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Chapter 6

Application of Simulation Modeling for Hurricane Contraflow Evacuation Planning

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Additional information is available at the end of the chapter

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1. Introduction

The Gulf Coast and Atlantic coastal states of the U.S. are often subjected to severe tropical storms and hurricanes. Hurricane season nominally extends from June 1 to November 30 of each year. From 1851 to 2006, there have been 279 landfalls on the mainland U.S. coastline, including 96 major hurricanes of Category 3 and above. Among these, the thirty most costly strikes resulted in an estimated total loss of approximately $346 billion in 2006 dollars, and took more than 19000 lives [1]. The usual response to these severe weather events is to evacuate inland from the coast. Normal traffic flows may turn into congestion, frustration and gridlock. This reduces the number of vehicles that can leave the coastal area if an evacuation order is issued. The potential risk for loss of life increases if the hurricane strikes stalled traffic, as people's efforts to evacuate might place them at greater risk than they would have faced if they had stayed put. In response to Hurricane Floyd (see Figure 1), extensive traffic delays occurred along inland evacuation routes throughout the state of South Carolina. Subsequently, The U.S. Federal Emergency Management Administration (FEMA) conducted regional meetings to identify approaches for better traffic planning, management, and coordination. These planning efforts have continued at the federal, regional, state, and local levels.

With modern weather forecasting techniques, the path and associated strength of an advancing hurricane can be predicted with some confidence. Progressively more attention has been paid to improving the planning and operations of hurricane evacuation to reduce unnecessary losses in the projected area of landfall or near landfall. Evacuation planning for a large area frequently involves multiple considerations, e.g. shelter location, evacuation routes, flow assignment, allocation of emergency response and law enforcement resources. Operational strategies may include real time traffic monitoring, advanced traveler alerts, signal timing adjustment for local arterials, and rerouting both local and interstate roads. In

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the United States, several Southeastern states have adopted the concept of "contraflow", or "reverse-laning", in hurricane evacuation. "Reverse-laning" is the process of reversing one direction of traffic on specific routes to facilitate overall evacuation flow. This procedure is generally applicable to interstate roadways, referred to as "denied access routes", since traffic control can be applied to interchanges and terminal areas. (See Figure 2) The idea is to reverse one direction of the roadway in order to accommodate the often substantially increased travel demand moving away from the impact area. Actual implementation of reverse-laning varies from state to state. For example, in the states of Texas and Florida, each county or regional area has its own evacuation plan, many of them involving contraflow. Contraflow operations are only executed in Texas if a mandatory evacuation order is issued by the respective mayor or county judge [2]. Reverse-laning plans for the major metropolitan areas are detailed by the Texas Department of Transportation [3]. In the event of voluntary evacuations, there is no actual lane reversal and the shoulders of the road are used as travel lanes. In Florida, the State's Department of Transportation coordinates the individual counties evacuation plans, such that the following roadways utilize contraflow for evacuation: I-75, I-10, I-4, the Florida Turnpike, and State Road 528 [4]. Louisiana and Mississippi share a unique plan for shared hurricane evacuation. Because of its small coastal population, Mississippi does not utilize contraflow within its own borders, since its roadways can handle evacuation traffic without modification. The city of New Orleans in Louisiana is a major population center, whose evacuation routes may go through Mississippi. The two states thus coordinate their contraflow operations to avoid confusion and disruption [5].

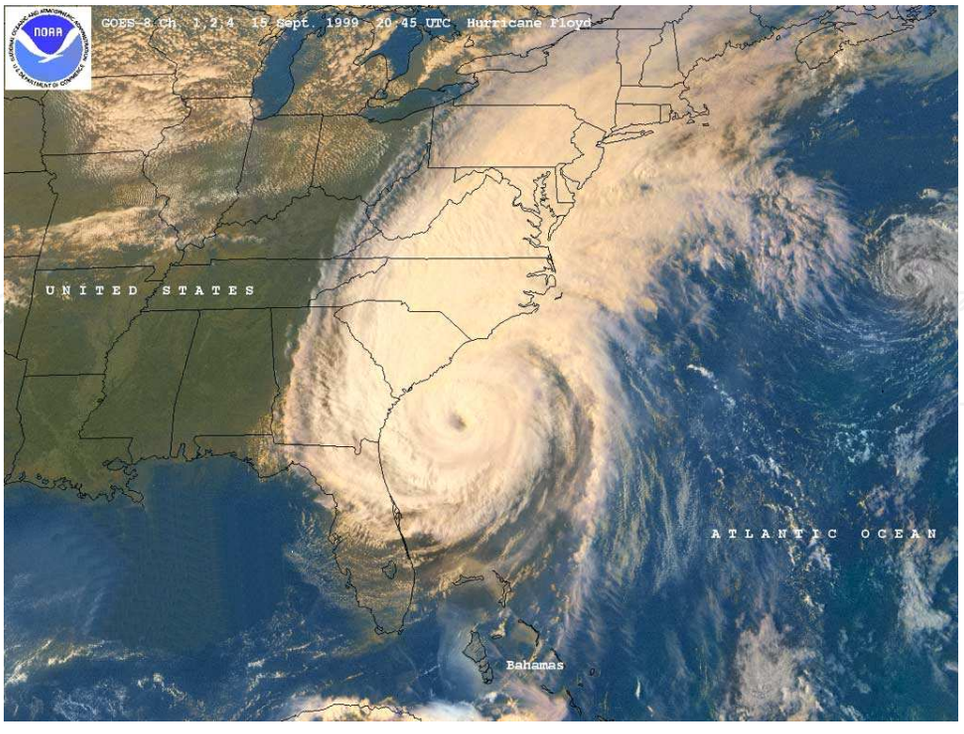


Figure 1. Hurricane Floyd approaching the South Carolina coast (September 1999)

