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2001 Meritorious Winner

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When a Hard Wind Blows the Traffic Slows

February 12, 2001

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1 Abstract

We examine the traffic flow dynamics of a large scale evacuation of the coastal cities in South Carolina. Such evacuations been required in the past due to predicted hurricane landfall. The evacuation of 1999 due to hurricane Floyd led to traffic jams across the state. This was both a severe inconvenience and a safety hazard. In order to reduce the time required to evacuate the endangered areas, one must understand the source of the congestion. We begin with an analysis of traffic flow and the how the process of congestion affects flow rates along interstate freeways. This provides an upper bound on freeway flow rate which leads to a lower bound on the time required to fully evacuate under ideal conditions. For a more realistic estimate, including the effects of thousands of people simultaneously trying to enter freeway evacuation routes, we formulate two models of the statewide movement patterns. The first model we construct is based on the premise that congestion occurs primarily at points in the roadway system where many people attempt to squeeze into a narrow road. This model leads to a system of differential equations on the nodes of a network. This model reproduces the traffic jam that occurred in 1999 during the hurricane Floyd evacuation. It estimates a 72 hour evacuation time and 15 hour drives for people evacuating from Charleston to the northwestern part of the state. It further shows that the effect of adding temporary shelter in Columbia, to accomodate the evacuees, would be small. We obtain an estimate for the number of people who will enter the state from Georgia in the event of an evacuation, and we find that this number is too small to greatly increase congestion. Lastly, this model predicts that reversing lanes on I26 will speed the evacuation of the coast, but will also result in large traffic jams outside of Columbia. The second model we construct is based on a geographical population density approach. It attempts to even out the population density of the evacuees. This model agrees with the 72 hour evacuation estimate, however exhibits too much sensitivity on its parameters to be useful as a prediction device.

2 Introduction

The main goal in attempting to model how traffic flows during an evacuation of the South Carolina Coast is to determine what went wrong in the 1999 evacuation and what evacuation strategies should be considered in the future. The debilitating traffic jams that resulted from Hurricane Floyd threatening the coast could have endangered the lives of those trapped on the highways had the hurricane continued towards South Carolina instead of turning North. It is necessary to improve upon the evacuation scheme so the problems of 1999 aren't repeated. Among the questions that need to be addressed are:

- 1 Is it even feasible to evacuate the entire South Carolina Coast in under three days?
- 2 How significant is the effect of reversing the flow of some coastal-bound lanes?
- 3 Will providing more temporary shelters in Columbia significantly reduce traffic problems?
- 4 How much can traffic from Georgia hinder the evacuation process?

By assuming that the majority of people evacuating the coast must use the main roads, it is possible to use simplified road structures to analyze traffic effects. A good model should be able to simulate at least the following four things:

- 1 Reproduce the traffic problems that occurred in the Hurricane Floyd evacuation when conditions are similar.
- 2 Provide localized information about traffic congestion
- 3 Indicate the total required time for evacuation.
- 4 Show how sensitive the simulation results are to problem parameters such as road capacity and population size.

The first requirement that the model reproduce known effects is necessary to determine if the model is reasonable. Analyzing what parameters have the greatest effect on the simulation results indicates the things that evacuation officials should focus on in order to produce a more effective evacuation scheme. An evacuation strategy is represented by considering a specific set of problem parameters such as road capacity. The effectiveness of different strategies is studied using two main criteria:

- How much time does the complete evacuation of the coast require using this strategy?
- How long does it take an average car to go from one city to another?

3 Why Do Freeways Clog Up?

We begin our analysis of the phenomenon of congestion with the question of what causes traffic to slow down. On city roads where there are stop signs, traffic signals, cross walks, etc, one expects that queuing effects would tend to propagate and slow the flow of traffic. In fact, these effects have been thoroughly analyzed in Ref [1]. However, on freeways there are no such flow regulation devices, so a car is free to move as fast as the traffic around it will allow—so long as it obeys the speed limit. Taking an analogy from fluid dynamics, freeway

traffic is like a laminar flow, and everyone moves along smoothly. Congestion occurs as the density of cars on a given stretch of freeway increases. With only a few other vehicles on the road, one can drive at the speed limit. However in bumper-to-bumper traffic, it can take many hours to move a scant few miles.

In modeling this behavior, we begin with the relationship between the average speed v (measured in miles-per-hour), and the density ρ (measured in cars-per-mile-per-lane). We will write v as a function of ρ . The flux rate of vehicles is then simply the product,

$$\Phi = v\rho N n_{ppc}, \quad (1)$$

where N is the number of lanes and n_{ppc} is the average number of people per car. This quantity represents the average total number of people passing a given point in an hour. The simplest model would be to take the relationship as linear.

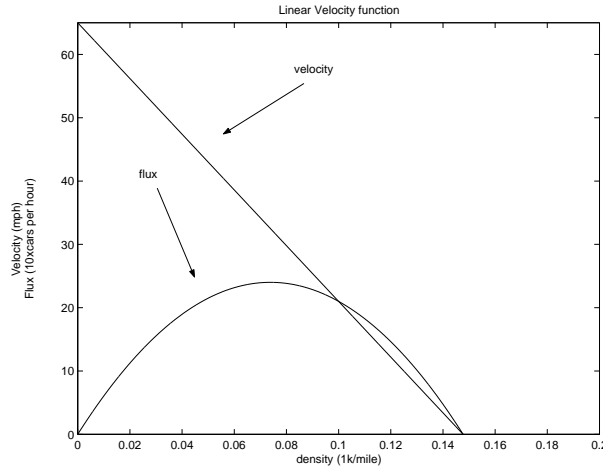


Figure 1: Velocity and flux in the linear model

However, from this figure it is clear that the linear model clips to zero flow too sharply. A softer curve is necessary—one with a low-density asymptote at the maximum speed k , and a high-density asymptote at zero mph . This leads us to propose the following model,

$$\frac{\partial v}{\partial \rho} = -Cv\left(1 - \frac{v}{k}\right). \quad (2)$$

This is the logistic growth equation. Solving it by separation of variables leads to,

$$v(\rho) = \frac{Dke^{-c\rho}}{1 + De^{-c\rho}} \quad (3)$$

Now we must determine reasonable values for the above constants. Setting $\rho = 0$ and solving for D , we obtain,

$$D = \frac{v_0}{k - v_0} \quad (4)$$

where v_0 is the average zero-density cruising speed. Since the average person doesn't drive at the maximum speed, we set $v_0=62$, and $k = 65$. An appropriate estimate for the stiffness C can be obtained as follows. At a density of 100 cars per mile per lane, each car is separated from the next by 50ft. Estimating the length of a car to be 15ft leaves a buffer distance of 35ft between cars. The maximum safe driving speed, given a 35ft separation, is approximately 20MPH. We therefore choose C such that $v(100) = 20$ MPH, which leads to the value $C = 40$. Below we plot Φ and v vs ρ .

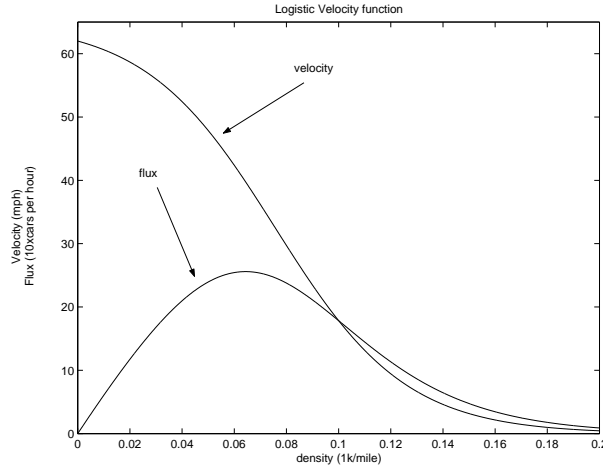


Figure 2: This logistic velocity produces a flux that tapers gradually to zero.

