Project H.E.R.O.: Hurricane Evacuation Route Optimization

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Introduction

Through modeling and computer simulation, we established an evacuation plan for the coastal region of South Carolina in the event of an evacuation order.

We derive nine evacuation routes running from the coastal region inland. Based on geography, counties are given access to appropriate routes. Combining flow theory with geographic, demographic, and time constraints, we formulate a maximum flow problem. Using linear optimization, we find a feasible solution. This solution serves as a basis for our evacuation model. The validity of the model is confirmed through computer simulation.

A total evacuation (1.1 million people) in 24 to 26 hours is possible only if all traffic is reversed on the nine evacuation routes.

Terms and Definitions

Flow F**:** the number of cars that pass a given point per unit time (cars per hour per lane, unless otherwise specified).

Speed s**:** the rate of movement of a single car (mph, unless otherwise specified).

Density k**:** the number of cars per unit length of roadway (cars per mile per lane, unless otherwise specified).

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Headway distance h_d: the space between the back of the leading car and the front of the immediately trailing car (ft). (Note: This is *not* a standard definition of headway distance.)

Headway time h_t: the time required to travel headway distance.

Car Length C: length from front bumper to rear bumper of a single car (feet).

Goals

Our first priority is to maximize the number of people who reach safety; in terms of our model, we must maximize the flow of the entire system. A secondary goal is to minimize the total travel time for evacuees; this means that we must maximize speed. As we establish, these goals are one and the same.

Assumptions

- **Vehicles hold 2 people on average.** This seems reasonable, based on the percentage of the population who would be unable to drive themselves and those who would carpool.
- **Vehicles average 17 ft in length.** This is based on a generous average following a quick survey of car manufacturers' Web sites.
- **Vehicles have an average headway time of 3 s.** This is based on numbers for driver reaction time, found in various driving manuals.
- **50 mph is a safe driving speed.**
- **Merging of traffic does not significantly affect our model.** See the **Appendix** for justification.
- **Highways 26, 76/328, and 501 are 4-lane.** [Rand McNally 1998]
- **Safety is defined as 50 mi from the nearest coastal point.** Counties that lie beyond this point will not be evacuated [SCAN21 2001].
- **Only the following counties need to be evacuated:** Allendale, Beaufort, Berkeley, Charleston, Colleton, Dorchester, Georgetown, Hampton, Horry, Jasper, Marion, Williamsburg, and a minimal part of Florence County (based on the previous assumption).
- **Myrtle Beach will not be at its full tourist population during a hurricane warning.** This seems reasonable because tourists do not like imminent bad weather.

- **The evacuation order will be given at least 24 to 26 h prior to the arrival of a hurricane.** This is based on the timeline of the 1999 evacuation [Intergraph 2001].
- **Boats, trailers, and other large vehicles will be limited from entering the main evacuation routes.** Being able to evacuate people should have a higher priority than evacuating property.
- **If we can get everyone on a road within 24 h and keep traffic moving at a reasonable speed, everyone should be at a safe zone within 25 to 26 h.** This is based on our assumption of what a safe zone is and our assumption of average speed.

Developing the Model

Abstracted Flow Modeling

Upon inspecting the evacuation route map, we decided that there are only nine evacuation routes. There appear to be more, but many are interconnected and in fact merge at some point. By identifying all bottlenecks, we separated out the discrete paths.

Using this nine-path map in combination with the county map, we constructed an abstracted flow model with nodes for each county, merge point, and destination, so as to translate our model into a form for computer use.

A Brief Discussion of Flow

The flow F is equal the product of density and speed: $F = ks$ [Winston 1994]. We can find the density k of cars per mile by dividing 1 mi = 5,280 ft by the sum $C + h_d$, the length of a car plus headway distance (in ft), so

$$F = ks = \frac{5280s}{C + h_d}.$$

Using the fact that headway distance h_d is speed s (ft/s) times headway time h_t (sec), we have

$$F = \frac{5280s}{C + sh_t} = \frac{5280}{\frac{C}{s} + h_t}.$$

Increasing s increases F. This result is exciting, because it shows that maximizing flow is the same as maximizing speed. The graph of F versus s gives even more insight (**Figure 1**). Increases in speed past a certain point benefit F less and less. So we might sacrifice parts of our model to increase low speeds but not necessarily to increase high speeds.