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Figure 2. Traffic control using temporary barriers during contraflow operations

During the past 60 years, 25 hurricanes have made landfall along the Gulf Coast. Of those, five (Hurricanes Frederick, Eloise, Opal, Ivan, and Dennis) have had the eye of the hurricane make landfall in Alabama [6]. Many other hurricanes, that may have not made actual landfall in Alabama, have caused significant damage (e.g. Hurricane Katrina in 2005). As an increasing number of Alabama's population lives in the eight counties closest to the Gulf of Mexico (See Table 1), it is becoming progressively more vulnerable to these extreme weather events [7]. The Alabama Department of Transportation (ALDOT) has developed a well-planned evacuation procedure for this coastal area of the state. In this plan, an approximately 140-mile section of Interstate roadway 65 (I-65) between exit 31 and exit 167 is identified as the contraflow segment. As noted in Figure 3, I-65 would be reverse-laned such that all traffic would flow north, from south of Alabama Route 225, near the large population center of Mobile, to Exit 167/168, just south of the greater Montgomery metropolitan area [8]. This concept was further refined after Hurricane Katrina, to provide emergency vehicles with an alternate route south via U.S. 31.

ALDOT's reverse-laning plan identifies four operating levels [8]. Level 1 begins with the start of each hurricane season. Level 2 is initiated when the U.S. National Weather Service (NWS) issues a hurricane watch for the Gulf Coast of Alabama, Mississippi, and the "panhandle" region of northwest Florida. Level 3 is indicated when the NWS watch is upgraded to a hurricane warning. During these first three operating levels, the required equipment are gradually staged and personnel prepare for contraflow operations. The actual reverse-laning occurs during Level 4, when the State's Transportation Director (in consultation with the Alabama Emergency Management Services) issues the order for contraflow, and extends until he orders termination of the operations [8].

County	Population	Persons/Vehicle
Mobile	400526	.96
Washington	17906	.73
Baldwin	156701	.73
Escambia	38336	.96
Conecuh	13453	.86
Monroe	23725	.96
Butler	20764	1.21
Lowndes	13210	1.21

Table 1. Alabama counties included in this study

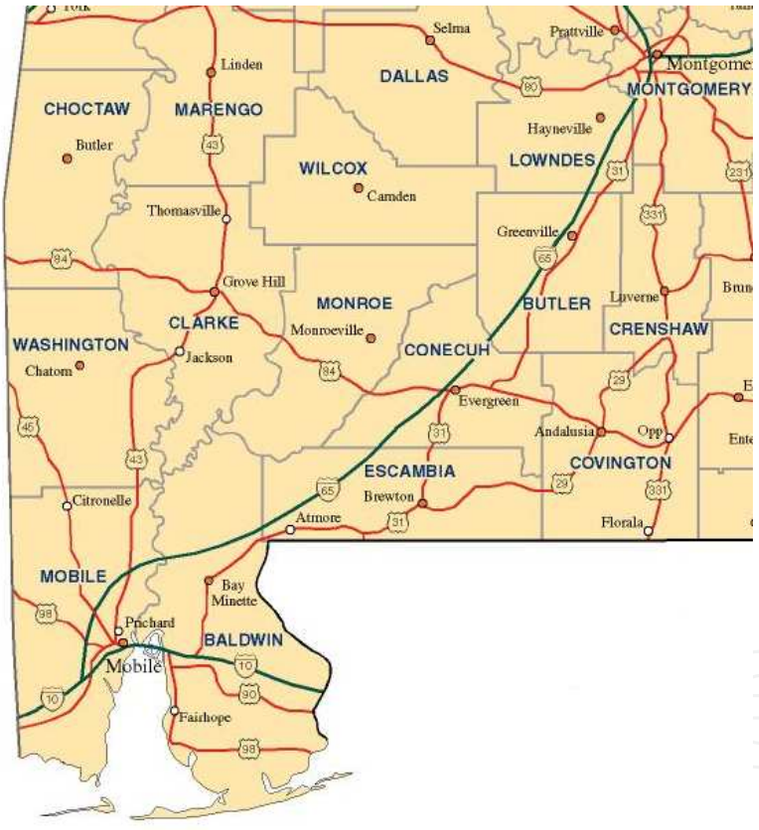


Figure 3. Map of contraflow segment in Alabama

2. Problem statement

The current practice in Alabama is a staged process. Equipment and personnel are deployed first, and the actual call for reversing the southbound lanes depends on the measured traffic

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condition and other relevant factors [8]. Although these contraflow operations increase the roadway capacity for evacuation, this reverse-laning is, by its necessity, a unique measure requiring extraordinary efforts. Practical implementation issues include traffic control, access management, use of roadside facilities, safety, labor requirements, and cost [9]. Therefore, care must be taken in the planning and real-time operations of contraflow evacuation. However, such decisions are often made in an ad hoc manner during actual implementation. Review of the literature indicates that a number of simulation frameworks [10-12] as well as several optimization models for evacuation flow assignment [13-17] have been developed to assist decision-makers during in emergency evacuations. However, the literature further indicates that few studies have directly addressed specific issues related to contraflow planning and operation. Kim et al. [18] and Lv et al. [19] try to determine which lanes in a transportation network should be reversed from a system perspective. Theodoulou and Wolshon [20] and William et al. [21] focus on detailed configurations of the starting point of the specified contraflow segment. Meng and Khoo [22] consider the onset and duration of contraflow in an integrated problem.