We can also plot v vs Φ and compare to the figure given in the Highway Capacity Manual (Ref [6]).

Our model predicts a maximum flux of approximately 2500 cars-per-hour-per-lane. The Highway Capacity Manual estimates a maximum flux of 2000, and according to the Traffic Engineering Handbook (Ref [5]), fluxes as high as 2262 have been recorded. We therefore regard this model as reasonable.

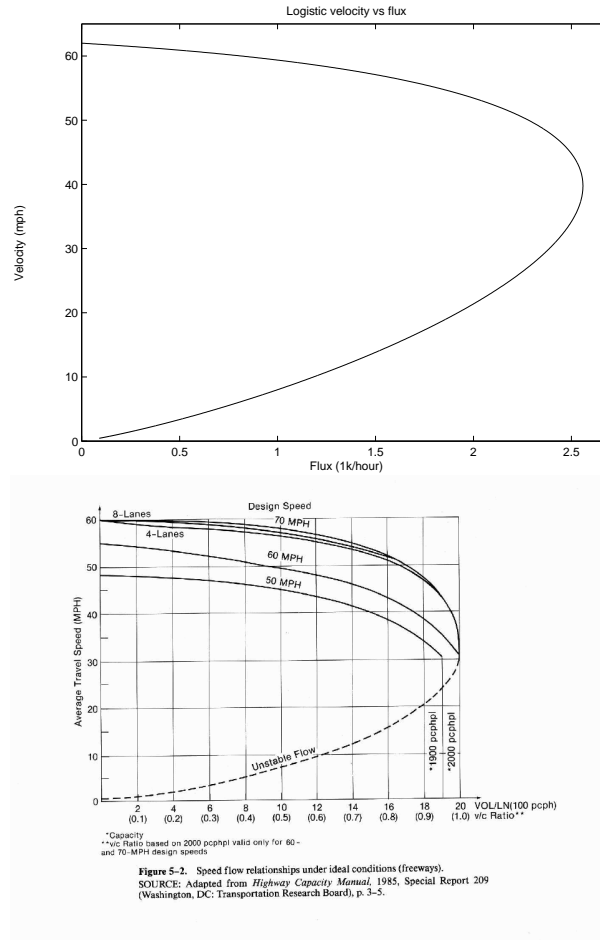


Figure 3: (top) Logistic model Velocity vs Flux graph. (bottom) Refs. [5, 6]. Note the excellent qualitative correspondence between our model and the Highway Capacity Manual's empirically based figure. Also note that any given flux can be maintained at two distinct velocities.

3.1 Application of the Model - A lower bound on Evacuation Time

Now for some quick estimates. Let's make the following assumptions:

- The Charleston greater metropolitan area has a population of 480,000 people (source Refs. [2, 3]).
- Evacuation occurs at the optimal traffic density (perhaps due to diligent traffic control on the part of the police and/or national guard.
- 70 % of Charleston's population will evacuate through I26 (which has two outbound lanes), while the rest will navigate the rural highways. This leaves 336,000 people who will want to leave via I26.
- The people who travel on the rural highways have negligible.

On the average, two people travel in each car. $n_{ppc} = 2$. The absolute maximum rate at which people can leave Charleston via I26 is then $n_{lanes} \times \Phi_{max} \times n_{ppc}$. The city can be completely evacuated in no less than

$$\frac{Population}{\Phi_{max} \times n_{lanes} \times n_{ppc}} = \frac{336,000people}{(2500 \frac{cars}{mile \cdot lane \cdot hour}) \times (2lanes) \times (2 \frac{people}{car})} = 33.6hrs. \quad (5)$$

Similar estimates give lower bounds on the evacuation time for Myrtle Beach, Georgetown, and Hilton Head, but these are *highly optimistic* numbers—they assume ideal traffic density conditions. As we know from the incident in 1999, realistic evacuation conditions can often be very far from ideal.

4 The Narrow Passage Model

Our first model of the evacuation process is based on the assumption that congestion occurs primarily at funnel points where many vehicles attempt to simultaneously squeeze through a restrictive passage. These funnel points are the freeway on-ramps within a city. An evacuation jam is a much larger scale version on the jam that invariably occurs after a football game when everyone tries to leave the parking lot at once.

4.1 Assumptions

Let us formalize the assumptions which shall go into this model.

- People live primarily in localized areas (cities)
- People move from one city to the next primarily along Interstate freeways.

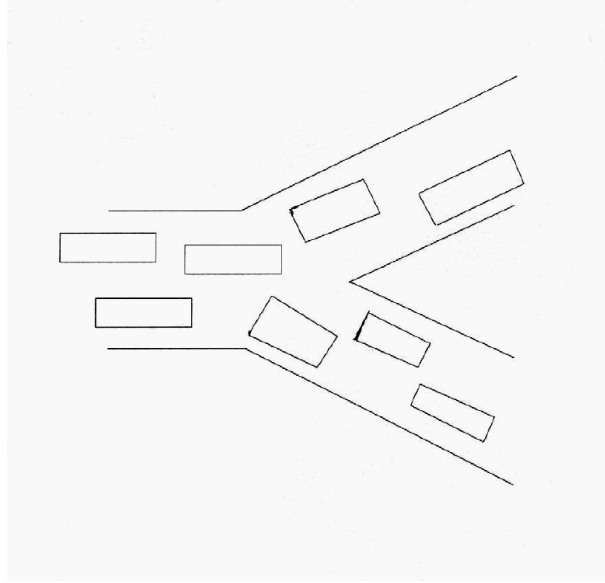


Figure 4: Schematic of bottleneck traffic jam.

- Because the rural highways have a much lower capacity, the number of people who use roads other than the interstates is negligible.
- Within the state, the number of vehicles is conserved. Vehicles may only enter or leave the system by crossing the state border.
- The only people traveling are those who are displaced by the evacuation order. We therefore need only consider this mobile population.
- Each city has only a limited amount of housing for the mobile population. Unless measures are taken, the capacity of a city to hold mobile population is 33% of its normal population. That is, a city of 100,000 could hold 133,000 people.
- Traffic moving in opposing directions does not interact.

4.2 Formulating the Model

We represent the state of South Carolina with the following directed graph structure. Each freeway junction and major city is represented by a node and the interstate evacuation routes are represented by the directed edges of the graph. Since the flow along the numerous rural highways is small (by assumption), this simple graph will be enough to analyze the nature of an evacuation process.

In laying down the mathematics of this model, we begin with the continuity equation as applied to mobile population, so that people will be conserved.

