The Crowd Before the Storm

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Introduction

Applying safety regulations and flow-density equations, we find the maximum rate of flow through a lane of road is 1,500 cars/h, occurring when cars travel at 27.6 mph.

We construct a computer simulation that tracks the exit of cars through South Carolina's evacuation network. We attempt to optimize the network by reversing opposing lanes on various roads and altering the time that each city should begin evacuating, using a modified genetic algorithm.

The best solution—the one that evacuates the most people in 24 h—involves reversing all the opposing lanes on evacuation routes. Increasing the holding capacity of Columbia is only marginally helpful. Georgia and Florida traffic on I-95 is only mildly detrimental, but allowing people to take their boats and campers greatly decreases the number of people that can be evacuated.

Background on Evacuation Plans

After the 1999 evacuation, the South Carolina Department of Transportation (SCDOT) designated evacuation routes for all major coastal areas, including 14 different ways to leave the coast from 32 regions. The routes take evacuees past I-95 and I-20. Although officers direct traffic at intersections, traffic on roads not in in the plan may have long waits to get onto roads in the plan. Moreover, the South Carolina Emergency Preparedness Division (SCEPD) does not call

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for any traffic type limitations (i.e., all campers, RVs, and cars with boats are allowed) [South Carolina Department of Public Safety 1999].

Assumptions

Assumptions About Hurricanes

- There is exactly one hurricane on the East Coast of the United States at the time of the evacuation.
- The hurricane, like Floyd, moves along the South Carolina coast. Most Atlantic hurricanes that reach the United States follow a northeasterly path along the coast [Vaccaro 2000].

Assumptions About Traffic Flow

- All cities act as points. The smaller streets within a city do not affect flow in and out of a city.
- The capacity of a city is the sum of its hotel rooms and the number of cars that can fit on the city's roads.
- The flow between intersections is constant.
- Density of traffic between intersections is constant.
- Charlotte and Gastonia in North Carolina; Spartanburg, Greenville, and Anderson in South Carolina; and Augusta, Georgia are infinite drains, meaning that we do not route people beyond them. Flow out of these cities should not create traffic jams. The cities are also large and therefore should be able to accommodate most if not all incoming evacuees.
- After the order to evacuate is issued, vehicles immediately fill the roads.
- Traffic regulators attempt to maintain the ideal density, using South Carolina's GIS system.
- All motorized vehicles are 16 ft long. This takes into account the percentage of motorcycles, compact cars, sedans, trucks, boats, and RVs and their lengths.
- On average, three people travel in one vehicle.
- The traffic that enters I-95 from Georgia or Florida stays on I-95 and travels through South Carolina.

Assumptions About People

- All people on the coast follow evacuation regulations immediately.
- Drivers obey the speed limit and keep a safe following distance.

Flow-Density Relationship

Flow is the number of vehicles passing a point on the road per unit time. The flow q on a road depends on the velocity v and density k of vehicles on the road:

$$q = kv. \tag{1}$$

Empirical studies suggest that velocity and density are related by [Jayakrishnan et al. 1996]:

$$v = u_f \left(1 - \frac{k}{k_j}\right)^a, \tag{2}$$

where k_j is the density of a road in a traffic jam, a is a parameter dependent on the road and vehicle conditions, and u_f, free velocity, is speed at which a vehicle would travel if their were no other vehicles on the road. Generally, the free velocity is the speed limit of the road.

We substitute **(2)** into **(1)** to obtain flow as a function of density:

$$q = ku_f \left(1 - \frac{k}{k_j}\right)^a. \tag{3}$$

This equation is linear in the free velocity. To find the ideal density that produces the fastest flow, we take the first derivative of the flow with respect to density and set it equal to zero:

$$u_f \left(1 - \frac{k}{k_j}\right)^a - au_f \frac{k}{k_j} \left(1 - \frac{k}{k_j}\right)^{a-1} = 0.$$

Solving for k, we find the ideal density k_i:

$$k_i = \frac{k_j}{a+1}.$$

Assuming that all roads behave similarly, we find a numerical value for the ideal density. Jam density is generally between 185 and 250 vehicles/mile [Haynie 2000]; we use the average value of 218 vehicles/mile. By fitting **(2)** to Kockelman's flow-density data for various cars, road conditions, and driver types in Kockelman [1998], we find that a has an average value of 3 (**Figure 1**). Therefore, the ideal density is 54 vehicles per mile.