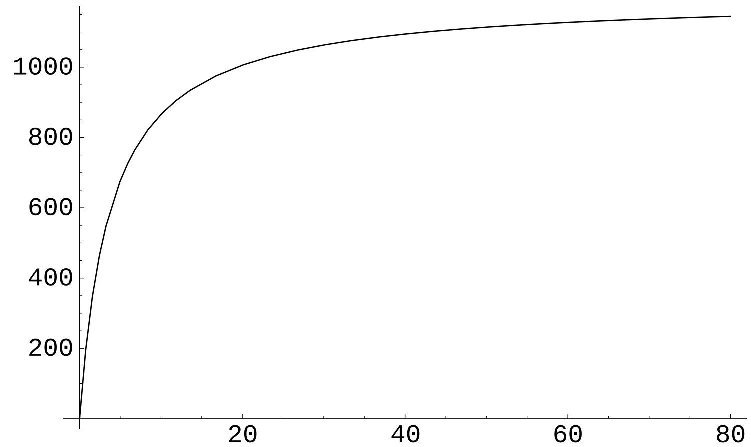

Figure 1. Flow vs. speed.

According to our assumptions, we have $C = 17$ ft and $h_t = 3$ sec, and converting to units of miles and hours, we get

$$F = \frac{1}{\frac{17}{5280s} + \frac{1}{1200}},$$

or

$$s = \frac{17}{5280} \cdot \frac{1200F}{1200 - F}. \tag{1}$$

At our assumed maximum safe speed of $s = 50$ mph, we have $F = 1114$ cars/h.

Determining Bounds

We combined our knowledge of county populations with the 24-h deadline and generated a minimum output flow for each county. We also determined the maximum flow for each node-to-node segment, based on the number of lanes. It would be unrealistic to assume that each segment would reach optimal flow, so we set maximum flow at 90% of optimal flow. This reduction in flow is meant to cover problems that arise from accidents, slow drivers, less than ideal merging conditions, or other unexpected road conditions. Putting $F = 0.9F_{\text{opt}} = (0.9)(1113.92)$ into **(1)**, we find $s \approx 19.6$ mph. We decided that this is an acceptable minimal speed.

Finding a Feasible Solution

We used the linear optimizing program LINDO to find a feasible solution; the solution takes 26 h. Since this scenario does not take into account geographical convenience, we did some minor hand-tweaking. The final product is in the **Appendix**.

The Simulation

To confirm the feasibility of our model, we conducted a computer simulation using Arena simulation software. The simulation encompassed 24 h of traffic flow on the nine evacuation routes assuming 90% flow efficiency. The model assumed that there was an unlimited number of vehicles ready to enter the simulation in all counties. The time headway between entering vehicles was considered to be normally distributed with a mean of 3 s and a standard deviation of 1 s. The simulation verified our model.

Implementation Requirements

For optimal performance of our model:

- Evacuees must follow the evacuation routes. The State of South Carolina should notify specific communities or households which route to take.
- Flow must be monitored on all evacuation routes; this requires metering entry of evacuees onto the evacuation routes. Allowing vehicles to enter an evacuation route too quickly may result in congestion at bottlenecks.
- Advance notification that there will be ticketing by photograph could enforce the restriction on towing boats and trailers, which might otherwise be ignored.

Applying the Model

Requirement 1

If an evacuation order included both Charleston and Dorchester counties 24 h prior to the predicted arrival of a hurricane, it would be necessary to reverse all four lanes of I-26 to ensure the evacuation of the entire population of the two counties. In our simulation runs, all of the exit routes from Charleston and Dorchester ran at full capacity (all lanes reversed, 90% of maximum flow) for 24 h to evacuate the counties completely. If the lanes are not reversed, it is doubtful that the two counties could evacuate in a timely fashion.

Requirement 2

To optimize use of the available bandwidth while ensuring that the entire population is displaced inland within 24 h, we opted for a simultaneous evacuation strategy: All counties begin evacuation at the same time.

Since hurricanes typically arrive in South Carolina moving northward, a staggering strategy would evacuate southernmost counties first. Our model has discrete evacuation routes servicing each part of the coastline, so it is not necessary to stagger evacuation. For example, since Beaufort County, which would be among the first counties to be hit in the case of a hurricane, and Horry County, which would be hit significantly later, do not depend on the same evacuation route, nothing is gained by delaying the evacuation of Horry County until Beaufort County has cleared out.

Requirement 3

To evacuate the entire coastal region within 24 h, we found it necessary to turn around traffic on *all* designated evacuation routes. With greater time allowance, not all routes would need to be turned around.

Requirement 4

Our model directs approximately 480,000 evacuees to Columbia. This surge entering a city of 500,000 would undoubtedly disrupt traffic flow. While three major interstates head farther inland from Columbia and could easily accommodate the traffic from the coast, the extreme congestion within the city would disrupt the flow coming into Columbia from the coast. It would be best to set up temporary shelters around the outskirts of Columbia (and at other destination sites) to avoid having too many people vying for space within Columbia itself.