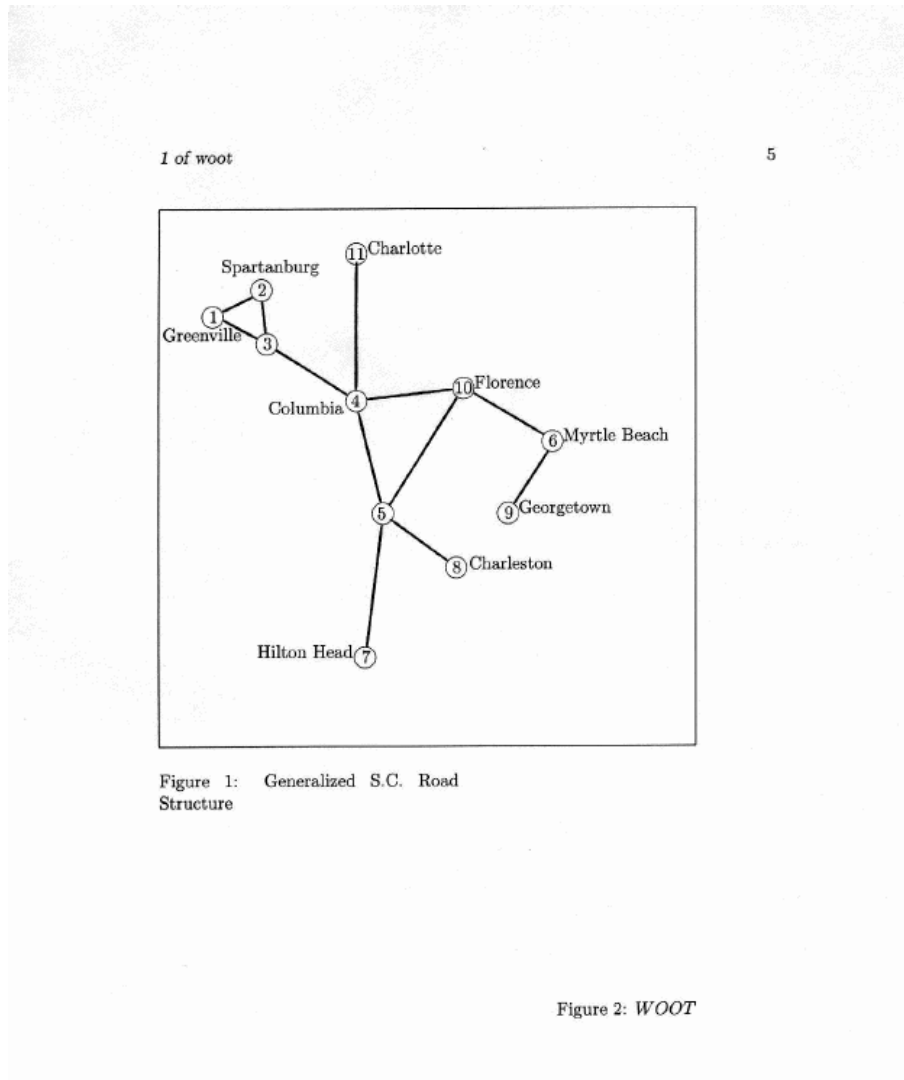


Figure 5: Graph Structure used to represent South Carolina.

Since the people mobilized by the evacuation order are the only ones moving, we are only concerned with this mobile population, and henceforward the term *population* will refer only to *mobile population*. Define P_i to be the population at the i^{th} node of the graph and Φ_{ij} to be the flux of people from the i^{th} node to the j^{th} node. On the discrete graph the continuity equation takes the form,

$$\frac{\partial P_i}{\partial t} = \sum_j \Phi_{ji} - \sum_j \Phi_{ij}. \quad (6)$$

The rate of change of population at i is the flux rate of people entering minus the flux rate of people leaving (since, in general, traffic may flow in both directions at once). If a connection from i to j exists then the flux Φ_{ij} (from eq. 1) is $\rho_{ij}v(\rho_{ij})N_{ij}n_{ppc}$, and v is the logistic velocity function discussed previously. The flux is zero if no connection exists.

The core of this model is in the expression of the traffic density ρ_{ij} as a function of graph parameters (such as road lengths), populations, and evacuation orders (coastal vs. non-coastal nodes). The following relationships will guide us:

- ρ_{ij} is inversely proportional to the length of road L_{ij} between i and j , as well as the number of lanes N_{ij} .
- ρ_{ij} is proportional to the population P_i , the hurricane danger level D_i , and the pressure of over-population A_i .
- The density should be maximal when either the danger level is maximal (the city MUST be evacuated), or when the pressure of over-population is maximal (no one can stay here if there is no available housing).

It will be convenient if $A_i, D_i \in [0, 1]$. The danger level is then 1 at all cities that are ordered to evacuate immediately, around 0.5 for a more controlled or relaxed exodus, and zero at safe inland cities.

For the over-population pressure factor A_i , we must consider the capacity of a city to house the fleeing evacuees. Let the maximum number of people that can be housed in city i be S_i . If less than 75% of lodgings are full then it is easy for a traveler to find a vacancy. However, as all the hotels and motels begin to fill up, more people are forced to continue further to the next city before stopping. We estimate that, without extra measures, a city has the capacity to house a mobile population that is up to 33% the size of its total population. Putting all of this together yields,

$$A_i = \begin{cases} 0 & P_i < \frac{3}{4}S_i \\ \frac{4}{S_i}P_i - 3 & \frac{3}{4}S_i \leq P_i \leq S_i \\ 1 & P_i > S_i \end{cases} \quad (7)$$

Having chosen a definition for D_i and A_i , we may now combine the relations given above into the central equation of this model,

$$\rho_{ij} = C \frac{P_i(A_i + D_i - A_i D_i)}{L_{ij} N_{ij}}, \quad (8)$$

where C is a constant of proportionality representing the ratio of the number of people trying to leave the node i at a given moment, to the number of people who want to leave i . We set its value qualitatively to 0.03 so that traffic out of major cities will be fairly dense, but not entirely choking.

This equation determines the behavior of this entire model. An important property of this device is that the density of cars leaving a city is strongly dependent on the size of the population trying to leave that city. If a very large number of people try to leave at once (such as what happened in Charleston, NC during the 1999 evacuation), the density will be very large, and under these conditions the average travel speed will drop to near zero. This is the precisely effect of too many cars squeezing into a narrow passage.

One significant behavior to note is that for low a population the flux is linearly proportional to the density (which is linearly proportional to the population). For an evacuating city therefore, we expect an exponential asymptotic decay once the population has fallen below a certain point. In this low density regime the model is inaccurate. Realistically, a population should drop at a constant rate as the traffic density decreases and the last few people are able to escape the hurricane. To correct for this effect,

- We will consider a city to be entirely evacuated once its population has fallen below 40,000 people.

5 Analysis of Congestion effects with the Narrow Passage Model

During the 1999 hurricane Floyd evacuation, a huge traffic jam occurred. In assessing the accuracy of a mathematical model, the first test should be an attempt to reproduce that congestion. In figure 6 we show the population of several important cities plotted over time.

From this figure one can see that the smaller coastal communities are entirely evacuated within 48 hours, while Charleston requires a full 72 hours to completely evacuate below the 40k threshold. One also notices that after approximately 15 hours Columbia has reached full capacity and so the evacuees must continue on to Charlotte, Spartanburg, or Greenville.

