# Blowin' in the Wind

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## Introduction

We present a model to determine the optimal evacuation plan for coastal South Carolina in the event of a large hurricane. The model simulates the flow of traffic on major roads. We explored several possible evacuation plans, comparing the time each requires.

Traffic flow can be significantly improved by reversing the eastbound lanes of I-26 from Charleston to Columbia. By closing the interchange between I-26 and I-95 and restricting access to I-26 at Charleston, we can reduce the overall evacuation time from an original 31 h to 13 h.

However, a staggered evacuation plan, which evacuates the coastline county by county, does not improve the evacuation time, since traffic from each coastal population center interferes little with traffic flowing from other areas being evacuated. Although reversing traffic on other highways could slightly improve traffic flow, it would be impractical. Restrictions on the number and types of vehicles could speed up the evacuation but would likely cause more problems than improvements.

## Theory of Traffic Flow

We require a model that simulates traffic flow on a large scale rather than individual car movement. We take formulas to model traffic flow from Beltrami [1998]. Although traffic is not evenly distributed along a segment of road, it can be modeled as if it were when large segments of road are being considered. We can measure the traffic density of a section of road in cars/mi. The traffic

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speed $u$ at a point on the road can be calculated from the density according to the formula

$$u(r) = u_m \left(1 - \frac{\rho}{\rho_m}\right),$$

where $\rho$ is the traffic density, $u_m$ is the maximum speed of any car on the road, and $\rho_m$ is the maximum traffic density (with no space between cars). We define the *flow* of traffic at a point on the road as the number of cars passing that point in a unit of time. The flow $q$ can be easily calculated as

$$q(\rho) = \rho u.$$

It is the flow of traffic that we desire to optimize, since greater flow results in a greater volume of traffic moving along a road.

# Assumptions

- During an evacuation, there is an average of 3 people per car. This is reasonable, since people evacuate with their entire families, and the average household in South Carolina has 2.7 people, according to the 1990 census.
- The average length of a car on the road is about 16 ft.
- In a traffic jam, there is an average of 1 ft of space between cars.
- The two above assumptions lead to a maximum traffic density of

$$\frac{5280 \text{ ft/mile}}{17 \text{ ft/car}} = 310 \text{ cars/mile/lane}.$$

- The maximum speed is 60 mph on a 4-lane divided highway, 50 mph on a 2-lane undivided country road.
- Vehicles follow natural human tendencies in choosing directions at intersections, such as preferring larger highways and direct routes.
- The traffic flow of evacuees from Florida and Georgia on I-95 is a continuous stream inward to South Carolina.
- When vehicles leave the area of the model, they are considered safely evacuated and no longer need to be tracked.
- There will not be traffic backups on the interstates at the points at which they leave the area of the model.
- A maximum of 30 cars/min can enter or exit a 1-mi stretch of road in a populated area, by means of ramps or other access roads. Up to the maximum exit rate, all cars desiring to exit a highway successfully exit.

- The weather does not affect traffic speeds. The justifications are:
  - During the early part of the evacuation, when the hurricane is far from the coast, there is no weather to interfere with traffic flowing at the maximum speed possible.
  - During the later part of the evacuation, when the hurricane is approaching the coast, traffic flows sufficiently slowly that storm weather would not further reduce the speed of traffic.
- There is sufficient personnel available for any reasonable tasks.

# Objective Statement

We measure the success of an evacuation plan by its ability to evacuate all lives from the endangered areas to safe areas between announcement of mandatory evacuation and landfall of the hurricane; the best evacuation plan takes the shortest time.

# Model Design

## The Traffic Simulator

Our traffic simulator is based on the formulas above. Both space and time are discretized, so that the roads are divided into 1-mi segments and time is divided into 1-min intervals. Vehicles enter roads at on-ramps in populated areas, leave them by off-ramps, and travel through intersections to other roads.

Each 1-mi road segment has a density (the number of cars on that segment), a speed (mph), and a flow (the maximum number of cars that move to the next 1-mile segment in 1 min). Each complete road section has a theoretical maximum density $\rho_m$ and a practical maximum density $\rho'_m$ (accounting for 1 ft of space between cars), which can never be exceeded.

