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**Gulf Freeway Evacuation Model**

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0. Management Summary

 Our team chose to examine the evacuation of six cities in the Gulf Freeway area stetching from Galveston in the south, to League City in the north. Any model created to solve the problem of evacuating a large number of people in a short time would need to account for real world complexities, such as multiple on-ramps, carrying capacities of highways, and the time required to close on-ramps in an emergency situation. To solve the problem, our team chose a network flow model for its scalability and logical simplicity. To analyze the effectiveness of the completed model our team used as much real world data as we could obtain to mathematically recreate an evacuation. The model then analyzed the data to ascertain how long it would take to evacuate the area and what sort of stress such an evacuation would put on the existing road systems. The model suggests that an evacuation of the area is possible in a timely manner and that the existing highway infrastructure is the mose efficient evacuation route for travelers to utilize.

1. Background

Throughout history, all communities have faced disasters, both natural and human-induced. A disaster has been defined as “a suddenevent bringing great damage, loss ordestruction,” including hurricanes, tornados, earthquakes, wildfires, volcano eruptions, tsunamis, nuclear reactor accidents, terrorism etc (“Disaster”). Protecting life against any disaster is a multifaceted problem faced by citizens, as well as, local, state, and federal governments. The United Nations International Strategy for Disaster Reduction (ISDR) encourages governments to protect against predictable natural hazards, like flooding, tsunami, and volcano eruptions. The U.N. recommends the use of measures like: risk assessments, early warning systems, evacuation plans, education of local citizens, and effective communication in order to mitigate the impact of predictable disasters (The United Nations, 2007).

Most of these tools can also be used for non-predictable disasters like bomb threats, bio-medical hazards, nuclear reactor accidents, and wildfires, where large-scale evacuation is likely to save lives. In the recent years, many of the local and state governments in the United States have learned the hard way that they have not been adequately prepared to handle mass evacuations, especiallyin the case of hurricanes. These natural disasters have caused devastation in the southeast and south central areas of the U.S., ravaging states such asLouisiana, Texas, Florida, Mississippi, and Alabama, just to name a few. In 2005, Hurricane Rita, a category four storm caused several problems for Houston and the Gulf Region residents. Evacuating the population was a massive logistical challenge, resulting in problems such as:

* Long traffic jams resulting in exhaustion of drivers, and death of sick and elderly passengers
* Shortage of fuel, water and food, as gas stations ran out of these commodities
* Overheating of some vehicles resulting in fire and death of passengers in the vehicle

One of the areas hit just this past year by Hurricane Ike was the Gulf Coast of Texas, pulverizing the city of Galveston, and affecting Houston. Every disaster is a learning experience, providing emergency personnel and government officials a better understanding of how to handle the situation more effectively the next time. In order to be better prepared for future disasters, governments and engineers need to work together to develop a more systematic method for organized, mass evacuation.

2. Problem Situation

Emergency evacuation is a huge challenge no matter what the disaster. Even minor improvements in evacuation procedures could mean the difference in saving lives. Our senior design team was tasked with the objective of modeling the evacuation of residents, in an emergency situation, from population centers in or near Interstate Highway 45 corridor, between Houston, Texas and the Gulf Coast. These cities include: Galveston, Tiki Island, Texas City Junction, La Marque, Dickinson, and League City.

Figure 1: Area Map

Over a period of twenty-four hours, our model simulates an emergency evacuation of these six cities. This simulation can give emergency planning teams an idea of how many people should be evacuatedfrom each city, per time period, and when to open and close on-ramps to allow access to the highway. The overall goal is to get the people out as efficiently as possible beginning with Galveston and gradually progressing to League City. A sequential evacuation from the southern-most city, Galveston, to the northern-most, League City helps to avoid large backups due to high volumes of traffic trying to evacuate simultaneously.

3. Analysis of the Situation

We decided to solve this problem using a network flow model. Even though our original problem only has six cities to consider, this model can be used for any number of cities, and we did not want that factor to restrict our model’s capabilities. We chose a network flow simulation because it is easily scalable, since population size, the number of cities, the number of time periods, and highway capacities can easily change based on different scenarios.