Selection of a suitable evacuation model is requisite to support the needs of the Alabama Department of Transportation Maintenance Bureau regarding their responsibilities for contraflow planning and evaluating possible responses to a hurricane event. The I-65 evacuation route has been subject to considerable analysis [23, 24]. Yet these analyses have focused only on capacity and congestion issues relating to I-65, itself. It has been suggested that selective control of specific on-ramps may improve the effectiveness of the overall evacuation routes. For example, prioritization could be based on level of danger (giving people living closest to the coast priority access to I-65, with other communities directed to other state roads). These planning alternatives could be evaluated through an improved evacuation planning model.

3. Research course

Review of the literature has noted considerable work on the development of decision rules and computer-based support systems to aid in decision-making [25]. A variety of mathematical models have been developed which focus on evacuation route planning. These network models of evacuation problems are extensions of the classical operations research assignment problem. For these problems, the basic form of the network is that of the more general minimal cost transshipment (or flow) network. In the network, the arcs represent the flow of people, the source nodes represent initial source inventories (points of entrance into the evacuation network), and the sink nodes represent the final inventories (in this case, destinations). Optimization models (e.g. linear programming, goal programming or dynamic programming) are another category of mathematical models. The model is formulated to either maximize (or minimize) the objective function (depending upon the purpose of the model) within the context of available resources and constraints [26]. Coastal hurricane evacuation can be seen as a network optimization problem aimed at selecting the "best" routes from a set of candidate roads within an existing roadway network. This selection involves deter-

mining where the potential evacuation routes' origin and destination points are located, their maximum traffic volumes, and the type of evacuation schemes resulting in a maximum vehicle exit rate with minimal travel times [27-30].

A significant issue in managing a disaster evacuation operation is the pattern of flow of the roadways, i.e., equilibrium or non-equilibrium flow. The equilibrium network is satisfied when the distribution of flow in the network follows Wardrop's stated principles [31-33]. These principles note that the total flow of evacuating vehicles eventually reaches an equilibrium state in which every car has the same travel time. Conversely, a flow pattern in a non-equilibrium flow model cannot satisfy these flow constraints since each vehicle uses a distinct route depending upon the overall evacuation strategy utilized [34]. The network evacuation problem can be further categorized as either discrete or continuous network repetitions. Discrete network analysis emphasizes the search of evacuation scenarios in terms of capacity enhancements [34] The objective of the analysis is to select those roads to be included in the evacuation network, incorporating the effects that such a decision may have on the volume of traffic leaving the area under distress.

4. Application area

Continuous network modeling focuses on maximizing the capacity expansion of existing, predetermined evacuation networks. Monte Carlo simulation via discrete simulation was originally considered for projecting the uncertainties in traffic flow during the study. When analyzing highly congested highways, or super-saturated conditions, consideration of constructing a new alternative road would seem reasonable. Unfortunately, this approach could lead to Braess's paradox, in which case, the vehicles on the existing highway and the new road would travel much slower than before. The cited paradox was discovered in 1968 by Dietrich Braess, and was originally developed regarding the congestion of signals in transmission networks [35]. Braess determined that increased capacity in congested electronic networks slows down communication. During the past decades, several authors have focused their efforts in understanding the implications of Braess's paradox [32, 35-37]. They have developed heuristics and mathematical models to predict and explain why this counterintuitive situation occurs. However, this knowledge has not been used by highway traffic planners. There is evidence of Braess's paradox in newly constructed roads around the world, as in the case cited of a road built in Stuttgart, Germany, which deteriorated traffic conditions to a point where it had to be closed down [37].

The major obstacle for the application of the mentioned heuristics and mathematical models to improve traffic conditions in congested highways, as is the case during a massive evacuation event, is the lack of knowledge on the premises of Braess's paradox. Subsequent work by Fonseca et al. [38] demonstrated that this could be extended to traffic analysis in a small city. Investigation was conducted regarding the further application of this approach to better project traffic congestion due to hurricane evacuation from the Gulf Coast. The main purpose of this study is to create a prototype model, following Braess's paradox premises, for improved hurricane evacuation planning.

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5. Method used

Probabilistic models analyze the natural variation of conditions, as opposed to determining a mathematical optimum. For example, Fu and Wilmot [39] applied a logit model to estimate the conditional probability of households evacuating during a given time period prior to hurricane landfall. Many conventional algorithmic models may not sufficiently apply to specific domain problem areas, e.g. traffic planning. The utilization of computer-based simulation is a frequent means of probabilistic modeling, as well as a well-accepted approach of modeling complex systems and activities. A simulation model is primarily mathematical in nature. Rather than directly describing the overall behavior of the system under investigation, the simulation model attempts to "replicate" this behavior by studying the interactions among its components. The system is divided into elements whose behavior can be predicted in terms of probability distributions, for each of the various possible states of the system and its inputs [26]. Model output is normally presented in terms of selected metrics that reflect the performance of a system. Simulation has many advantages. It can provide a complete view of the total operations flow. Perhaps the most important advantage of a simulation is that it provides the opportunity for what-if analysis; i.e. it can project the impact of factors under a variety of conditions. The various decision alternatives then may thus be evaluated economically without disrupting existing operations, or incurring unnecessary costs.

During a hurricane evacuation, where the massive flow of vehicles takes place within a relatively short span of time, the traffic network moves from a situation of over-congestion to over-saturation. Under over-saturation conditions, traffic flow optimization is not feasible due to the overwhelming network inflow rate as compared to the exiting rate; thus, the utilization of computer-based simulation is a more appropriate means of modeling the complexity of the flow pattern. The evacuation network involved is this study corresponds to a discrete network presenting a flow pattern in equilibrium. Different levels of traffic representations are used by different classes of simulation models. In microscopic simulation models, the interactions of individual vehicles “are captured by using algorithms that represent vehicle acceleration and deceleration, passing maneuvers, and lane changing behavior” [40]. Tanaka [41] provides such a microscopic simulation model of hurricane evacuation on a single lane highway. The amount of detail, that is required at the microscopic level, becomes overwhelming when trying to model a large-scale evacuation over a large area. Macroscopic or mesoscopic models are favored under such circumstances. Macroscopic models are used to simulate traffic flow based on speed and traffic density relationships, and do not model the interactions between individual vehicles. Mesoscopic simulation models address individual vehicles in the transportation system, but capture their relationships using aggregate relationships. To enhance the modeling capability for real evacuation events and help the decision-maker in contraflow planning, this research will investigate the macroscopic approach, and develop a proof of concept simulation tool.

