Jammin' with Floyd: A Traffic Flow Analysis of South Carolina Hurricane Evacuation

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Introduction

We analyze the 1999 Hurricane Floyd evacuation with a traffic-flow model, explaining the extreme congestion on I-26. Then we look at the new South Carolina Hurricane Evacuation Plan, which includes lane reversals. We analyze their effect; they would significantly benefit traffic leaving Charleston. With lane reversals, the maximum number of vehicles passing any point on I-26 is 6,000 cars/h.

We develop two plans to evacuate the South Carolina coast, the first by geographic location, the second by license-plate parity.

We explore the use of temporary shelters; we find that I-26 has sufficient capacity for oversized vehicles; and we determine the effects of evacuees from Georgia and Florida.

Traffic Flow Model

The following definitions and model are taken directly from Mannering and Kilareski [1990].

The primary dependent variable is level of service (LOS), or amount of congestion, of a roadway. There are six different LOS conditions, A through F, with A being the least congested and F being the most congested. We focus on the distinction between levels E and F:

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- *Level of Service E* represents operating conditions at or near capacity level. All speeds are reduced to a low but relatively uniform value, normally between 30 and 46 mph.
- *Level of Service F* is used to define forced or breakdown flow, with speeds of less than 30 mph. This condition exists wherever the amount of traffic approaching a point exceeds the amount that can traverse that point. Queues form behind such locations.

If we enter LOS F, the roadway has exceeded its capacity and the usefulness of the evacuation has broken down. An evacuation strategy that results in a highway reaching LOS F is unacceptable.

For a given highway, we can determine the maximum number of vehicles that can flow through a particular section while maintaining a desired level of service. To make this more concrete, we define the characteristic quantity *maximum service flow*.

Definition. *Maximum Service Flow* (MSF_i) for a given level of service i, assuming ideal roadway conditions, is the maximum possible rate of flow for a peak 15-min period, expanded to an hourly volume and expressed in passenger cars per hour per lane (pcphpl). To calculate the MSF of a highway for a given LOS, we multiply the road's capacity under ideal conditions by the volume-to-capacity ratio for the desired LOS. More formally,

$$\mathrm{MSF}_i = c_j \, \frac{v}{c}_i, \tag{1}$$

where c_j is the capacity under ideal conditions for a freeway with Design Speed j, and $(v/c)_i$ is the maximum volume-to-capacity ratio associated with LOS i. For highways with 60- and 70-mph design speeds, c_j is 2,000 pcphpl [Transportation Research Board 1985]. Since LOS E is considered to be "at capacity," $(v/c)_{\mathrm{E}} = 1.0$. The design speed of a road is based mostly on the importance and grade of the road; roads that are major and have shallower grades have higher design speeds. The elevation profile along I-26 shows that South Carolina is flat enough to warrant the highest design speed.

An immediate consequence of **(1)** is that to maintain $\mathrm{MSF}_{\mathrm{E}}$ or better (which we consider necessary for a successful evacuation), the number of passenger cars per hour per lane must not exceed 2,000 for any highway.

For it to be useful in model calculations, we need to convert the maximum service flow to a quantity that conveys information about a particular roadway. This quantity is known as the service flow rate of a roadway.

Definition. The *service flow rate* for level of service i, denoted SF_i, is the actual maximal flow that can be achieved given a roadway and its unique set of prevailing conditions. The service flow rate is calculated as

$$\mathrm{SF}_i = \mathrm{MSF}_i N f_w f_{\mathrm{HV}} f_p, \tag{2}$$

in terms of the adjustment factors:

N: the number of lanes,

f_w: the adjustment for nonideal lane widths and lateral clearances,

f_{HV}: effect of nonpassenger vehicles, and

f_p: the adjustment for nonideal driver populations.

We assume that the lanes on I-26 and other highways are ideal, (i.e., $f_w = 1$): at least 12 ft wide with obstructions at least 6 ft from traveled pavement [Mannering and Kilareski 1990]. To account for driver unfamiliarity with reversed lanes and stress of evacuation, we set $f_p = 0.7$ for reversed lanes and $f_p = 0.8$ for normal lanes, in accordance with [Mannering and Kilareski 1990]. The model also employs an adjustment factor, denoted f_{HV}, for reduction of flow due to heavy vehicles such as trucks, buses, RVs, and trailers. Later we discuss the effects of heavy vehicles on traffic flow.

Strengths and Weaknesses

This model is easy to implement, the mathematics behind it is quite simple, and it is backed by the National Transportation Board. We establish its reliability by using it to predict traffic flow patterns in the 1999 evacuation.

We assume that the number of lanes does not change, which requires that there are no lane restrictions throughout the length of the freeway and no lanes are added or taken away by construction.

The major weakness of our model is that it fails to take into account the erratic behavior of people under the strain of a natural disaster.