We used the algebraic modeling language AMPL, with a CPLEX solver to find the optimal solution to our network flow problem. We chose this language because of its simple, easy to understand syntax, its generality of its set and indexing expressions, and its reliability for developing and maintaining complex models.

As this problem is quite vast, we did have to make a number of assumptions when solving this problem in a limited time frame.

* The population figures used in our model represent the number of cars rather than each individual person. The number of vehicles leaving from each city was calculated by assuming an average of three people per car; subsequently, the population of each city was divided by three.
* The model currently accounts only for civilian cars and not emergency vehicles or large trucks.
* Our model solely uses Interstate Highway 45 as the main route for evacuating the Gulf cities.
* Our model simulates 144, ten-minute intervals of time, which sum to represent a twenty-four hour period.
* The actual cost values for each arc aresomewhat arbitrary, however, the magnitude of the numbers is key because they are used to influence the model’s outcome. The values are used in such a way, as to discourage the model from allowing people to remain in their original cities during later time periods or stranding evacuees.

This model has the potential to be utilized by the Texas Department of Transportation (TxDot), the Federal Emergency Management Agency (FEMA), or any other emergency-planning agency in times of mass evacauation.

4. Technical Description of the Model

4.1 Model Type and Variable Structure

The basic type of model that we chose can be classified as a multiperiod, unidirectional network flow model. Our model creates a set of linked nodes based on the number of cities that an evacuation maybe planned for. Each city is created as a unique node in each time period of the model. For example, the model would expand Galveston[x] or Houston[y] to Galveston[1], Galveston[2], and Houston[1], Houston[2] etc. The subscripts above represent the time period that the node occurs in. Each city has a population pool from which city inhabitants enter the model and begin to evacuate to safety. An accompanying set of arcs links each city node.

 Arcs are generated between city nodes based on the type of traveler that the given arc represents. We have subdivided the evacuees of our model into five classes: entering[i,j],onHighway[i,j], safe[j], stranded[i], and waiting[i,j]. The subscripts i and j reflect the city number and time period that the arc in question is associated with, respectively.

Entering arcs link each city node to the accompanying population center. Multiple entering arcs into each city give the model the ability to represent on-ramps. By creating individual variables for each on-ramp, the model can choose which ramps to close and open as time moves forward. The on-ramp control feature allows evacuation planners to funnel city inhabitants through a single location during a mandatory evacuation. Having all citizens pass through a single point allows emergency responders to be more certain of how many people are left in the city.

When designing our model, the ability of law officers to close or open an on-ramp originally presented a problem. We needed to introduce a method by which an on-ramp, once closed, would remain closed for the duration of the model. To accomplish this, our model uses a constraint which checks the status of each on-ramp in the previous time period, then writes a value to determine if the ramp in the next time period should be open or closed.

onHighway arcs allow travelers to flow from one city to the next in the evacuation pattern. Our model distinguishes itself from other network flow models by having a linear relationship between the nodes. An evacuee cannot skip between nodes in the network. He or she must proceed from the first city to the second, to the third, and so on. Taking into account the sequential nature of our nodes, our model could almost be reclassified as a linear network flow model. In the case of onHighway[i,j] the city from which the evacuee departs determines the i subscript and not the city to which he or she is going.

safe[j] variable represent the success of the model. Any evacuees that arrive at the last city are then moved into the safe arcs, which exist in each time period. Contrastingly, stranded[i] arcs collect the models failures by capturing all of the evacuees still remaining in the model at the last time period.