6. Status

The network consists of a single major US Interstate highway (I-65) with a set of 20 available on-ramp exits, and eight associated counties. The closing or opening of these ramps to traffic bound north represents the main decision variable of the analysis. Accepted development methodology identifies five primary phases: 1) data acquisition, 2) system design, 3) system construction, 4) verification and validation, and 5) experimentation and analysis. During the data acquisition phase, the key concepts and relationships were identified. Although the focus of this effort was on the development and evaluation of an evacuation planning simulation model for I-65, investigation also identified a large number of literature articles devoted to individual and collected hurricane evacuation case studies. These included the "Alabama Hurricane Evacuation Study" [42], and the National Oceanic and Atmospheric Administration's Hurricane Planning and Evacuation Assessment Reports [43]. These references emphasize best practices and lessons learned from a number of hurricane evacuations, as opposed to identifying specific algorithmic models for planning purposes. They did prove valuable as sources of data. Both the "Alabama Hurricane Evacuation Study – Summary Report", and the related "Alabama Hurricane Evacuation Study – Transportation Study [42, 44] were particularly useful in detailing issues regarding evacuation behavior. In addition to the literature search, the ALDOT traffic database was interrogated to obtain traffic data regarding interstate and state highways. Table 2 shows the estimates of the traffic volumes emerging from each on the 20 selected ramps during an eventual hurricane evacuation.

Exit Number	Exit Location	Total Vehicels
22	Washington Mobile	441743
31	Baldwin	53664
34	Baldwin	53664
37	Baldwin	53664
45	Baldwin	53664
54	Escambia	9983
57	Escambia	9983
69	Escambia	9983
77	Escambia	9983
83	Conecuh Monroe	10112
93	Conecuh Monroe	10112
96	Conecuh Monroe	10112
101	Conecuh Monroe	10112
107	Butler	4307
114	Butler	4307

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Exit Number	Exit Location	Total Vehicels
128	Butler	4307
130	Butler	4307
142	Lowndes	3654
151	Lowndes	3654
158	Lowndes	3654

Table 2. I-65 exit locations and respective traffic levels

This led to the development of an overall proof of concept simulation model, initially focusing on management of entry ramps, applied to selected areas of the I-65 extended network. The evacuation model was constructed utilizing the discrete simulation software, *Arena*, which was interfaced with *Excel* macros for improved data input processing. Arena is a software product of Rockwell Automation, and combines both high-level modeling and general-purpose procedural programming. The software incorporates interchangeable templates of graphical simulation objects and statistical data analysis modules [45]. The discrete simulation model assesses the effect of closing selective ramps on the overall traffic evacuation rate, i.e., the number of vehicles evacuated from the area in question per hour. Consistent with Braess' Paradox, it was hypothesized that having all ramps open to vehicles exiting the region might actual be detrimental for the overall evacuation effort since in-flow congestion may be generated by entry ramps located within a few miles from each other; and due to the difficulty encountered by emergency and law-enforcement vehicles bound south when all ramps are exclusively for north-bound traffic. The models of each devised scenario were run at least 30 times to ensure the correctness of the statistical analyses performed.

The resulting simulation, for hurricane evacuation of inhabitants in the vicinity of the City of Mobile, Alabama, consists of a system of one top-level and two supporting models (see Figure 4). The top-level model is based on the entry of vehicles from the 20 on-ramps to I-65. The two supporting models assist the primary model with related traffic events such as car breakdowns and accidents, traffic control measures, inter-arrival signaling, and unforeseen emergency incidents. In the top-level model, entering vehicles are created through a controlled wait-and-signal mechanism [45]. (See Figure 5.) Attributes such as time of arrival, final destination exit, and accident incident proneness are established. These attributes are assigned based on cumulative probability distributions generated by empirical data collected during the data acquisition phase of this research project. Whenever a vehicle enters the highway, it is delayed by factors such as the travel distance and number of vehicles already on the road. The moving car keeps going through a loop of congested entries until its assigned exit attribute equals its final destination attribute. Once this loop sequence ends, the overall vehicle throughput and average travelling speed are then calculated by the simulation. The top-level model is equipped with a resolution factor variable. To prevent the system from growing beyond the software's transaction capacity, the resolution factor was set to 25. Thus, every moving entity within the system represents a group of 25 vehicles, travel-

ling bumper-to-bumper. Additionally, a maximum batch number of entering vehicles at each entry ramp was set based on the total amount of people residing in the communities close to the corresponding ramp, and the pre-established evacuation ratio. This evacuation ratio is an estimate of the fraction of the population exiting from a particular area as determined by ALDOT officials. Other variables such as road length and number of lanes, average headway (i.e., the average distance between entities on the road), as well as lane occupancies are also used in the top-level model to determine the time a vehicle spends on the highway during the evacuation process, the travelled distances, evacuation rates, average delays, and travelling speeds. For example, the overall road occupancy level is increased according to the resolution factor and the rate of arrivals, and this leads to the calculation of the overall delay experienced by drivers already travelling on the Interstate.