The simplicity of our model also limits its usefulness. It can only be applied to normal highway situations, not to a network of roads.

Improving Evacuation Flow

Gathering data from a various sources, we estimate the number of vehicles used in the 1999 evacuation. According to Dow and Cutter [2000], 65% of households that were surveyed chose to evacuate. About 70% of households used one vehicle or fewer, leaving 30% of households taking two vehicles. Of the evacuees, 25% used I-26 during the evacuation. Based on population estimates [County Population Estimates ... 1999] and average number of people per household [Estimates of Housing Units ... 1998], and assuming a relatively uniform distribution of people per household, we calculate the number of vehicles used during the evacuation (**Table 1**).

Table 1.
Evacuation participation estimates for Hurricane Floyd, in thousands.

	Population	Evacuees	Evacuating Households	Vehicles	Vehicles on I-26
Southern	187	122	47	61	—
Central	553	359	139	181	—
Northern	233	152	59	76	—
Total	973	632	245	319	61

Reversing Lanes

According to our model, the capacity of a highway is directly proportional to the number of lanes. This implies that lane reversal would nearly double the capacity of I-26.

Approximately 319,000 vehicles were used to evacuate the coastal counties of South Carolina. Of evacuees surveyed by Dow and Cutter [2000], 16.3% evacuated between noon and 3 P.M. on Sept. 14. Assuming independence between the above factors, in the hours between 9 A.M. and noon, I-26 must have been clogged by an attempted influx of about 3,300 vehicles/h. Even if evenly distributed, this was more than the 3,200 vehicles/h that the two Columbia-bound lanes of I-26 could take under evacuation conditions. The result was LOS F—a large traffic jam. Our model predicts that this jam would have lingered for hours, even after the influx of vehicles had died down.

What if the coastal-bound lanes of I-26 were reversed?. With corrections for nonideal conditions, our model predicts an SF_E of 6,000 pcphpl. Therefore, reversing the lanes of I-26 has the potential to increase service flow rate by a factor of 1.6.

Simultaneous Evacuation Strategies

By Hurricane Path

Hurricanes sweep from south to north. Because a hurricane commonly travels at a speed of less than 30 mph, the southernmost counties of South Carolina would be affected at least two hours before the northernmost ones.

However, analysis indicates that a staggered evacuation strategy would not improve the speed of the evacuation. The evacuation routes are largely parallel to one another and rarely intersect. Thus, the evacuation of each county should affect only the traffic on evacuation routes of nearby counties. Therefore, postponing evacuation of counties farther from the hurricane would be counterproductive.

By County

What about avoiding simultaneous evacuation of adjacent counties? We recommend evacuating Jasper, Beaufort, Charleston, Georgetown, and Horry counties in the first wave, and leaving Hampton, Colleton, Dorchester, and Berkeley until 3–6 h later, depending on the time of day. This solution would decrease the probability of traffic reaching LOS F on any highway without significantly delaying the evacuation. The nearby state of Virginia has a similar plan for evacuating county by county [Virginia Hurricane ... 1991].

By License Plate Number

By dividing cars into two categories, depending on the parity of the last digit on their license plate, we could separate traffic into two waves without giving preference to residents of any county. Our solution would request that the even group evacuate 3–6 h after the odd group was given the evacuation order. This would spread out the hours of peak evacuation traffic, resulting in improved traffic conditions and decreased risk of LOS F being reached. A comparison of **Figures 1** and **2** demonstrates the change in time distribution of evacuation when half of the drivers evacuate six hours later. Clearly, the distribution is much smoother, reducing the likelihood of reaching LOS F.

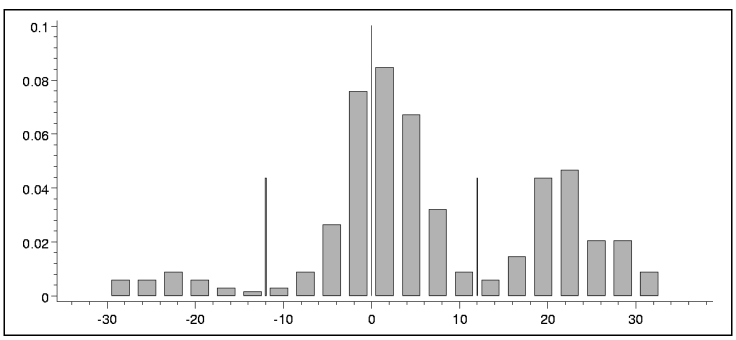

Figure 1. Hurricane Floyd: Fraction of evacuating population vs. hours after the 1999 mandatory evacuation order [Dow and Cutter 2000].