Finally, the waiting class of variables includesall of those people who choos to remain in their particular city from one time period to the next. The model utilizes this class of variable to reflect the realization that not everyone will choose to leave the city during the evacuation, as proved by Hurricanes Katrina, Rita, or Ike. Refer to the flow chart below for a simplified, visual representation of this model

4.2 Flow Chart

Figure 2: Flow Chart

4.3 Objective Function and Constraints

The objective function of our model can be executed in one of two ways. The first is simply to maximize the number of evacuees that reach the safe arc. The second, more useful method is to assign costs to each variable arc in the model. waiting and stranded arcs demand higher costs, in order to discourage the model from stranding evacuees, or allowing them to stay in a city until a time period so late that they are unable to evacuate. The objective function of the second method minimizes the total cost of the sum of flow across an arc multiplied by the cost assigned to that arc. The model’s constraints are logically simple, merely serving to enforce road capacity limits and fulfill flow conservation at each node in the form of: Flow in – flow out = 0.The output from our model is available in Appendix A.

4.4 Data Sources

Data was compiled from several sources. Dr. Shannon Crum, Director of Data Management Transportation Planning, and Programming Division, from the Texas Department of Transportation (TXDot), supplied us with information regarding the flow rate in cars per hour that an interstate could accommodate (Crum, 2009). Population values were taken from the 2005 census and, where possible, from the websites maintained by the city councils (Texas State Data Center, 2009). Number of lanes per highway section and number of on-ramps per city were determined from visual confirmation provided by Google maps. Capacity values of on-ramps were estimated as a percentage of highway capacity based on information provided by a former TXDoT intern (Oestrick, 2009).

5. Analysis and Managerial Interpretation

The purpose of the model was achieved in that it did evacuate the various city populations in the given time-span of twenty-four hours and it did not strand any evacuee. The data used to solve this problem was based on a number of assumptions and was partly theoretical. The Gulf Freeway evacuation model outputs over 33,000 lines of data; however, the valuable information is contained within 2,100-lines at the bottom of the output. In this last section, the model focuses on maximizing the number of people who get to safety by minimizing the cost of doing so and gives us additional information about the network's flow.

The first observation to be made about the model is that no car is ever put into one of the “waiting” arcs between time periods. This means that once a car gets on the highway, it stays on the highway, never stopping until it has made its way to safety. This is a good indicator, as it proves the model is able to avoid highway traffic bottlenecking and congestion, and is able to keep a steady flow through the system.

 A related observation is that populations farther from safety seem to be favored by the model. These populations are given a “priority” above populations from latter cities. Evacuating the southern cities first, avoids competition over valuable highway space between northern and southern evacuees. The priority given to cities that need to evacuate earlier can help soothe at least some of the traffic congestion faced during emergency evacuations. One of the problems faced during Hurricane Rita (2005) was severe traffic congestion resulting from the lack of an official plan dictating which residents to evacuate first. To remedy this, in 2008, with Hurricane Ike, a zip code evacuation plan was enacted, in which the zip code closest to the coast evacuated first, followed by inland zones evacuating in succession (OneStorm Family Hurricane Preparedness, 2008). Combining the zip code system with our model’s priority feature would help solidify the order in which residents were made to evacuate, thereby reducing the large volumes of traffic stuck on the highways.

A close look at the model will reveal that the most constraining factor is the capacity of the on-ramps. With only a few exceptions, any utilized on-ramps are filled to capacity. This actually aids the overall functionality of the model, as it helps prevent the highway network from becoming congested and clogged. The on-ramp controls seem to work as a function of the on-ramp capacity. When the model utilizes a ramp, it turns the ramp on; and when the same ramp is not utilized, it is turned off. Once and on-ramp is closed, the ramp remains closed for the duration of the model. While this seems intuitive, this functionality serves as a preventative measure, not allowing any cars into the system that may decide to disregard evacuation instructions from law enforcement personnel.

6. Conclusions and Critique

Our model suggests that the highway and on-ramp system, as it is designed and currently stands, is more than capable of handling an evacuation over a 24-hour period. The populations in all six cities were successfully evacuated, the on-ramp controls proved useful, as the model was able to open and close ramps as needed, and no cars were left waiting or stranded.