## Moving Traffic Along a Single Road

The flow for each road segment is calculated as

$$q(\rho) = \frac{\rho u}{u_m}.$$

If the following road segment is unable to accommodate this many cars, the flow is the maximum number of cars that can move to the next segment.

## Moving Traffic Through Intersections

When traffic reaches the end of a section of road and arrives at an intersection, it must be divided among the exits of the intersection. For each intersection, we make assumptions about percentages of cars taking each direction, based on the known road network, the capacities of the roads, and natural human tendencies. If a road ends at an intersection with no roads leading out (i.e., the state border), there is assumed to be no traffic backup; traffic flow simply continues at the highest rate possible, and the simulation keeps track of the number of cars that have left the model.

Conflicts occur when more cars attempt to enter a road section at an intersection than that road section can accommodate. Consider a section of road that begins at an intersection. Let:

$q_{\max} = \rho'_m - \rho$ = the maximum influx of cars the road can accommodate at the intersection,

$q_1, \ldots, q_n$ = the flows of cars entering the road at an intersection, and

$q_{\text{in}} = \sum q_i$ = the total flow of cars attempting to enter the road at the intersection.

If $q_{\text{in}} > q_{\max}$, then we adjust the flow of cars entering the road from its entrance roads as follows:

$$q_i' = \frac{q_i}{q_{in}}\, q_{\max}.$$

Therefore, $q_i'$ is the number of cars entering the road from road $i$. The flow of traffic allowed in from each road is distributed according to the flow trying to enter from each road. Clearly, $\sum q_i' = q_{\max}$.

## Simulating Populated Areas

A section of road that passes through a populated area has cars enter and leave by ramps or other access roads. We assume that the maximum flow of traffic for an access ramp is 30 cars/min. We estimate the actual number of cars entering and leaving each road segment based on the population of the area.

Cars cannot enter a road if its maximum density has been reached. For simplicity, however, we assume that cars desiring to exit always can, up to the maximum flow of 30 cars/min per exit ramp.

We desire to know how the population of each populated area changes during the evacuation, so that we can determine the time required. Therefore, we keep track of the population in the areas being evacuated, Columbia, and certain other cities in South Carolina. If all people have been evacuated from an area, no more enter the road system from that area.

Areas do not have to be evacuated immediately when the simulation starts. Each area may be assigned an evacuation delay, during which normal traffic is simulated. Once the delay has passed, traffic in the area assumes its evacuation behavior.

## Completing an Evacuation

The six coastal counties of South Carolina (where Charleston includes the entire Charleston area) and the roads leading inland from these areas must be evacuated. When the population of these areas reaches zero, and the average traffic density along the roads is less than 5 cars/mi, the evacuation is complete and the simulation terminates.

## Implementing the Model

We implemented the model described above in a computer program written in C++. The logic for the main function is as follows: For each road, we let traffic exit, resolve traffic at intersections, move traffic along the rest of the road, and finally let cars enter the road. We loop until the evacuation is complete.

Traffic flow is considered simultaneous; the traffic flow along every road is determined before traffic densities are updated. However, exits occur first and entrances last, to accurately simulate traffic at access ramps.

# Model Results

## Simulating the 1999 Evacuation

To simulate the evacuation of 1999, we prepared a simplified map that includes the interstates, other the 4-lane divided highways, and some 2-lane undivided roads. We simulated the evacuation of the coastal counties—Beaufort, Jasper, Colleton, Georgetown, and Horry (including Myrtle Beach)—and the Charleston metro area. The inland areas we considered are Columbia, Spartanburg, Greenville, Augusta, Florence, and Sumter. In addition, we simulated large amounts of traffic from farther south entering I-95 N from the Savannah area. A map of the entire simulation is shown in **Figure 1**.