Let us consider the trip of a typical resident of Charleston. Joe is unmarried and lives in an apartment near the waterfront, so when the hurricane evacuation is announced, he immediately hops in his car with his pet poodle and heads northwest along I26. Unfortunately, everyone else in Charleston had the same idea and the traffic is at a near standstill. Figure 7 outlines Joe's trip. We can see that Joe encounters a monumental traffic jam outside Charleston, but past

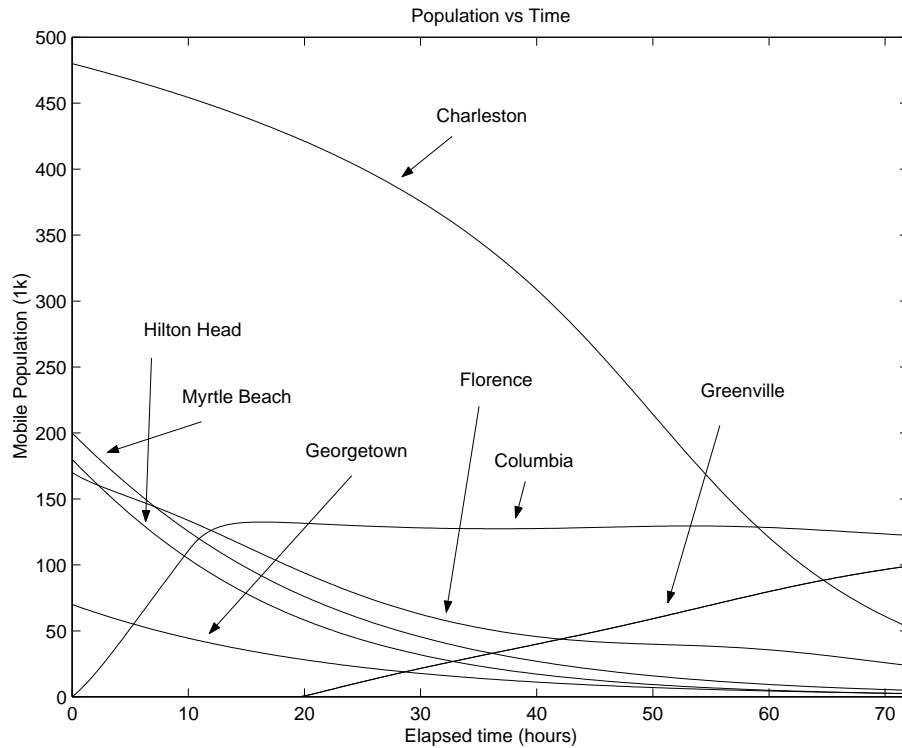


Figure 6: Evacuation under the 1999 conditions.

the I95 junction traffic clears up. The three hour drive takes Joe 15 hours to complete.

5.1 Adding some shelter in Columbia

By our estimates Columbia has shelter space for only 150,000 people, while many times this number will need to be evacuated from the coast. By any logic, several hundred thousand people will be forced to pass further north to Spartanburg, Greenville, and Charlotte.

According to the Narrow Passage model, traffic flows fairly smoothly out of Columbia. The average speed of cars outbound from Columbia is over 50 MPH during the entire evacuation process. In fact, the outbound flux is quite near the optimal 2500 cars per lane per hour. This model predicts very little jamming past Columbia. The reason for this is that the primary jams at the coastal cities and at the junction between I95 and I26 prevent limit the flow of traffic into Columbia to a manageable level. A similar filtering effect limits traffic from Florence to Columbia.

From the formulation of the model, one sees that congestion can only pro-

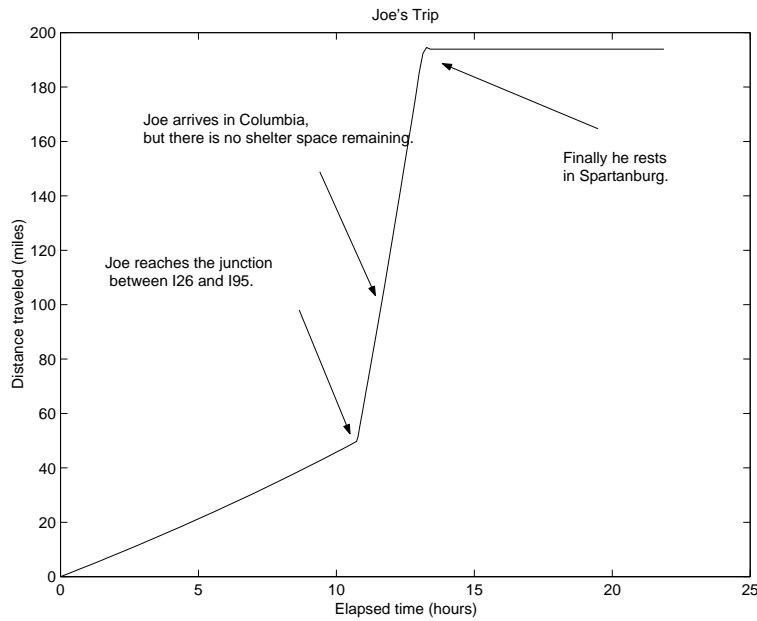


Figure 7: Joe's trip from Charleston to Spartanburg.

rogate in the direction away from the coast, so congestion in the central region of the state will not slow evacuation from the coast.

Adding temporary shelter would be a great convenience to many people who would otherwise be forced to travel another eighty miles to the Greenville area, but it would not significantly reduce traffic jams because these problems occur primarily between the coast and Columbia.

Thinking of Joe again, this time he arrives in Columbia after twelve agonizing hours of sitting in traffic, and he is just in time to claim one of the last remaining shelters, forcing several elderly people and a pregnant woman to drive all the way to Greenville.

5.2 The Georgia Effect

It has been suggested that many of the coastal residents of Georgia and Florida fled north along I95 and compounded traffic problems in South Carolina during the evacuation. With the Narrow Passage model one can estimate the effect of this population influx on traffic conditions.

We start with a few key assertions:

- Hurricanes move in clockwise arcs in the Atlantic ocean. They approach from the south or southeast, and then turn north or northeast at some point (Ref [4]).

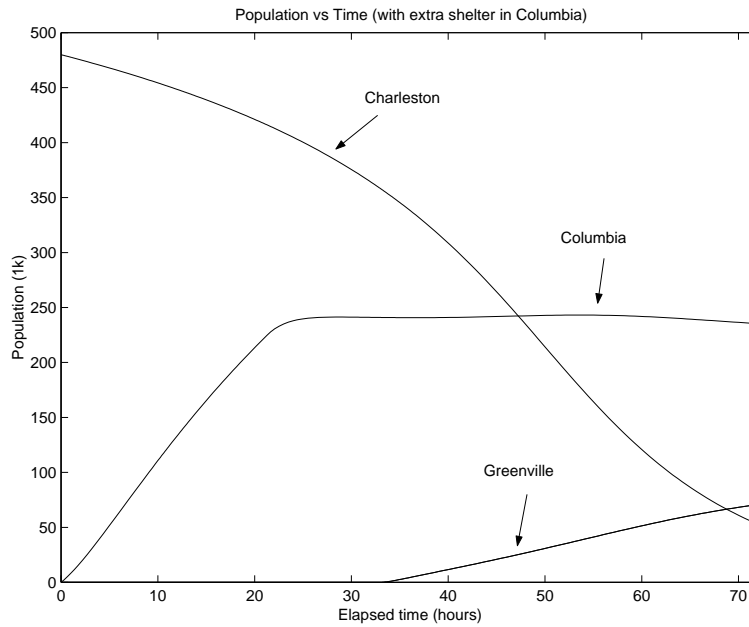


Figure 8: Evacuation with shelter for an additional 200,000 added at Columbia. Once this capacity has been reached, people are forced to move on to Greenville and Spartanburg.

- It is difficult to predict the point at which the hurricane will turn.

Given that a hurricane's path will curve clockwise by an unpredictable amount, Florida and Georgia will be the first states to perceive danger when a large storm approaches. Half a day may pass before it is clear that South Carolina will also be affected strongly enough to warrant evacuations. Therefore we expect that fleeing residents of Florida and Georgia on I95 will arrive in South Carolina at approximately the same time as evacuations are beginning in South Carolina.