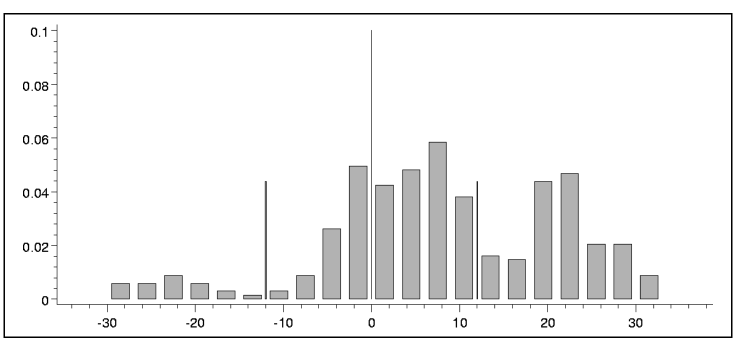

Figure 2. Even/odd license plate plan: Projected fraction of the evacuating population vs. hours after the mandatory evacuation order [Dow and Cutter 2000].

Lane Reversal on Smaller Highways

As only 29% of evacuees took I-26 or I-95, the majority took smaller roads inland. Because our model results in linear growth of flow with number of available lanes, lane reversals should improve evacuation rates on all roads. Because the evacuation routes are nearly perpendicular to the coastline, there is little risk of opposing traffic being disrupted by these reversals. The logistics of such an action, however, might be prohibitive.

The number of personnel needed to facilitate the I-26 lane reversal is 206 [??? 2000]. Smaller highways have less distance between exits, which suggests that more personnel per mile would be needed to blockade highway entrances. The total length of highway on all evacuation routes is approximately ten times as great as the length of I-26. Therefore, a truly prodigious amount of human effort would be necessary to implement lane reversals on all evacuation routes.

It would be imprudent to spend resources for what we estimate to be only a marginal gain in actual highway use. According to Dow and Cutter [2000], these alternative routes did not even approach capacity during the last evacuation. Since our license-plate evacuation strategy increases the overall throughput of major evacuation routes through lane reversal and smoother time distribution, there is no reason to expect a heavier load on state and country roads.

So, there is little evidence to support the utility of lane reversal on all smaller roads. Still, reversing lanes on a small number of evacuation routes might prove useful. The three major population centers of the coast (Beaufort, Charleston, and Horry counties) have different evacuee distributions. Therefore, those highways which most merit reversal are I-26, I-501 from Myrtle Beach to Marion and 301 from Marion to Florence, and the southern corridor from Beaufort County to the Augusta area.

Effect of Additional Temporary Shelters

In 1999, South Carolina housed about 325,000 people in shelters [Dow and Cutter 2000]. In a hurricane, one-third of evacuees go to each of shelters, family and friends, and commercial establishments [Zelinski and Kosinski 1991]. According to South Carolina Hurricane Information [2001], the number of predesignated shelters in Columbia is insignificant. However, there must be an efficient way to funnel the evacuees to the evacuation sites, such as a central coordination center with an up-to-date list of where the next group of cars should go.

Vehicle Type Restrictions

Although our model generally calculates flow using only normal passenger cars, it is not difficult to take other types of vehicles into account. The equation used to calculate the heavy-vehicle adjustment factor is

$$f_{\mathrm{HV}} = \frac{1}{1 + 0.6P}, \qquad \textbf{(3)}$$

where P is the proportion of nonpassenger vehicles (RVs, trailers, and boats).

Using this equation, our model predicts an upper bound on the proportion of nonpassenger vehicles that occur without causing LOS F. We demonstrate this with a sample calculation using I-26. Earlier, we estimated the $\mathrm{SF_E}$ of I-26, including reversed lanes, as 6,000 pcphpl. We also estimated that a maximum of 3,300 vehicles/h would enter I-26, ignoring the possibility of spikes in activity. Therefore, the minimum safe value of f_{HV} is approximately 0.55, which means that I-26 has enough leeway to support any mix of passenger cars and heavy vehicles. There is no need to restrict large vehicles on I-26.

Georgians, Floridians, and the I-95 Corridor

According to Georgia's hurricane evacuation plan [Hurricane Evacuation Routes 2001], I-95 is not a valid evacuation route. However, thousands of Floridians and Georgians flocked north on I-95 during Hurricane Floyd. In Savannah, the most popular evacuation route was I-16, which goes directly away from South Carolina [Officials deserve high marks . . . 1999]. In South Carolina, as shown in **Figures 1** and **2**, the farther away the destination, the smaller the percentage of the evacuee population that plans to go there. Taking all this into account, a realistic upper bound for the percentage of Georgians or Floridians using I-95 is 20%.

Any population entering South Carolina on I-95 from Georgia or Florida is mostly bound for major cities; an upper bound on the traffic headed through Columbia would be 75%. Since Floyd's landfall was extraordinarily unpredictable, we propose that it was one of the largest evacuations that will affect South Carolina.

