug 06PM	633	455	79
28-Aug 07PM	764	775	64
28-Aug 08PM	615	750	59

28-Aug 09PM	600	676	48
28-Aug 10PM	538	560	38
28-Aug 11PM	531	539	22
Total Counts	18197	21769	7980

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