In the Narrow Passage model the level of congestion is sensitive to the population. If only 80,000 Georgians come in on I95 then their effect is too small to be apparent, but if 250,000 come in then jamming at the I95-I26 junction can be quite severe. It is useful to note that Narrow Passage predicts that approximately 120,000 people will flee from Florence to North Carolina via I95. This number can be taken as an estimate of how many people will flee from Georgia to into South Carolina along I95. In the 1999 evacuation the influx from Georgia was probably higher than this predicted outflux because the influx included both people from Georgia and Florida. Under the geometry we have considered Narrow Passage does not allow large lateral migrations. However, by restructuring the graph to include more lateral connections such migrations could be

easily included in this model.

From this analysis we make the following estimate:

- Approximately 160,000 people enter South Carolina via I95. They arrive at the I95-I26 junction at approximately the same time as evacuations begin in South Carolina.

Suppose 160,000 people flee north along I95 from Florida and Georgia. We model this situation as if the out-of-state people begin at the I95-I26 junction node. With these circumstances the predictions of the Narrow Passage evacuation model are shown in figure 9.

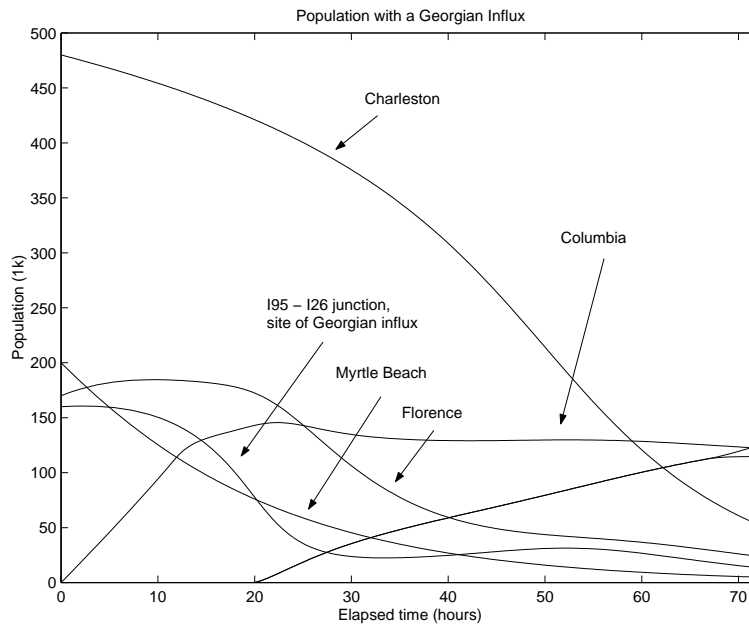


Figure 9: Evacuation with a 160,000 person influx from Georgia on I95.

Returning once more to our unfortunate friend Joe, we see that now (figure 11) his trip takes a full 18 hours. He encounters severe congestion on the entire stretch from Charleston the Columbia. But once past Columbia the freeways move at a high speed.

5.3 Stay Calm Everybody!

If the approach of the hurricane can be predicted three days before landfall, then an effective method of evacuation traffic management is for everyone stay calm and leave in an orderly fashion. We realize that this is difficult to maintain in the face on an approaching tempest. Nevertheless, it is an idea worth

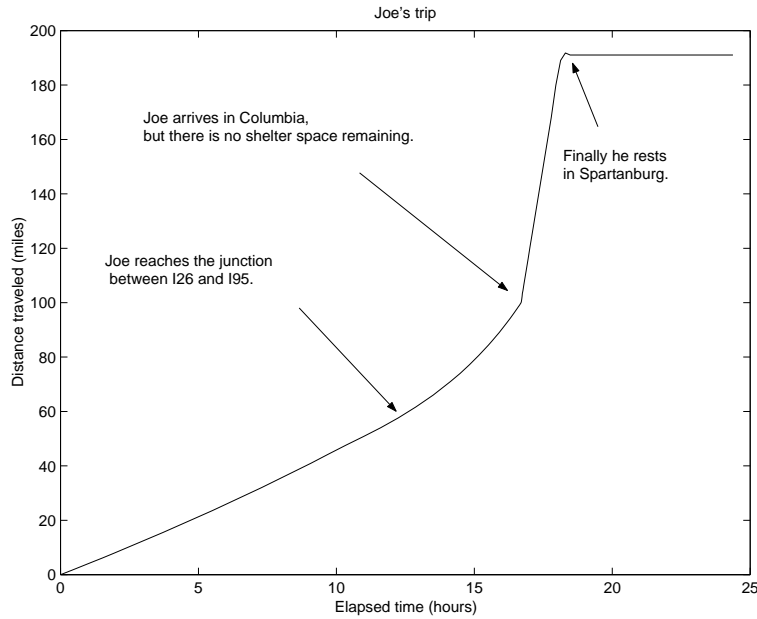


Figure 10: Joe's trip takes 18 hours when those darn people from Georgia jam I26 from here to Kalamazoo.

examining. Since the principle area of congestion has been between Charleston and Columbia, we will concentrate on that area here.

We found that by beginning with a controlled evacuation in Charleston, the process could be completed in the same 72 hours that was required for the simultaneous evacuation, however traffic speeds averaged around 50 MPH, which is entirely acceptable. This effect occurs because a given flux can be maintained at either of two speeds—at a high density and low speed, or a lower density with a higher speed (see figure 3).

5.4 Reversing lanes on I26

To prevent future jams like the one of 1999, the state of South Carolina (Ref [8]) has proposed reversing the direction of the two eastbound lanes of I26 (lane reversals are also planned for many of the rural highways which we do not consider in this model), thereby allowing four lanes of evacuation traffic. Analyzing the effectiveness of lane reversals on I26 is trivial from within the framework of Narrow Passage model, since the number of lanes is a parameter that is already engineered into the equations.

Figure 12 shows a simulated evacuation, with I26 lane reversal and an influx from Georgia. Here very little congestion occurs between Charleston and Columbia as the roads can now accommodate twice the number of cars. Traffic

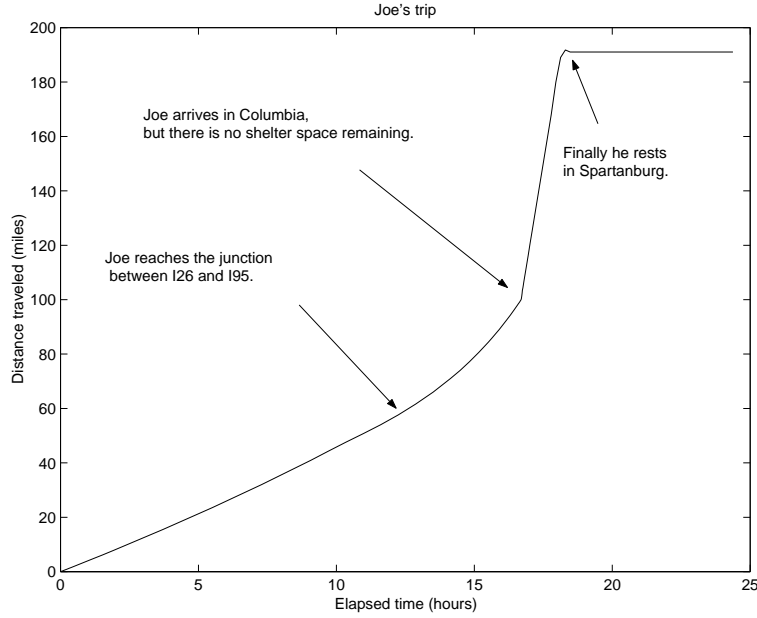


Figure 11: Joe's trip takes 18 hours when those darn people from Georgia jam I26 from here to Kalamazoo.

moves at around 52 MPH on the stretch of I26 leading to Columbia. However, the filtering effect of the congestion that we saw when there were only two outbound lanes has now vanished, and within ten hours of evacuation the population of Columbia skyrockets to almost twice the capacity and the freeways leading out of Columbia become too dense to move at more than a crawl pace, even if lanes have been reversed there too. Population in Columbia peaks after 20 hours at 225,000. The 160,000 influx from Georgia is somewhat negligible when compared to the more than half a million residents of Charleston and Hilton Head passing through Columbia. In this situation, temporary shelter in Columbia would dramatically decrease this congestion.