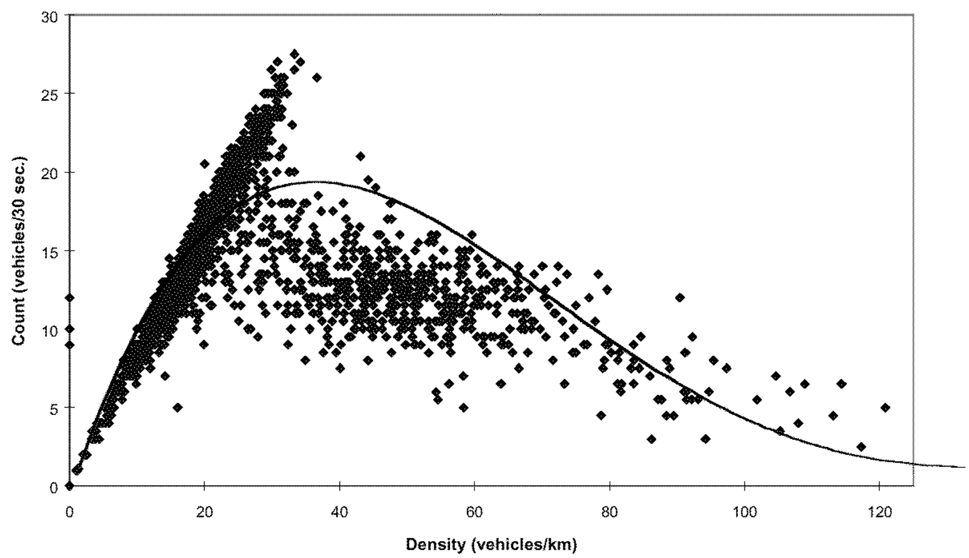

Figure 1. Plot of observed counts vs. density. Data from Kockelman [1998] with our curve of fit of the form **(2)**.

To account for reaction time, vehicles must be spaced at least 2 s apart [NJDOT 1999]. For vehicles spaced exactly 2 s apart, we can find the density of a road where all vehicles are traveling at speed v. The distance d_c required by a vehicle traveling at speed v is the sum of the vehicle's length and its following distance:

$$d_c = l + \frac{2v}{3600},$$

where the units are miles and hours. The maximum safe density of a road is the maximum number of vehicles on the road (the length of the road divided by the space required for each vehicle) divided by the length of the road:

$$k = \frac{1}{l + \frac{2v}{3600}}.$$

If each car is 16 ft (3.03×10^{-3} mi) long and the density is ideal, then the maximum safe velocity of the vehicles is 27.6 mph.

Knowing the ideal density and the maximum safe velocity at that density, we use **(1)** to find the maximum flow:

$$q = kv = 1500. \tag{4}$$

The free velocity parameter is needed to find the flow at situations other than ideal. Using **(2)**, we find that the free velocity is 65.2 mph—close to the highway speed limit, thus validating the approach for finding the free velocity. Substituting the known and derived values of free velocity, jam density, and the exponential parameter into **(3)**, we quantify the flow-density relationship:

$$q = 62.5k\left(1 - \frac{k}{218}\right)^3.$$

Traffic Flow Model

Mapping the Region

We programmed in Java a simplified map of South Carolina that consists of 107 junctions (cities) and 154 roads. A junction is an intersection point between two or more roads. A road connects exactly two junctions. Our map includes most of the roads in by SCEPD's model and many more. Data for the number of cars, boats, and campers in each city used in the computer model can be found in the **Appendix**. [EDITOR'S NOTE: We omit the **Appendix**.]