The results of running this simulation with conditions similar to those of the actual evacuation produced an evacuation time of 31 h to get everyone farther inland than I-95. This is significantly greater than the actual evacuation time and completely unacceptable. The increase in time can be explained by two features of the actual evacuation that are missing in the simulation:

- Only 64% of the population of Charleston left when the mandatory evacuation was announced [Cutter and Dow 2000; Cutter et al. 2000]; our model assumes that everyone leaves.
- Late in the day, the eastbound lanes of I-26 were reversed, eliminating the congestion.

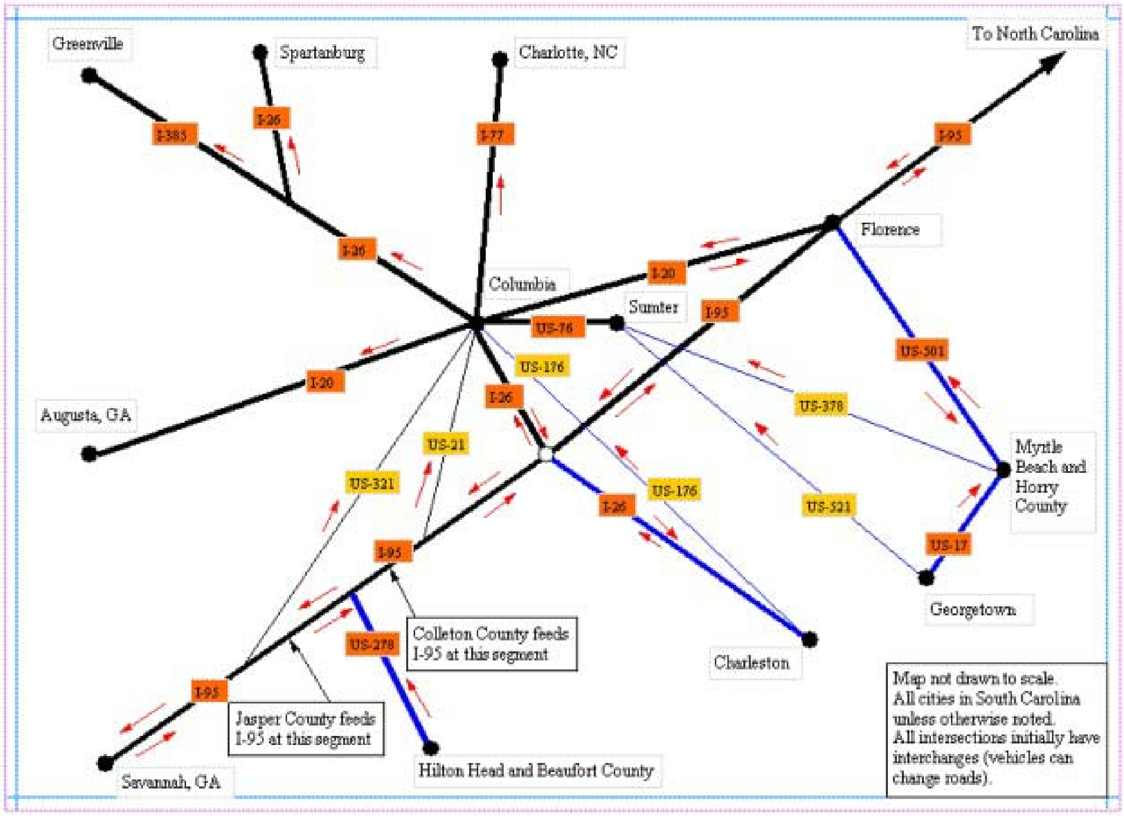


**Figure 1.** Map of the simulation.

# Simulating Reversal of I-26

In this simulation, I-26 E was turned into a second 2-lane highway leading from Charleston to Columbia. The evacuation time was reduced to 19 h. Under all conditions tested, reversing traffic on the eastbound lanes of I-26 significantly reduces evacuation time.

# Simulating a Staggered Evacuation

A staggered evacuation of the coastal counties of South Carolina, going from south to north with 1 h delays, decreases the time for evacuation to 15.5 h—2.5 longer than the best time (described below). This is because the second-slowest county to evacuate, Horry County, is the northernmost and the last to evacuate. An analysis of the evacuation routes used reveals why there is no improvement: The roads for the large counties do not intersect until they reach Columbia. Given that the evacuation of Charleston County takes 13 h, the evacuations of the other large counties (Horry and Beaufort) would need to be advanced or delayed at least this much to have any effect.