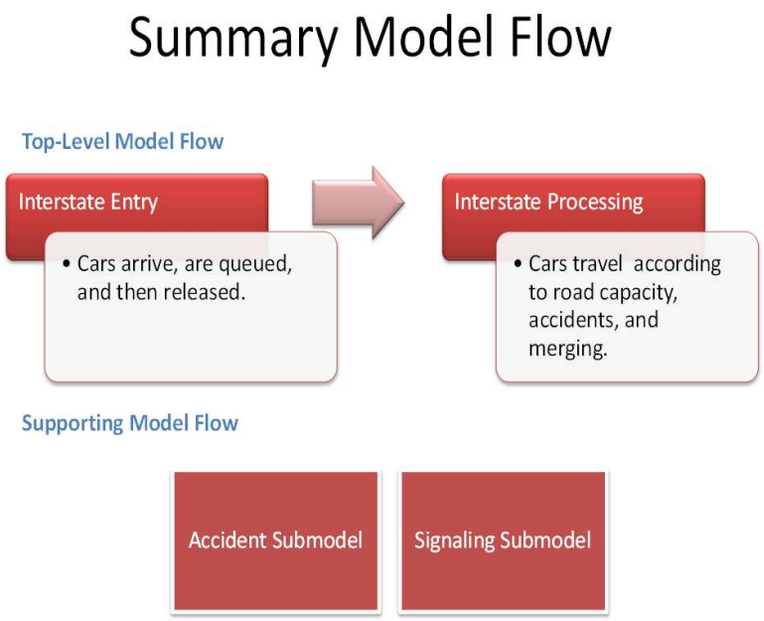


Figure 4. Evacuation simulation model architecture

The supporting models that contribute to the top-level model are the accident and signal models. The accident model determines the frequency of accidents on the highway during the evacuation process. Whenever the accident event is scheduled, a predetermined system delay becomes into effect in the model. The variables used in this supporting model (i.e. the accident factor and the accident delay time) are generated through user-defined probability distributions based on interviews with ALDOT transportation engineers. The other supporting model (the signal model) determines the timing of entities releases into the top-level model from the entry ramps. This is a stochastic process defined by pre-established probability distributions (i.e. Poisson and Binomial distributions) as well as heuristics established by the project analysts.

Figure 6 depicts the simulation logic for creating vehicles in the model. The traffic flow begins with the 20 ARRIVE blocks. Within each of these 20 ARRIVE blocks, the batch size is set

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equal to the quantity of entities that should be entering the interstate at each allowed time. This is accomplished by dividing the number of cars that will be allowed to enter at each exit by the resolution factor, and then, rounding the result to get the number of entities. "ANINT" is an internal system function which simply performs rounding [45].

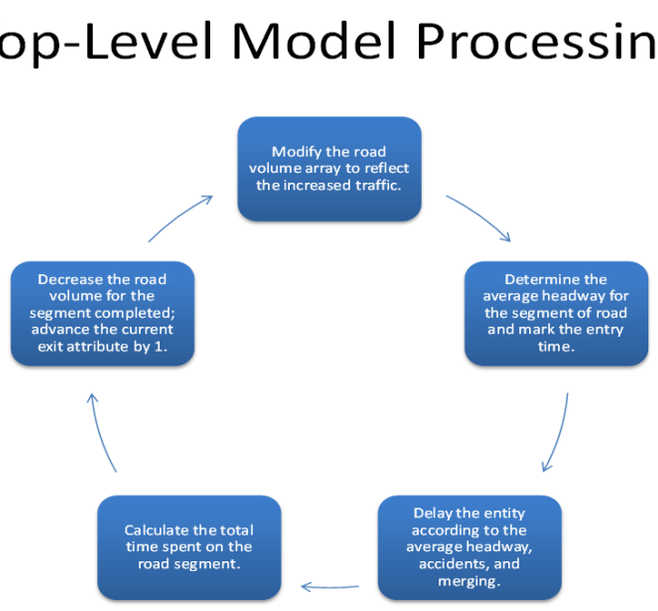


Figure 5. Transaction processing in the top-level model

The rate at which these batches are created is set equal to the frequency at which the cars are released. This is accomplished, as the next step in the ARRIVE blocks, by referencing the proper row in the SigDelay() array, which holds the three possible signaling frequencies to allow cars entry to the interstate. A second array, ExitSig(), stores the signal (1, 2, or 3) that each car will respond to at each exit. For example, the fourth ARRIVE block would have SigDelay(ExitSig(4)) as the formula for time between creations. This would reference the fourth row of the ExitSig() array, and discover that cars at the fourth exit are signaled by Signal 2. The formula would then reference the second row in the SigDelay() array to find the proper time between creations. The maximum number of batches, that each of these 20 ARRIVE blocks can create, is equal to the product of the total number of possible vehicles at the exit and the corresponding evacuation factor, divided by the resolution factor. This number is also rounded to be an integer

Within these ARRIVE blocks, the current time is indicated by the attribute TimeIn, and the entry exit index is indicated as ArrExit. The attribute CurrExit is set equal to ArrExit, and is later used to advance entities along the interstate. The final attribute set at this point is OffExit, which obtains its value from a discrete distribution with the help of the OffCumPr() array. Before the simulation begins, the user accesses the Off-Exit Cumulative Probability array, and inputs the cumulative probabilities that a car will get off the interstate at a specified exit number. OffExit references this array when drawing from the discrete distribution to

find the entity's corresponding interstate exit. If, by chance, OffExit happens to be less than or equal to ArrExit, OffExit will be set to 20, that is, the last exit of the Interstate. Entities then proceed to the WAIT block, where they are held until the proper signal for their exit occurs. The proper signal for the exit is found by referencing the ExitSig() array. For example, the 14th ARRIVE block, and thus the 14th WAIT block, would find its signal through the expression ExitSig(14). The release limit is set equal to the number of cars that will be released at each signal divided by the resolution factor.