The Gulf Freeway Evacuation Model still requires further development to take into account real world factors that impact evacuation. At this point, the network flow is unidirectional, meaning that cars can flow only in one direction. An expanded model would contain bidirectional flow, allowing cars to move through the system in both directions. While using a bidirectional model would allow populations to move towards danger, it increases functionality when combined with the idea of storm shelters in cities. An evacuee faced with the prospect of being stranded on the highway when the storm hits, could reverse his or herdirection, and take cover in a storm shelter in a previous city. These shelters would be embedded in cities along the storm path, and be able to provide limited populations with a safe haven from the storm. This concept also adds to the overall realism and credibility of the model.

Another topic to take into consideration is contra-flow or lane reversals, where both sides of the highway flow in the same direction, away from the evacuation zone. This idea has both pros and cons associated with it, necessitating a detailed study to determine if IH-45 can accommodate contra-flow. One definite plus is that it speeds up the evacuating process and gets people out of the danger zone quicker than just utilizing one direction of the highway. However, there needs to be access for emergency personnel to travel in the opposite direction from the evacuees, to get to any people still stranded in the danger zones. Additionally, as Dr. Shannon Crum, from the Texas Department of Transportation pointed out, one of the problems associated with contra-flow is the blockage it causes when it ends. When lane reversals end, there are not enough lanes available to accommodate the traffic flow at the final destination (Crum, 2009).

Addtionally, this model needs to be expanded to include emergency personnel such as police and ambulances that have to get to people in the evacuation zones. The simulation needs the ability to make distinctions based on the type of vehicle trying to evacuate – cars, buses, ambulances, police, large trucks, etc, so that the flow rate of the vehicles can be taken into consideration. The speed of the vehicles does have a considerable impact of how quickly the traffic will flow through.

Another potential expansion area is in cost scheduling. The current model has costs hard-coded into the data file containing populations, capacities, etc. The development and implementation of a cost-scheduling algorithm that is expandable to scale with the model and still provides functional cost ratios between arcs would make the model truly universal, needing nothing more than physical parameters of the evacuation route to be inputted into it.

As a final point, no matter how many additional factors are added to this model to make it more efficient, it is a simulation after all and cannot account for every possible situation in an emergency.Human nature and extenuating circumstances are impossible to model. Even the best-designed highway system will become impassable, if the entire population attempts to use it at the same time, as is too often the scenario with people waiting until the absolute last minute to evacuate. Even worse, accidents or stalled vehicles could stop flow through the network for extended periods of time. Therefore, as the model clearly shows, evacuations must begin early, but more importantly, maintain a steady flow, absent of massive surges or flow stoppages that will clog the network, causing a chain reaction of backups and delays.Webelieve the Gulf FreewayEvacuationModel is an important beginning in solving the emergency evacuation problems faced in times of a disaster. With additional research, input from experts in the field, and enhancements to our current model, the Gulf Freeway Evacuation Model could actually be implemented in the future.

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Appendix A: Output

CPLEX 10.0.0: optimal integer solution; objective 155609

1554 MIP simplex iterations

0 branch-and-bound nodes

totalCost = 155609

onHighway[c,t] [\*,\*] (tr)