This time Joe makes it to Columbia in only a couple hours, and there he finds an available shelter. However, thousands of others—those who dally rather than departing promptly like Joe—are forced to drive all the way to Charlotte or Greenville. On the positive side, the endangered areas are entirely evacuated in under 40 hours (compare with 72 hours required without I26 lane reversal).

6 Population Distribution Model

Here we present an alternative model for the evacuation traffic. The core of this model is in considering the geographical relationship of population density

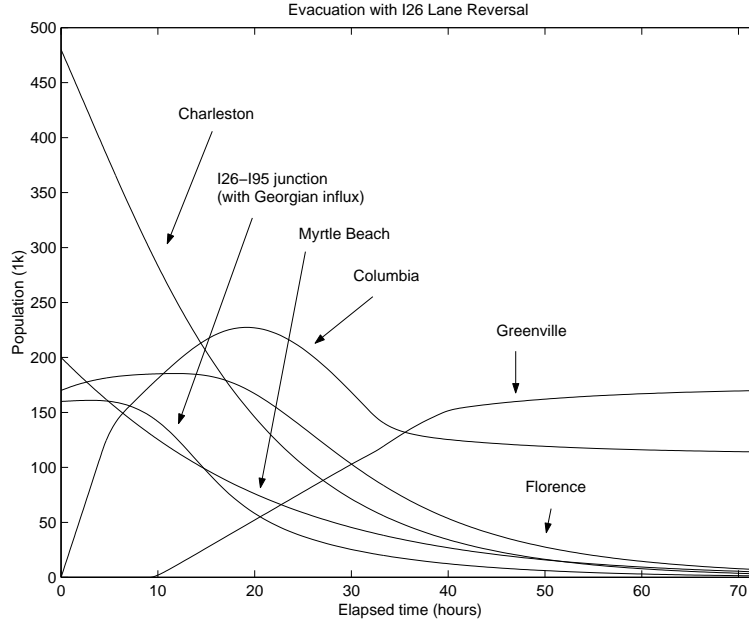


Figure 12: Narrow Passage model of evacuation with I26 lanes reversed. Here all four lanes carry westbound traffic away from the coast.

among major cities that lie along major highways. We continue to use the same differential equation to describe movements between the cities, but with a different way of evaluating peoples' desire to move to the neighboring city. Namely, we obtain a vector which points in the direction they want to head towards, along with magnitude representative of how strongly they want to head in that direction.

6.1 Assumptions

- Most of the population lives in clusters centered at different cities.
- First priority of the general population is to get away from cities on the coast.
- Second priority is to move away from overcrowded cities.
- People do not move when conditions of neighboring cities are no better than the city at which they are located.

6.2 Formulating the Model

To get the general picture of the population density distribution of South Carolina, we rely on the assumption that people generally live in clusters centered at cities. We assume that the population of any city is typically distributed with radial symmetry, with most of the population near the city center. We use 2 dimensional Gaussian distribution to approximate such distribution. Then our estimated population density, f_{city} , of a city located at a point (C_x, C_y) will be

$$f_{city}(x, y) = \frac{A}{\sigma_{city}^2} \exp\left(-\frac{(x - C_x)^2 + (y - C_y)^2}{\sigma_{city}^2}\right) \quad (9)$$

where σ_{city} is a measure of the spread of the city, and A is the renormalization so that integration over this density will result in total city population. For a city with total population $P_{city}(t)$ at time t , $A = \frac{P_{city}(t)}{\pi}$.

We use the natural coordinate system of longitude and latitude to position the cities accordingly. We will get the total population density, f_{sc} , by superposition of city densities

$$f_{sc}(t) = \sum_{city} f_{city}(t) \quad (10)$$

We can describe the overcrowding of the cities by multiplying the inverse of the city capacity, $\frac{1}{K_{city}}$, by each city population density. A larger city can absorb more people compared to a smaller city where readily available shelter is much more limited. Overcrowding density is given by,

$$O_{sc}(t) = \sum_{city} \frac{f_{city}(t)}{K_{city}}. \quad (11)$$

We determine the location people desire to be with *desired location function*, F . This function will depend on two different things:

- Evacuation order. Cities near the coast must be evacuated to avoid Hurricane Floyd.
- Overcrowding in cities. Limitation of hotels and shelters lead people to seek alternate locations.

Evacuation order should be the dominating factor near the coast where Hurricane Floyd is expected to arrive, so overcrowding factor should only become noticeable in relatively safe areas.

We start with a function that resembles a plateau. Desire level is roughly proportional to the distance from the coastline to the safe inland area. This

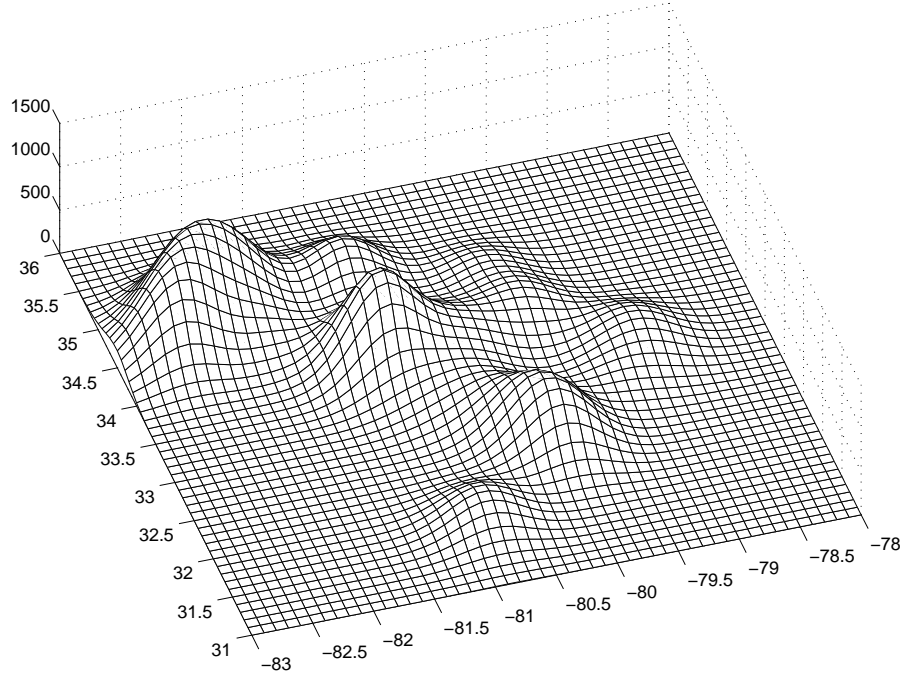


Figure 13: Population Density of South Carolina

function was created with three piecewise planes. Then the desire level is corrected by the overcrowding density. A less crowded area is more desirable, so the overcrowding density is subtracted.