Behavior of Cities

Each point in the program stores a city's population and regulates traffic flow into and out of the roads connected to it. First, it flows cars out of the city into each road. The desired flow out—the maximum number of vehicles that the road can take—is defined by the flow-density equation **(4)** for the road that the cars are entering. If the total number of vehicles that can be exited exceeds the evacuee population of the city, then the evacuees are distributed proportionally among the roads with respect to the size of the road.

Next, the city lets vehicles in. The roads always try to flow into the city at the ideal flow rate. The city counts the total number of cars being sent to it and compares this to its current evacuee capacity. If the evacuee capacity is less than the number of vehicles trying to enter, the city accepts a proportion of the vehicles wanting to enter, depending on the road size. A check in the program ensures that the number of vehicles taken from the road does not exceed the number of cars on the road at that time.

After repeating the entering and exiting steps for each road, the city recalculates its current evacuee population, removing all the vehicles that left and adding all the vehicles that entered.

Behavior of Roads

We define each road by its origin junction, destination junction, length, and number of lanes. The number of lanes is the number of lanes in a certain direction under nonemergency circumstances. For example, a road that normally has one lane north and one lane south is considered a one-lane highway. If the number of lanes on a road changes between cities, we use the smaller number of lanes. To analyze the possibility of turning both lanes to go only north or only south, our program would double the number of lanes.

During an evacuation, traffic never needs to flow in both directions, because the net flow of a road that flowed equally in two directions would be zero. Therefore, each road has a direction defined by its origin junction and destination junction. While the origin junction is normally the point closer to the coast, the program analyzes the possibility of having the road flow from its "destination" to "origin." In some cases, this could provide the optimal flow out of the coastal areas by finding alternative routes.

We model traffic congestion as a funnel. As long as vehicles are on the road, they attempt to exit at the ideal flow rate. However, if the road begins to fill, then the number of vehicles entering the road varies depending on the flow-density equation **(4)**. We determine the new density of the road via

$$D_i = \frac{n_i + \Delta n_i}{d},$$

where n_i is the initial number of vehicles on the road, Δn_i is the difference between the cars entered and cars exited, and d is the length of the road (mi).

Optimization Algorithm

We use a modified genetic optimization algorithm, beginning from South Carolina's current solution into the evacuation. The simulation stores a possible solution as two chromosomes: a city chromosome, storing the time to start evacuating coastal cities, and a road chromosome, storing directions and reversals of the roads. Stored with the solution is the number of people left in the evacuation zone after 24 h, the usual advance notice for evacuation.

The simulation randomly chooses a chromosome and a gene to mutate. We use a uniform distribution to choose first the chromosome, then the gene, and finally a value for that gene. City genes can take the value of any time step between 0 and 12 h before starting to evacuate. Road direction can be in either the specified direction, the reversed direction, or closed. Opposing lanes can be either reversed or not reversed. If the changed chromosome leaves fewer people in the evacuation region in 24 h, it replaces the old chromosomes.

Results

Knowing that the maximum flow of a one-lane road is 1,500 cars per hour, we first tested South Carolina's current evacuation route with our modified flow equations, which allow for more people to leave the evacuation region. After 24 h, 556,000 people (58% of the people needing to leave) were still left in the cities needing evacuation. If only I-26 was reversed, the people left dropped to 476,000 (50%). However, if people were allowed to take their boats and campers with them, the number left was 619,000. Therefore, boats, campers, and extra cars generally should not be allowed to evacuate.

After 10,000 iterations, the solutions were still improving. Therefore, we restarted the program with all roads beginning with lanes reversed and cities evacuating immediately. After 10,000 iterations, the program could not find a better solution than one in which 233,000 people (25%) are left.

If I-95 is too congested due to traffic from Georgia and South Carolina (i.e., I-95 is not used in the simulation), the number of people left is 254,000, 9.4% more than if the highway had been clear.