## Reversing Other Highways

Reversing traffic on smaller highways might improve traffic flow, but this is not a practical option. None of the roads besides I-26 is a controlled-access road; therefore, it is impossible to ensure that the traffic entering the reversed lanes would all move in the desired direction. A single vehicle entering and attempting to travel in the undesired direction would cause a massive jam.

The possible minor highways to Columbia that could be reversed are U.S. highways 321, 176, 521, 378, 501, and 21. All are non-controlled-access roads, meaning that there are no restrictions on where vehicles may exit or enter. Together, they have 450 mi of roadway. A quick examination of U.S. 501, the highest-capacity of these, reveals two intersections per mile with other roads. Considering this as typical, there are 900 intersections outside of towns that would need to be blocked. Factoring in the no fewer than 60 towns along the way, the blocking becomes prohibitive.

Therefore, reversal of minor highways leading inland is not feasible. The only road that can be feasibly reversed is I-26.

## Adding Temporary Shelters to Columbia

According to our simulation, the population of the Columbia area after the evacuation (in the best-case scenario) was 1,147,000, a massive number above the 516,000 permanent residents. If more temporary shelters were established in Columbia, there would be less traffic leaving the city and therefore more congestion within the city. This would reduce the rate at which traffic could enter Columbia and lead to extra traffic problems on the highways leading into it. The effect of this congestion is beyond our computer simulation.

We investigated buildings for sheltering evacuees. Using `smartpages.com` to search for schools, hotels, and churches in the Columbia area, we found the numbers of buildings given in **Table 1**. We assumed an average capacity for each type of building. According to the table, Columbia can shelter 1,058,251; this leaves a deficit of 89,000.

**Table 1.**
Post-evacuation sheltering in the two counties (Richland and Lexington) that Columbia occupies.

| Type | Buildings in Richland | in Lexington | Total | People sheltered Per building | Number |
|---|---|---|---|---|---|
| Permanent residents | | | | | 516,251 |
| Schools—general * | 83 | 113 | 196 | 900 | 176,400 |
| Hotels/motels | 80 | 32 | 112 | 500 | 56,000 |
| Churches | 568 | 386 | 954 | 250 | 238,500 |
| Schools—other** | 63 | 16 | 79 | 900 | 71,100 |
| | | | | Total | 1,058,251 |

*We assume that schools average 600 students and can shelter 900.
**Includes academies but excludes beauty schools, trade schools, driving schools, etc.

However, Charlotte NC had only a very small increase in population due to evacuation (from 396,000 to 411,000). The people that Columbia cannot shelter can easily find shelter in Charlotte.

## Restricting Vehicle Types and Vehicle Numbers

Restrictions on numbers and types of vehicles would indeed increase the speed of the evacuation. However, there are no reliable ways to enforce such restrictions. Consider the following arguments:

- Forbidding camper vehicles may be unsuccessful, since for a sizable fraction of tourists the camper is their only vehicle.
- Restricting the number of vehicles to one per family:
  - The record-keeping involved would be prohibitive.
  - For some families, more than one vehicle is needed to carry all of the family members.

## The I-95 Traffic Problem

We assume that if the interchange is not closed, at least 75% of the people coming up from Florida and Georgia on I-95 will take I-26 to Columbia. This is because the next major city reachable from I-95 is Raleigh, 150 mi further on. In our simulation, not closing this intersection (but keeping the eastbound lanes of I-26 reversed) increases the evacuation time to 19 h.

## The Best Simulated Evacuation Plan

By altering various model parameters, we reduced the overall evacuation time to 13 h:

- Reverse the eastbound lanes of I-26.
- Close the exit on I-95 N leading to I-26 W.
- Limit the flow of traffic from Charleston to I-26 W.