The average direction and the magnitude of people's travel desire vector is estimated by the gradient of the desired location function. The magnitude of the travel desire vector in particular direction can be obtained with the directional derivative,

$$\text{grad}F \cdot u. \quad (12)$$

where u is the unit vector in the direction at which directional derivative is to be evaluated at. Since people are restricted to traveling along highways, we look at directional derivative in the direction of the highway connecting major cities.

Density of the highway starting at city i to j , ρ_{ij} , should be

- Proportional the average directional derivative along the highway connecting the two cities,

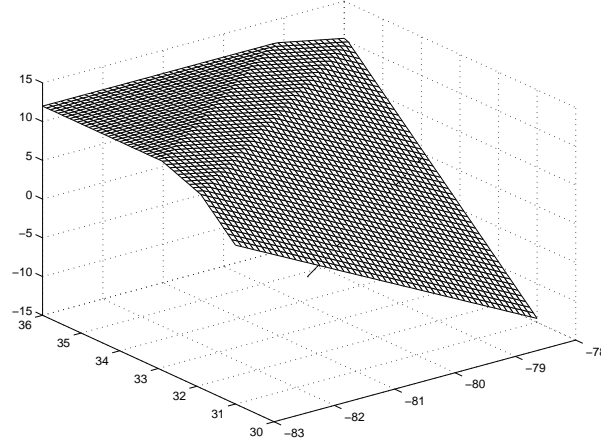


Figure 14: Plateau function - line shows the coastline of South Carolina

- Proportional to the population of both neighboring cities, P_i and P_j ,
- Inversely proportional to the total capacity of the cities, and
- Inversely proportional to the capacity of the highway, $n_{lanes}dist(i, j)$.

here negative density can be interpreted as positive density heading in the opposite direction. This is consistent because the above definition is antisymmetric. That is, $\rho_{ij} = -\rho_{ji}$. If there is no highway connecting cities i and j , we set the density to be zero.

This combined with the logistic velocity equation 3 will yield the set of differential equation governing this model

$$\frac{dP_i}{dt} = - \sum_j n_{ppc} N_{ij} \rho_{ij} v \quad (13)$$

6.3 Results

Below is the plot of the mobile population vs time in few of the cities of interest. The majority of the coastal city population is evacuated in about 72 hours.

The Population curve for Florence is representative of what happened at most cities connecting coastal cities and Columbia. Population climbs during the first 30 hours or so, then their population propagates on to Columbia.

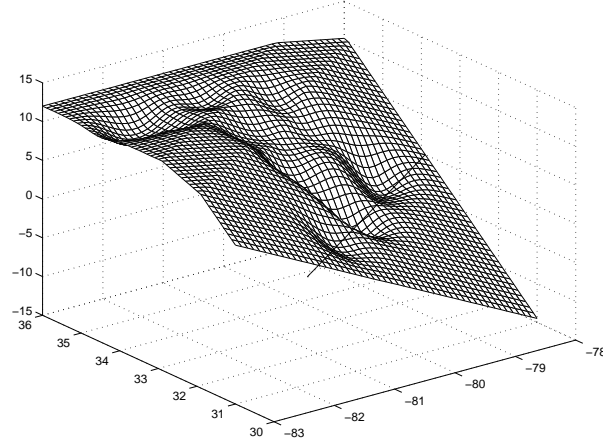


Figure 15: Desired location function - line shows the coastline of South Carolina

During the build up of population in these connecting cities, traffic entering Columbia slows down. Once population starts to come down again among the connecting cities, flux at Columbia starts to pick up again.

Columbia lies on the critical point where dominant term in desired location function F switches over from the evacuation order to overcrowding density. People at Columbia are not so worried about the hurricane anymore, but they want to find a place where they can stay. Naturally, a lot of population move on to Rock Hill, then on to Charlotte in North Carolina, or to Spartanburg in North Western corner of South Carolina.

Reversing the lanes of south bound traffic on I26 was implemented by the doubling number of lanes in the formula for interstate highway 26. Surprisingly, this did not increase the evacuation time of coastal cities in this model. What happened was that initial speed of evacuation increased significantly, but quickly developed extremely unbalanced population density, which resulted in heavier traffic jam by Columbia.

Adding temporary shelters to Columbia increased the city's ability to absorb more incoming population, but it didn't have much impact prevent traffic jam. This was simulated by increasing the city capacity of Columbia, $K_{columbia}$. It only delays the traffic jam slightly, because people in Columbia is not motivated to move away from the city until it gets overcrowded. Temporary shelter is on first come first served basis, and no reasonable amount of these shelters will be able to absorb the entire fleeing population from the coastal cities.

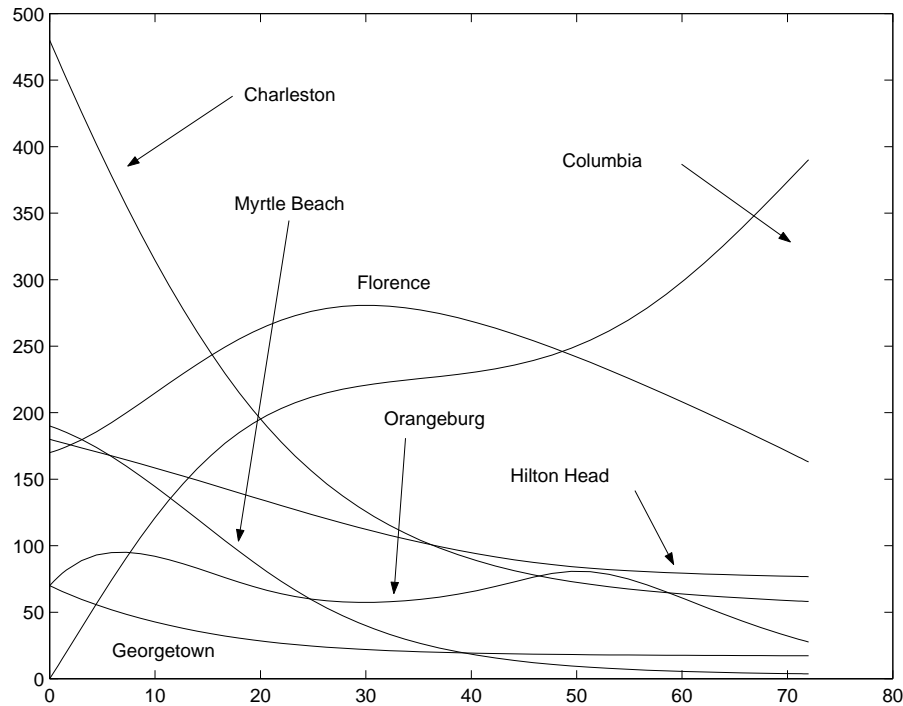


Figure 16: Mobile Population (1k) vs Time (hr)

6.4 Is the Model Reasonable?

Most of the simulated results obtained from seem to be not too far from what happened in South Carolina in 1999, but the model does not have the credibility to predict things as it is now, because of the instability of the behavior when one slightly changes one of the parameters. What we found while tuning the effect of the overcrowding density in the desired location function is that behavior at Columbia was sensitive to the parameter. Too small of an effect does not motivate the population in Columbia to move out of the city, causing the population to sky rocket, bringing highways near Columbia to a standstill. Too much of an effect moves population out of Columbia, but instead of sharing and equalizing the excess population that came all the way up to Spartanburg and Greenville, it drove the population away from each other. This is not very realistic.

Furthermore, dynamically updating the desired location function is computationally very expensive. Adding geographical relationship to the population did not effectively even out the excess population as we initially hoped, and it seems that it is too much trouble for what it contributes to the simulation. Traffic jams from the coastal cities shown above could be reproduced without

the overcrowding density term in the desired location function.