: 1 2 3 4 5 :=

0 210 0 0 0 0

1 210 210 252 0 0

2 210 210 210 252 0

3 210 210 210 210 252

4 210 210 210 210 210

5 210 210 462 210 210

6 210 210 210 462 210

7 210 210 210 210 504

8 42 210 210 210 210

9 168 42 210 210 210

10 126 168 42 210 210

11 168 126 168 42 210

12 126 168 126 168 42

13 126 126 168 126 168

14 84 126 126 168 126

15 84 84 126 126 168

16 0 84 84 126 126

17 168 0 84 84 126

18 168 168 0 84 84

19 84 168 336 0 84

20 126 84 336 378 0

21 168 126 84 378 504

22 126 168 294 84 462

23 126 126 168 294 84

24 84 126 126 168 420

25 0 84 252 126 294

26 0 0 84 252 252

27 210 0 0 84 378

28 126 210 0 0 168

29 0 126 462 0 0

30 126 0 126 462 0

31 0 126 0 126 504

32 168 0 126 0 126

33 210 168 0 126 0

34 168 210 336 0 126

35 168 168 378 378 0

36 168 168 336 378 504

37 210 168 336 378 504

38 168 210 336 336 504

39 210 168 378 420 462

40 210 210 294 462 504

41 168 252 378 336 588

42 168 168 420 420 462

43 168 168 336 504 546

44 210 210 378 378 630

45 210 252 420 420 462

46 126 210 462 462 504

47 126 126 420 462 546

48 210 126 336 504 546

49 210 210 336 378 588

50 210 252 420 378 462

51 210 252 462 504 462

52 168 252 420 462 588

53 210 168 462 420 546

54 210 210 378 462 504

55 210 210 420 420 546

56 168 210 420 462 504

57 126 168 378 420 546

58 126 126 168 378 546

59 210 126 126 168 462

60 210 210 336 126 252

61 210 210 210 378 210

62 168 210 210 210 378

63 210 168 210 210 252

64 210 210 168 210 294

65 210 210 210 168 294

66 210 210 420 210 252

67 210 210 378 504 294

68 210 210 420 462 588

69 168 210 420 504 546

70 168 168 336 546 588

71 168 168 336 336 616

72 168 168 336 420 420

73 210 168 336 336 504

74 210 210 336 378 420

75 210 210 420 378 462

76 168 210 420 420 462

77 210 168 357 420 462

78 168 210 378 357 504

79 210 168 420 420 441

80 168 210 336 504 462

81 210 168 420 378 546

82 210 210 378 504 462

83 210 210 378 462 546

84 210 210 420 462 462

85 210 210 378 462 504

86 210 210 378 504 546

87 210 210 336 420 504

88 168 210 336 420 420

89 210 168 378 336 420

90 168 210 336 420 336

91 210 168 378 462 420

92 126 210 336 462 462

93 84 126 210 420 462

94 210 84 126 210 420

95 168 210 84 126 210

96 42 168 378 84 126

97 126 42 336 462 84

98 84 126 42 462 462

99 42 84 294 42 462

100 42 42 84 294 42

101 126 42 42 84 294

102 210 126 84 42 84

103 210 210 126 84 42

104 42 210 378 126 84

105 0 42 378 420 126

106 0 0 42 504 420

107 0 0 0 42 504

108 126 0 168 0 42

109 0 129 168 252 0

110 42 0 255 294 252

111 168 42 0 381 294

112 84 168 42 0 423

113 0 84 168 42 0

114 126 0 84 168 42

115 42 126 0 84 168

116 126 42 252 0 84

117 0 168 168 294 0

118 0 0 378 294 336

119 42 0 210 462 294

120 0 42 210 336 504

121 0 0 252 294 378

122 0 0 84 336 378

123 0 0 168 84 378

124 0 0 0 210 126

125 0 0 0 0 252

126 126 0 42 0 84

127 0 126 42 168 84

128 210 0 168 168 210

129 210 252 42 294 168

130 0 210 462 168 294

131 84 0 336 462 168

132 168 84 0 378 462

133 122 168 84 0 378

134 0 122 336 84 0

135 42 0 164 336 84

136 168 42 42 206 336

137 0 168 42 84 206

138 0 0 336 126 84

139 42 0 126 336 126

140 0 42 0 126 336

141 0 0 210 0 126

142 0 0 0 210 0

143 0 0 0 0 210

;

waiting[c,t] [\*,\*] (tr)