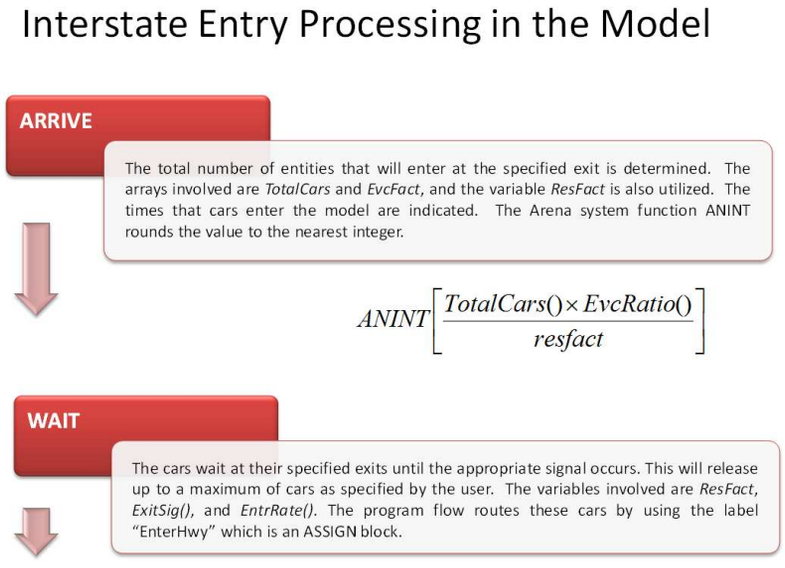


Figure 6. ARENA processing of vehicles entering the interstate roadway

When an entity (i.e. vehicle) enters the interstate (see Figure 7), it goes to the first ASSIGN block on the upper left. First, the road volume array RoadVol(), which stores the total number of cars is adjusted upward by the resolution factor. Since the entity's current exit is stored in the attribute CurrExit, the road volume can be adjusted upward simply by the formula RoadVol(CurrExit) = RoadVol(CurrExit) + resfact. After the road volume array compensates for the additional cars, the attribute AvHeadwy, which represents average headway, is calculated. Basically, this calculation takes the length of the road, multiplies it by the number of lanes on the road, and subtracts out the length of road that all the cars are using (assuming an average car length is 15 ft). All of this is then divided by the length of road that the cars are using to ultimately come out with the average headway. The constant 5,280 represents a unit conversion from miles to feet, and the constant 15 represents the average car length. Finally, the time in to the current exit, ExTimeIn, is marked so the total time spent on the current strip of road can be calculated.

Also, as noted in Figure 7, the time to be spent on the current road segment is calculated in the DELAY block. The formula references a table referred to as SpeedTbl, which uses the assumption that a linear relationship exists between average headway and speed (1 car length = 10 mph), and that the maximum speed on the interstate is 70 mph. Table functions in Are-

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na will automatically interpolate, so when an average headway of 2.37 ft/car is used as an input, the function will output 23.7 mph. In the delay formula, the constant of 60 is used for unit conversion purposes, i.e. that 1 hour = 60 minutes. AccFact() and MrgFact() are arrays that contain values between 0 and 1 which will delay the traffic proportionally according to the factors they present. For instance, if the 16th exit had an accident, AccFact(16) would be set to 0.6 to reflect that the accident is slowing traffic down to 60% of what it would be otherwise. Additionally, if the ninth exit is left open for cars to enter the Interstate, MrgFact(9) would likely be set equal to a number less than 1, whereas closed exits would maintain a factor of 1 since merging would not be affecting traffic at closed exits. "TF" is a system function of Arena that stands for "Table Function." Unit analysis shows that the final result is in minutes, since the numerator is (miles * minutes/hour) and the denominator is (miles/hour).

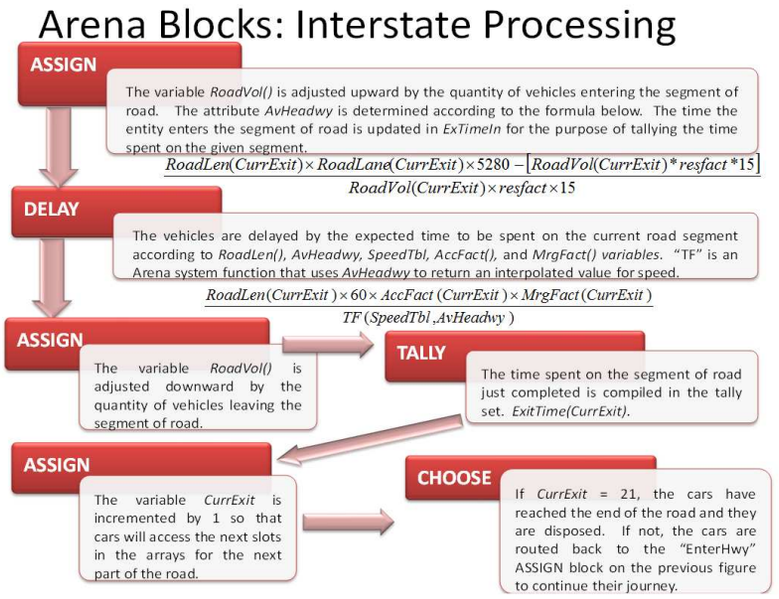


Figure 7. ARENA logic for vehicles on the interstate roadway

The next ASSIGN block, in Figure 7, adjusts the road volume downward as the entity has now completed the current road segment. The TALLY block subsequently records the total time spent on the specific exit. The next ASSIGN block advances CurrExit by 1 as the entity has completed the road segment, and is now advancing to the next segment. Finally, the CHOOSE block checks to see whether the entity has reached the exit it will leave the interstate (if CurrExit = OffExit) or to see if the car has reached the Montgomery contraflow terminus (if CurrExit = 21). If either of those conditions is true, the entity is disposed. Otherwise, the entity is routed back around to the first ASSIGN block in Figure 7 where the next segment of road has its road volume incremented upward.