The third item is necessary to reduce congestion along I-26 in the Charleston area. If too many cars are allowed on, the speed of traffic in Charleston drops significantly. Although this unlimited access results in a greater average speed on the section of I-26 between Charleston and the I-95 interchange, the slowdown in the Charleston area is exactly the type of backup that caused complaints in 1999 and resulted in a greater total time to evacuate the city.

# Conclusions

It is possible to evacuate coastal South Carolina in 13 h. Assuming that a hurricane watch is issued 36 h prior to landfall, the state can allow an ample delay between voluntary evacuation announcement and a subsequent mandatory order. However, state agencies must take considerable action to ensure that the evacuation will go as planned:

- Close the interchange between I-26 and I-95. Traffic on I-26 must remain on I-26; traffic on I-95 must remain on I-95.
- The two eastbound lanes of I-26 must be reversed immediately upon the mandatory evacuation order.
- In Charleston, restrict entrance to I-26 to 15 cars / min at each entrance ramp.

Everyone in the areas to evacuate must be notified. Within South Carolina, the existing Emergency Alert System includes many radio stations that can inform the public of the incoming hurricane, the steps to take during evacuation, and which roads to use.

Residents must be more convinced to evacuate than they were during Hurricane Floyd. Appropriate measures must be taken to ensure that residents evacuate and evacuate far enough inland.

# Model Strengths and Weaknesses

## Strengths

The model's predictions have a number of features found in a real evacuation or other high-density traffic flow:

- An initial congested area around the entrance ramps gives way to a high-flow area when there is no entering traffic.
- Overall traffic speed in high-flow areas is around 35 mph.
- Merging traffic causes a major decrease in flow.

## Weaknesses

The model does not take into account

- **city streets**, which are important in moving people from the highways to shelter in Columbia.
- **accidents**. A single accident or breakdown could result in several hours of delay. Tow trucks should be stationed at regular intervals along major roads.

- **local traffic on the non-controlled-access highways**, which would slow traffic on those roads.

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# Students Develop Optimal Coastal Evacuation Plan

SOUTHFIELD, MICH., FEB. 12— During September 13–15, 1999, Hurricane Floyd threatened landfall along the coast of South Carolina. In response to weather advisories and a mandatory evacuation order from the governor, hundreds of thousands of people simultaneously attempted to evacuate the coastal regions including Charleston and Myrtle Beach, causing unprecedented traffic jams along major highways. Although the evacuation was successful in that no lives were lost (largely since Floyd did not have as great an impact in the expected area), the evacuation was a failure in that it was not executed quickly nor completely enough to ensure the safety and well-being of all evacuating citizens had Hurricane Floyd made landfall in the Charleston area.

Since that problematic evacuation in 1999, state officials have been working on plans for a safe, efficient evacuation of the South Carolina coast, preparing for the event that a hurricane like Floyd threatens the coast again. They posed the problem to teams of mathematicians all over the country.

After working for four days, a group of talented students evolved a specific plan to safely and quickly evacuate every coastal county in South Carolina (nearly 1 million people) within 13 hours, using a computer simulation of their own design. The plan involves the reversal of the two coastal-bound lanes on Interstate 26 (the main east-west highway), as well as traffic control and detours throughout the major roads heading inland.

The students' plan guides the mass traffic flow to areas the students felt were capable of sheltering large numbers of evacuees. The main destination was Columbia, the capital and largest inland city in South Carolina. Other destinations were Spartanburg, Florence, Sumter, and Greenville in South Carolina; Augusta in Georgia; and Charlotte in North Carolina. The plan also accounted for the possibility of very heavy traffic coming northward from Georgia and Florida on I-95, fleeing from the same hurricane, which could adversely affect the evacuation in South Carolina.

Additionally, the students set forth plans to shelter the more than 1 million people who would be in Columbia after the evacuation is complete. By making use of all the city's schools, hotels, motels, and churches as shelters, nearly all the evacuees could be sheltered. The few remaining evacuees could easily find shelter north in Charlotte, which in 1999 received few evacuees.

— Mark Wagner, Kenneth Kopp, and William E. Kolasa in Southfield, Mich.