: 1 2 3 4 5 6 :=

0 0 0 0 0 0 0

1 0 0 0 0 0 0

2 0 0 0 0 0 0

3 0 0 0 0 0 0

4 0 0 0 0 0 0

5 0 0 0 0 0 0

6 0 0 0 0 0 0

7 0 0 0 0 0 0

8 0 0 0 0 0 0

9 0 0 0 0 0 0

10 0 0 0 0 0 0

11 0 0 0 0 0 0

12 0 0 0 0 0 0

13 0 0 0 0 0 0

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36 0 0 0 0 0 0

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41 0 0 0 0 0 0

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43 0 0 0 0 0 0

44 0 0 0 0 0 0

45 0 0 0 0 0 0

46 0 0 0 0 0 0

47 0 0 0 0 0 0

48 0 0 0 0 0 0

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66 0 0 0 0 0 0

67 0 0 0 0 0 0

68 0 0 0 0 0 0

69 0 0 0 0 0 0

70 0 0 0 0 0 0

71 0 0 0 0 0 0

72 0 0 0 0 0 0

73 0 0 0 0 0 0

74 0 0 0 0 0 0

75 0 0 0 0 0 0

76 0 0 0 0 0 0

77 0 0 0 0 0 0

78 0 0 0 0 0 0

79 0 0 0 0 0 0

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81 0 0 0 0 0 0

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84 0 0 0 0 0 0

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86 0 0 0 0 0 0

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103 0 0 0 0 0 0

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105 0 0 0 0 0 0

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110 0 0 0 0 0 0

111 0 0 0 0 0 0

112 0 0 0 0 0 0

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114 0 0 0 0 0 0

115 0 0 0 0 0 0

116 0 0 0 0 0 0

117 0 0 0 0 0 0

118 0 0 0 0 0 0

119 0 0 0 0 0 0

120 0 0 0 0 0 0

121 0 0 0 0 0 0

122 0 0 0 0 0 0

123 0 0 0 0 0 0

124 0 0 0 0 0 0

125 0 0 0 0 0 0

126 0 0 0 0 0 0

127 0 0 0 0 0 0

128 0 0 0 0 0 0

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136 0 0 0 0 0 0

137 0 0 0 0 0 0

138 0 0 0 0 0 0

139 0 0 0 0 0 0

140 0 0 0 0 0 0

141 0 0 0 0 0 0

142 0 0 0 0 0 0

143 0 0 0 0 0 0

;

stranded[c] [\*] :=

1 0

2 0

3 0

4 0

5 0

6 0

;

safe[t] [\*] :=

 0 168 19 210 38 672 57 630 76 630 95 588 114 168 133 630

 1 168 20 252 39 672 58 672 77 630 96 378 115 210 134 546

 2 168 21 168 40 630 59 672 78 630 97 294 116 336 135 168

 3 168 22 634 41 672 60 588 79 672 98 252 117 252 136 252

 4 420 23 630 42 714 61 378 80 609 99 630 118 168 137 504

 5 378 24 252 43 588 62 336 81 630 100 630 119 504 138 374

 6 378 25 588 44 672 63 504 82 714 101 210 120 462 139 252

 7 378 26 462 45 756 64 378 83 630 102 462 121 672 140 294

 8 672 27 420 46 588 65 420 84 714 103 252 122 546 141 504

 9 378 28 546 47 630 66 420 85 630 104 210 123 546 142 294

 10 378 29 336 48 672 67 378 86 672 105 252 124 546 143 168

 11 378 30 168 49 672 68 420 87 714 106 294 125 294 144 378

 12 378 31 168 50 714 69 714 88 672 107 588 126 420

 13 210 32 672 51 588 70 672 89 588 108 672 127 252

 14 336 33 294 52 588 71 714 90 588 109 210 128 252

 15 294 34 168 53 714 72 742 91 504 110 168 129 378

 16 294 35 294 54 672 73 546 92 588 111 420 130 336

 17 252 36 168 55 630 74 630 93 630 112 462 131 462

 18 252 37 672 56 672 75 546 94 630 113 591 132 336

;

entering[c,r,t] [1,\*,\*]

: 1 2 3 4 5 6 7 8 9 :=

0 42 42 42 42 42 0 0 0 0

1 42 42 42 42 42 0 0 0 0

2 42 42 42 42 42 0 0 0 0

3 42 42 42 42 42 0 0 0 0

4 42 42 42 42 42 0 0 0 0

5 42 42 42 42 42 0 0 0 0

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