Dummy transactions are used in the simulation model to represent accidents, and are created at a set time interval (in minutes) stored in a single variable called *AccFreq*. For each simulated accident event, an *ASSIGN* block allocates the exit where the accident is to occur

(*AccExit*) according to a user-defined probability distribution named *AccCumPr()*, as well as a factor to represent the resulting slower traffic (*AccFact*). Under ideal conditions, *AccFact* is equal to 1 for any given road segment. However, after the *ASSIGN* block determines that an accident has happened at a particular exit, the respective *AccFact* is re-set to a number smaller than 1 (e.g., 0.7) based on the probabilistic equations embedded in the model. The accident is allowed to persist for a certain duration of time, *AccRcvr*. After that time has elapsed, the accident factor for that specific exit is returned to one. Figure 8 depicts the ARENA logic embedded in the simulation's Accident Submodel.

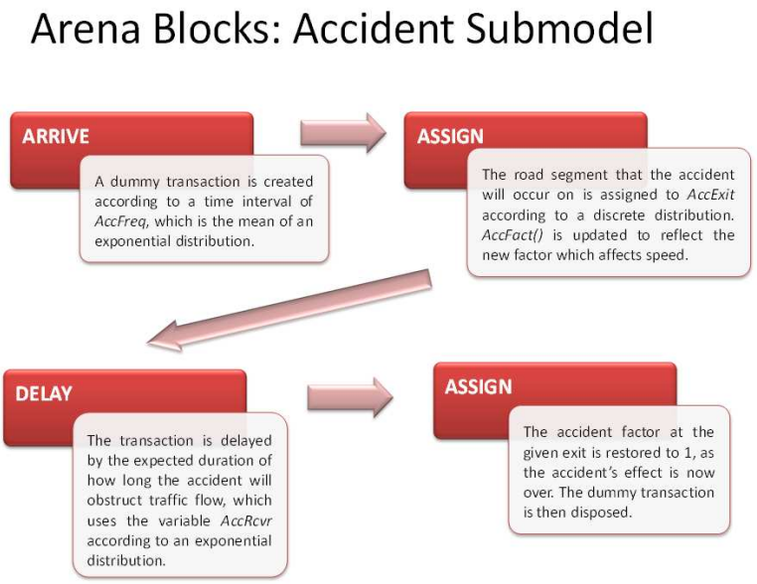


Figure 8. ARENA logic for considering the effects of accidents on the traffic flow

7. Results

With parameters set for the initial model, i.e. all 20 ramps open, the simulation was run for a twelve hour period, consistent with the duration of one of the previous I-65 contraflow operations. The resolution factor, i.e., the entity to car ratio, was set to 25, and the entry rates for each on-ramp were set in accordance with the data presented in Tables 1 and 2. For this initial model, a greater number of vehicles were allowed to get on the Interstate closer to the coast than at other entry points located further north, representing actual observed evacuation behavior [44]. Hence, such on-ramps experienced a faster rate of signals for the release of batches of vehicles. Due to the limited availability of hotel accommodations for evacuees, between Mobile and Montgomery, the final destination attribute for each simulated vehicle was established through a probability scheme based on the assumption that there is an equal chance (i.e. 20%) for a travelling car to exit the interstate at any of the five exit ramps of I-65 in the City of Montgomery. Test statistics were collected from the simulation after 30

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independent replications. The average number of vehicles that reached their final destination during any 12-hour period was 113,318. That is, with all on-ramps open for traffic evacuation, the average evacuation rate was 9,442 vehicles/hour.

Alternative Utilizing Closure of Exits 130 and 57:						
IDENTIFIER	ESTD. MEAN DIFFERENCE	STANDARD DEVIATION	0.950 C.I. HALF-WIDTH	MINIMUM VALUE	MAXIMUM VALUE	QTY OBS
Cars	135	136	273	4.01e+003	6.88e+003	30
				3.87e+003	5.55e+003	30
FAIL TO REJECT H0 ="/ MEANS ARE EQUAL AT 0.05 LEVEL						
Alternative Utilizing Closure of Exit 142:						
IDENTIFIER	ESTD. MEAN DIFFERENCE	STANDARD DEVIATION	0.950 C.I. HALF-WIDTH	MINIMUM VALUE	MAXIMUM VALUE	QTY OBS
Cars	-13.6	131	262	4.01e+003	6.88e+003	30
				3.97e+003	5.57e+003	30
FAIL TO REJECT H0 ="/ MEANS ARE EQUAL AT 0.05 LEVEL						
Alternative Utilizing Closure of Exit 128:						
IDENTIFIER	ESTD. MEAN DIFFERENCE	STANDARD DEVIATION	0.950 C.I. HALF-WIDTH	MINIMUM VALUE	MAXIMUM VALUE	QTY OBS
Cars	-39.7	145	290	4.01e+003	6.88e+003	30
				3.92e+003	6.41e+003	30
FAIL TO REJECT H0 ="/ MEANS ARE EQUAL AT 0.05 LEVEL						
Alternative Utilizing Closure of Exit 54:						
IDENTIFIER	ESTD. MEAN DIFFERENCE	STANDARD DEVIATION	0.950 C.I. HALF-WIDTH	MINIMUM VALUE	MAXIMUM VALUE	QTY OBS
Cars	56.1	138	276	4.01e+003	6.88e+003	30
				3.79e+003	5.46e+003	30
FAIL TO REJECT H0 => MEANS ARE EQUAL AT 0.05 LEVEL						

Table 3. Statistical analysis using two sample t means comparisons

The main focus on the study was to investigate that effect that selectively closing entry ramps from entering traffic had on the overall evacuation process of the Alabama Gulf region during a hurricane situation. The closing of entry ramps was modeled by re-directing vehicles from the arrival at the closed on-ramp to subsequent entry points further north, taking into consideration the time of travel through side roads, the availability of these side roads, as well as the open entry ramps' own traffic volumes. In the simulation, this traffic rerouting was conducted through a random variable distribution of vehicles to entry ramps

located no further than thirty miles away from the closed entry point. This was a combinatorial procedure consisting of two phases. The first step was the analysis of twenty simulation models each pertaining to the closing of a particular entry ramp in the model. The next step was to simulate the closing of multiple entry ramps through permutations of two and three entry ramps closing at a time.