Increasing Columbia's evacuee capacity helps the evacuation only marginally, removing only 948 more people from danger.

Regardless of the situation, the solutions always have cities that start evacuating immediately: Staggered solutions are not optimal.

Stability Analysis

We tested the flow equations in the evacuation simulation by varying the exponential parameter, the free velocity, and the jam density. When the exponential parameter was increased or decreased by 1, the number of people evacuated changed by only 0.2% and 1.0%. Doubling or halving the free velocity caused variations of 3.4%. Doubling and halving the jam density caused variations of 2.2%. The length of the car did not affect the number of people emptied from the city because the following distance was so large compared to the length of the car. Finally, we doubled and halved the iterative time step of the evacuation simulation, which did not change number of people evacuated. Thus, this model was robust in every variable tested.

Strengths and Weaknesses

Strengths

- The model can be used for any evacuation. For, example, if a meteor were predicted to hit the Atlantic Ocean and flood a strip of land 50 mi wide along the Atlantic Coast, this model could be used to evacuate residents of South Carolina to areas not affected by the flood.

- Moreover, the program is flexible enough to work for any possible map; it is not specific to the individual roads and cities of South Carolina.

- The model is stable with regards to all variables tested, and the optimization algorithm runs very quickly.

Weaknesses

- The greatest weakness of this model is that it assumes that people will follow directions: use the two-second following distance rule, travel at the speed limit, and travel on assigned roads.

- The model assumes density homogeneity along each road after each iteration, while in reality the density varies.

- The model can handle only situations where the roads are empty at the beginning of the simulation.
- We underestimated the holding capacity of the cities, leading to a slower exit from the unsafe regions. Thus, although the relative changes in the results are probably correct, the actual number of people in danger after 24 hours is probably fewer.
- The optimization algorithm can get stuck in local minima.

Conclusion

Reversing traffic on all evacuation routes evacuates the most people. Traffic from Georgia and Florida is not a problem, but many boats and campers would significantly decrease flow.

Hence, we suggest that roads be reversed and that to maintain maximum flow, traffic regulators not allow the number of cars in a stretch of road to exceed 54.4 per lane per mile, by regulating on- and off-ramps at cities.

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The Crowd Before the Storm: Improved Hurricane Evacuation Routes Planned

COLUMBIA, SC, FEB. 12—A new mathematical model prepared for the South Carolina Emergency Preparedness Division should end aggravating and dangerous backups when a hurricane threatens South Carolina. In response to the monstrous traffic jams that turned I-26 northbound out of Charleston into a parking lot during the Hurricane Floyd evacuation, the new model distributes traffic over several smaller routes.

One of the new program's controversial traffic-control methods is to make *all* lanes of traffic on evacuation routes to run in the same direction, away from the beach, to improve traffic flow.

People with campers, RVs, boats, and more than one car should leave as early as possible if a hurricane is predicted; once the new plan is implemented, families may be permitted only one car, to reduce traffic.

The model counteracts these minor inconveniences by evacuating 75% of the population at risk within 24 hours, compared to 42% under South Carolina's current plan.

Although more people may be evacuated, don't expect to get out of the region too quickly. The model predicts that the fastest evacuation will occur if all cars travel at 28 mph. At that rate, it will take you 4 hours to get out of the evacuation region.

The model used a "genetic algorithm" approach, which involves testing possible solutions against each other and "breeding" new ones from the best ones so far. Further analysis showed that reversing lanes of all roads along the evacuation routes is the best method for quick evacuation. The computer tested 10,000 minor changes without finding a more effective solution.

Increasing the housing and parking capacity of Columbia by constructing a shelter there would be only mildly helpful. On a more positive note, residents do not need to worry about traffic from Georgia and Florida slowing the evacuation.

— Jonathan David Charlesworth, Finale Pankaj Doshi, and Joseph Edgar Gonzalez, in Richmond, Virginia.