Our reasoning is as follows: Hurricanes of lesser strength have fewer evacuees. If the landfall of the hurricane is more southerly, there is less need to evacuate South Carolina and North Carolina and so there will be less traffic on the freeway. Lastly, if the hurricane tends more towards the north, the number of evacuee drivers from Georgia and Florida will be decreased greatly. So, we can take Floyd as a relative upper bound on evacuees.

I-26? I-95?

From CNN's coverage of the lead up to Hurricane Floyd's landfall, in Georgia, we know that "the evacuation orders affected 500,000 people." We bound this rough estimate by 600,000. So the upper bound of people using I-95 can be estimated as $(0.20)(0.75)(600,000) \approx 90,000$, or about 45,000 vehicles, spread over a two-day period. From Dow and Cutter [2000], we know that about 10% of South Carolina evacuees used I-95, so the Georgians and Floridians effectively doubled the traffic on I-95, which is a huge impact on the model that we have proposed.

Improvements in the Model

Our model needs additional evacuation data. With precise statistics regarding number of evacuees, routes taken, time distributions, and traffic conditions, we could apply it to a greater variety of situations.

Additional refinements might be made to the parameters of the model with information on the highways themselves. The lane widths and distances to roadside obstacles affect the service flow rate, and knowing the exact layout of the highways would enable us to take them into account.

We could also use information regarding the resources available to the state: how many personnel and vehicles would be available to run lane reversals.

With sufficient information, we could use this model to create a simulation of a hurricane evacuation. We would treat the highways of South Carolina as edges in a network-flow problem and run a discrete computer simulation to test our premises and conclusions regarding evacuation policies.

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Maurice Knocks on Door, No One Home

—(AP), Columbia, S.C. Hurricane Season has come with a fury here to South Carolina, where Hurricane Maurice, the 13th named storm of the season, bears down on Charleston this evening. A record 80% of the population has been evacuated through the new evacuation plan.

When Hurricane Floyd narrowly missed South Carolina in 1999, the lack of preparedness for an evacuation of such a magnitude was highly evident. The state government asked the Research All Day Corporation (RAD Corp.) to come up with a new evacuation plan that would help the coastal residents escape the ferocity of a similar storm.

The RAD Corporation's team of world-class hurricane experts and top-notch traffic engineers analyzed the situation and developed a new evacuation plan. "The basic idea of the plan stems from simple math," explained Dr. K. Esner, Director of RAD Modeling. "Two sets of two lanes almost doubles the evacuation rate."

When asked to explain further, Dr. Esner continued, "On I-26, where there was a colossal traffic jam in 1999, we decided to reverse the flow of the coastal-bound lanes at the first decision of a mandatory evacuation." In this way, people leaving Charleston, the most populous city in South Carolina, could take either the normal two lanes of I-26 or the two "contra-flow" (reversed) lanes of I-26 all the way to

Columbia.

The evacuees in the many Columbia shelters seemed in good spirits. There was much less traffic-related annoyance than was felt in 1999. John C. Lately, a British resident of Myrtle Beach, joked, "You realize that in England, driving on the left is commonplace; I felt right at home."

There was nothing but praise for the RAD engineers. "A remarkable difference was seen between the chaos of evacuating for hurricane Floyd in 1999 and the evacuation today," said Joseph P. Riley, Jr., mayor of Charleston. "This time, the drive between Charleston and Columbia took 4 hours instead of 18. And it's a good thing, too; this time the storm didn't miss."

Another feature of the new evacuation plan was the breakup of the evacuating public into two groups. "One of our concerns about the 1999 Floyd evacuation was the volume of cars all trying to access the emergency roads at the same time," explained Dr. Esner. He continued, "To alleviate the traffic volume pressure, we wanted to divide the population into two groups. We had two different proposals; we could break up the population geographically or basically divide the population right down the middle, using even/odd license plate numbers."

With the proposed RAD plan, people with even license plates left in the first group, right when the evacuation order was given, and people with odd license plates or vanity plates left starting 6 hours later. "I thought the plan was crazy," remarked Charles Orange, a 24-year-old Charleston resident. "They told us to evacuate by license plate number; you'd never think high school math would help you one day, but this is one time it did!" he exclaimed.

Using the 1999 data, the RAD researchers calculated that breaking the evacuating population into two equal groups and delaying one group by 6 hours led to a condition where the volume of cars at no time exceeded the maximum volume that the road could handle. In this way, there was no problem with traffic jams, and Charleston became a ghost town, safe for Maurice to make its appearance.

The majority of the people left on the beaches are surfers and media, but even they are sparse in number; all that remains is a hurricane without an audience.

Hurricane Maurice could not be reached for comment.

— Christopher Hanusa, Ari Nieh, Matthew Schnaider, in Claremont, Calif.