To guarantee statistical soundness of the hypothesis testing procedure, all simulation trials involved 12 hours of simulated time, each replicated 30 times. The null hypothesis of the study implied that the means for the evacuation rate remained the same for the original model with all 20 entry ramps open, and for every other permuted model under examination. The hypothesis testing was performed in a pair-wise fashion, i.e. original model versus alternate model, and an alpha level of 5% was used in all tests. Statistical testing was performed on the data generated by the simulation model to identify variation in relevant traffic variables affecting the north-bound traffic flow. According to Braess' Paradox [36], having all ramps open to vehicles exiting the region may reduce the evacuation traffic flow since in-flow congestion may be generated by entry ramps located within a few miles from each other; and due to the difficulty encountered by emergency and law-enforcement vehicles bound South when all ramps are exclusively for north-bound traffic.

Table 3 displays the most pertinent results from the statistical analyses. The authors determined that there are five entry ramps that can be strategically controlled by ALDOT personnel during an evacuation situation without slowing down the overall evacuation traffic flow. These entry ramps are Exit 54, Exit 57, Exit 128, Exit 130, and Exit 142. Exits 54, 128, and 142 can be closed from entering traffic individually without affecting of overall evacuation rate of vehicles. When closed individually, exits 57 and 130 posed a detrimental effect on the overall evacuation effort. However, it is interesting to note that when they are closed at the same time, their combined effect does not alter the overall flow of evacuating traffic on the interstate.

8. Further research

It is proposed to begin investigation of the larger roadway network through a further evolution of this research to better meet the needs of emergency planners. Decision support systems (DSS) are software systems that utilize sophisticated algorithmic approaches to address problems. Within a DSS, the model base contains the specific analytical methods used for processing the accessed data. The utilization of computer-based simulation, within a DSS, is a long-accepted means of modeling complex systems and activities. The objective of this proposed effort is to establish an incident evacuation decision support system employing a series of traffic analysis algorithms that consider: 1) identification of prevalent traffic flow conditions during a predetermined time window, 2) recognition of incident occurrence, 3) incident characterization, and 4) subsequent routing. These routing algorithms would provide the basis for a network simulation model of the three-state region (Alabama, Louisiana and Mississippi). By employing actual or simulated traffic sensor input, planning alterna-

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tives can be evaluated with consideration of traffic congestion levels and adverse roadway conditions. The integration of DSS capabilities within a traffic data collection system framework will provide a means to identify high-leverage areas where manpower resources could be applied in order to improve the overall traffic flow and throughput of the evacuation route. This will allow the envisioned system to act as an intelligent filter and highlight current problems so that emergency personnel can quickly address them. By conducting what-if analysis, the enhanced system can project the effects of changes in selected variables on the overall traffic flow. This aspect is vital in case of hurricane evacuation activities, when the path of a hurricane quickly shifts, requiring rapid replanning. The various decision alternatives can then be evaluated economically without disrupting existing operations, or incurring unnecessary costs.

9. Conclusions

Vehicle usage of roadways continues to increase across the United States, and results in many roadways operating at near capacity during normal peak periods [46]. This situation is compounded under emergency evacuation situations. Effective planning can decrease traffic congestion, fuel consumption, and the response time of emergency vehicles. It has, in recent years, taken on added significance for federal, state, and local governments by reducing delays and increasing the number of vehicles evacuated from hazardous areas [47]. A variety of algorithmic methods, ranging from simple statistical tools to probabilistic neural networks, have been successfully developed to aid traffic planners. A number of them have been applied to identifying areas of potential traffic congestion under an evacuation situation. Fonseca et al. [48] provide a survey of the literature in this area. The overall traffic capacity of the affected areas can be increased by strategically selecting evacuation measures oriented to the avoidance of congestion. This paper discusses the incorporation of Braess' Paradox within a computer-based simulation framework to better evaluate evacuation traffic throughput.

Alabama traffic officials and emergency personnel want to have the most effective way of ensuring the safety of coastal residents when the danger of severe tropical weather is eminent. Through this study, a comprehensive simulation of I-65, within the State of Alabama, was conducted to access its effectiveness as potential evacuation route during a hurricane situation. It was discovered that by having all 20 entry ramp exits open to merging vehicles bound north, an average of 113,318 vehicles will reach the City of Montgomery safely within a 12-hour period. However, having all exits blocked from traffic bound south poses great difficulty to emergency-response officials needing to access areas in the path of the storm. Through a rigorous and exhaustive process, it was determined that five of the twenty ramps can be strategically controlled to resolve conflicts when restricted flow of vehicles bound south on the Interstate shoulder is needed (as in the case of emergency vehicles responding to accidents on the reverse-laned I-65). The authors have developed a detailed simulation model to analyze discrete networks representing the flow of traffic along planned evacuation routes, with consideration of the effects of Braess' Paradox. The findings of this study

serve as evidence for the need of similar studies to be conducted in other main routes of contraflow evacuation along the coastal areas of the United States. Although other areas in the U.S., as well as other countries, may not utilize contraflow, the application of simulation modeling has proven to be an effective tool for hurricane evacuation planning.

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