7 Summary

We have presented two models for the evacuation of coastal cities in South Carolina due to an approaching hurricane. Under the conditions of 1999's hurricane Floyd evacuation, both models pass the preliminary test of recreating the tremendous traffic jam that occurred during the evacuation.

The Narrow Passage model simplifies the traffic jam phenomenon by assuming that jamming only occurs at points where too many people wish to use the same road simultaneously. It further assumes that people only travel via interstate highways. The Population Density model takes a slightly more geometric approach and looks more at geographic relationships and their influence in the evacuation process. This model also incorporates the rural highways which are neglected by the Narrow Passage model.

Both models incorporate a relationship between the average speed of traffic and the density of cars. This relationship is derived from the estimate that the maximum safe speed given a following distance of 35ft is 20MPH.

The Narrow Passage model predicts that approximately 150,000 residents of the coastal regions in Florida and Georgia will enter South Carolina on I95. The model predicts that at this level, their impact to congestion is small, however if over 300,000 people enter the state, then huge congestion problems are predicted between Charleston and Columbia. On the subject of I26 lane reversal, this model also predicts that evacuation time will be greatly decreased. However it also predicts that the increased rate of exodus from Charleston will result in new traffic jams in Columbia and on I26 to north.

The Population Density model looks good in principle, but it exhibits too much sensitivity to be reliable as a prediction device.

Nevertheless, both models predict that without new measures, evacuation of the coast will require 72 hours to complete. Both models also show that the effect of creating temporary shelter in Columbia would be of little significance.

One possibility we raise is that if evacuations are controlled and regulated—perhaps by evacuating a couple counties at a time—while total evacuation time would not be changed, the evacuees would not find themselves stuck in bumper-to-bumper traffic. At least the trip would be a little more pleasant.

The central issue in a large scale evacuation is that the interstate freeway system simply cannot support the volume of traffic that occurs. There will invariably be delays, so the best one can hope for is to minimize the congestion. In this respect, the combination of reversing the lanes on I26 and implementing controlled rate evacuation in major coastal cities is the most promising strategy. These two techniques should be used in combination.

References

- [1] Haight, Frank A. *Mathematical Theories of Road Traffic* Institute of Transportation and Traffic Engineering, U. of California Special Report. March 1960.
- [2] South Carolina Department of Commerce.

http://www.callsouthcarolina.com/Maps/Map-Pop_Density.htm
- [3] Population Estimates Program. Population Division, U.S. Census Bureau, Washington D.C. July 1999
- [4] Pasch, Richard J. *TPC Atlantic Floyd 1999 Preliminary Report* 7-17 September, 1999

http://www.nhc.noaa.gov/1999floyd_text.html
- [5] Pline, James L. *Traffic Engineering Handbook* 4th Edition. Prentice-Hall. New Jersey 1992
- [6] Transportation Research Board, National Research Council. *Highway Capacity Manual, Special Report 209*. Washington D.C. 1985
- [7] Rinck, Jessica. *Storm Sparks Largest U.S. Exodus*. The Augusta Chronicle. Sept. 16, 1999
- [8] *Hurricane evacuation/lane reversal information*

http://www.sctraffic.org/lane_reversal.html

Jamming to Floyd

Researchers in the J.E.R think tank say that traffic jams resulting from large scale evacuations of the South Carolina Coast are predictable and to some extent avoidable. In September 1999 as Hurricane Floyd approached, the order to simultaneously evacuate the entire South Carolina Coast resulted in a mind boggling traffic jam worthy of the Smuckers label. Some of the Worst traffic conditions occurred on Interstate 26 as some half a million people from Charleston and surrounding areas on the coast tried to evacuate to Columbia via that highway. The J.E.R researchers have developed a model of traffic flow under the assumption that the entire South Carolina Coast must be evacuated. The simulation reproduces the I26 traffic jam and provides other traffic information by predicting population variance over time in the key South Carolina cities.

Kevin E. Nivek, a Washington DC palindrome researcher says, "Well, one obvious advantage of having a traffic flow simulation is the ability to analyze the effect of different evacuation strategies without having to wait for another Floyd-like hurricane to threaten the Carolina coast." One question is whether the same level of congestion would occur under similar evacuation conditions or whether the extreme gridlock experienced in the attempt to flee Floyd was a freak occurrence. The unfortunate answer according to J.E.R reports is that in an endeavor as large as evac-

uating a million people, traffic problems are an inevitable inconvenience. According to their simulation, without changing the hurricane evacuation strategy, it takes up to three days for a complete and thorough evacuation of the coastal area.

It has been suggested that in the 1999 evacuation of the coast, traffic problems were severely exacerbated by the untimely influx of Georgians on Interstate 95 which intersects I26 between Columbia and the coast. J.E.R. research data suggests that is not the case and that the conjecture may have therefore been biased by a desire to blame the Georgians. When the traffic flow simulation is run with a virtual Georgia filter that blocks I95 access to Georgians only, road congestion decreases somewhat, but overall evacuation times are only marginally decreased. Another proposed solution to improve traffic is to add shelters in Columbia for people fleeing the coast so that there might be less road congestion due to large numbers of cars having to leave the city. Although the simulation shows that road congestion can indeed be reduced, it also shows that increasing the capacity of Columbia does not greatly affect the total evacuation time. In fact the data show that among all the controllable factors, road capacity and the total number of cars using the roads are the two most significant parameters. Increasing capacity by reversing coastal bound traffic on

I26 alone cuts the projected evacuation time by more than one third. Reducing the number of cars on the road has similarly dramatic effects. So to lower the evacuation time, J.E.R. recommends that evacuation officials consider reversing some coastal-bound lanes in emergencies and also that they encourage families to leave extra cars, campers, and mobile homes behind to reduce congestion on roads.

The J.E.R. researchers also suggest that limiting the rate at which people can leave coastal cities can drastically reduce road congestion without increasing the total evacuation time. Their simulations contain information about how long on average it takes for a car to go from one city to another. When no artificial limits are placed on the outflow of people from the coast, even with some of the previously suggested evacuation strategies in place, the simulations show that during an evacuation it can still take the average car from Charleston two to five times as long as normal to get to Columbia. Researcher No.42 at J.E.R. headquarters explains how controlling the flow of cars can lower the average travel time and not affect the duration of the entire evacuation, "One can achieve the same flow of cars on a road by having tightly packed cars move slowly or by having loosely packed cars moving quickly. Why cram two people through a door when they can go through one at a time? The groups may enter the room at the same overall rate, but the people who go in one at a time will be much happier. This is the rationale behind limiting the rate at which people get on the roads. The average travel time decreases and the traffic flow on the roads doesn't drop." Another researcher, who wished to remain anony-

mous, expressed doubts about the feasibility of controlling the outflow of people. "I wouldn't want the job of holding back people who are trying to escape a hurricane's wrath."

The idea behind the J.E.R. traffic simulation is that after the hurricane warning has been given, each city has associated with it a danger value which is proportional to peoples' desire to leave that city. A J.E.R. spokesperson gives a general description of their simulation process, "Our first step in simulating the evacuation process is to give coastal cities danger values much higher than those of inland cities. Then when calculating how many people try to go from one city to another, we consider not only the difference in danger levels, but also other factors such as city population and the maximum capacity of a city. Perhaps in the future we should also consider the difference in the number of Krispy Kreme doughnut shops between cities. Anyway, we can calculate the speed of the average traveler based on the density of cars on the road, which of course increases as more and more people try to use the road. That's how our simulation can give a description of how long it takes the average person to get from one city to another during a coastal evacuation."