Requirement 5

Because heavy vehicles take up more road space and generally require a greater headway time, they adversely affect our model. Heavy vehicles are allowable if they are the only available means of transportation, as may be the case for tourists in recreational vehicles. Boats and trailers are strictly forbidden on the evacuation routes. A rule of one car per household can be announced, but the model can probably handle up to two cars per household. Our assumption of two people per car can still hold up, given the number of people who are unable to drive themselves to safety.

Requirement 6

With the flow and time constraints defined within our model, the entrance of large numbers of additional evacuees onto the designated evacuation routes from I-95 would cause serious disruptions. The traffic on I-95 coming from Georgia and Florida may turn west onto any nonevacuation roadway. Ideally, better evacuation routes could be established within Georgia and Florida to minimize their evacuees entering South Carolina.

Limitations

Time forced us to simplify our model. Here are extensions that we would have liked to include:

Factor in the "first-hour" effect. The western counties could potentially have full use of the evacuation routes for a limited time at the very beginning of the evacuation. The population of the eastern counties would take time to reach the western counties; but once they did, both groups would have to share the route.

Do more work with the impact of large vehicles.

Explore headway time in greater detail. We know that headway time is not dependent on speed in an ideal world, but does human psychology make headway time dependent on speed? Also, although we assume that all vehicles exhibit the same stopping pattern, we know that car size and brake condition have an effect. We would like to find a more accurate concept of headway time.

Inspect all nine routes on-site. We assume that any road listed by the SCDOT as a hurricane evacuation route is well maintained and appropriate for that use, and that these are the only appropriate routes.

Expand the complexity of our model. We kept the number of paths to a manageable level, but it would be nice to factor in the smaller routes.

Develop mechanisms to implement our model. This would involve planning out a block-by-block time-table, metering techniques, merging techniques, traffic reversal techniques, and large-vehicle restriction techniques.

Add accidents, breakdowns, and other problems to the model specifically, rather than just lumping them into "efficiency."

Study the potential costs of complete traffic reversal.

Study the population fluctuations of Myrtle Beach, so that we would know how many tourists to expect in the event of a hurricane.

Authorities Fear Floyd Repeat, Enlist Help of Undergraduates

ARDEN HILLS, MN, FEB. 12—Responding to complaints over the disorder of South Carolina's 1999 coastal evacuation in preparation for Hurricane Floyd, authorities enlisted the aid of three undergraduates from Bethel College. The task set before the three young mathematicians was to plan an orderly and timely evacuation of South Carolina's coastal region.

A denial of funding for travel expenses prevented the students from making an on-site inspection, but they managed to get a feel for the territory based on maps and census reports. Using a technique they dubbed "Abstracted Flow Modeling," the team constructed several computer models of what a full coastal evacuation would involve. Using all the tools available to them and a little human intuition, the trio created a 26-hour scenario for the full evacuation of more than 12 counties.

Such an evacuation would involve all people in the area being divided among 9 separate evacuation routes and released in a timed fashion. Using the timings and routings suggested by the Bethel team, the entire coast could be evacuated within a reasonable time and the travel time for individual vehicles could be kept to a minimum.

Compared to the 1999 evacuation, when fewer than 800,000 people were evacuated, the Bethel model can evacuate more than 1.1 million people. Much of this increase can be attributed to grid-lock prevention, lane-doubling, and access restriction to the main highways.

Concerned citizens should be on the lookout for announcements concerning route assignments and departure timings for their neighborhoods.

— Nathan Gossett, Barbara Hess, and Michael Page in Arden Hills, MN

Appendix

Abstracted Flow Model

We created the flow model in **Figure A1** to represent what we perceived as 9 routes from the coast of South Carolina to the interior of the state. Rectangles represent locations and ovals represent junctions. The arrows represent flow direction. The flow assigned to various segments can be found in **Table A1**.

Table A1.
Flow rates by route and county.

County	Population (thousands)	Junction	Flow (cars/min)
Jasper	17	1a	5.9
Hampton	19	1b	6.6
Allendale	11	1c	3.8
Beaufort	113	1a	17.1
		2a	22
Colleton	38	2a	4.4
		2b	4.4
		3	4.4
Charleston	320	2b	2.6
		3	29
		4	17.6
		26	51
		5	5.5
		6a	5.5
Dorchester	91	4	15.8
		26	15.8
Berkeley	142	5	27.4
		6a	21.4
Georgetown	55	6a	3
		6b	16.1
Williamsburg	37	6a	3.5
		6b	9.3
Florence	125	6b	4
		7b	4
Horry	179	6b	4
		7	51
		8	33.4
Marion	34	7b	5.9
		7a	5.9

Merge Considerations

We do not want congestion at merges, so we maintain a constant traffic density in a "merge zone." Let A and B be the pre-merge flows and C be the post-merge outflow. Then we must have $C = A + B$ to avoid congestion.

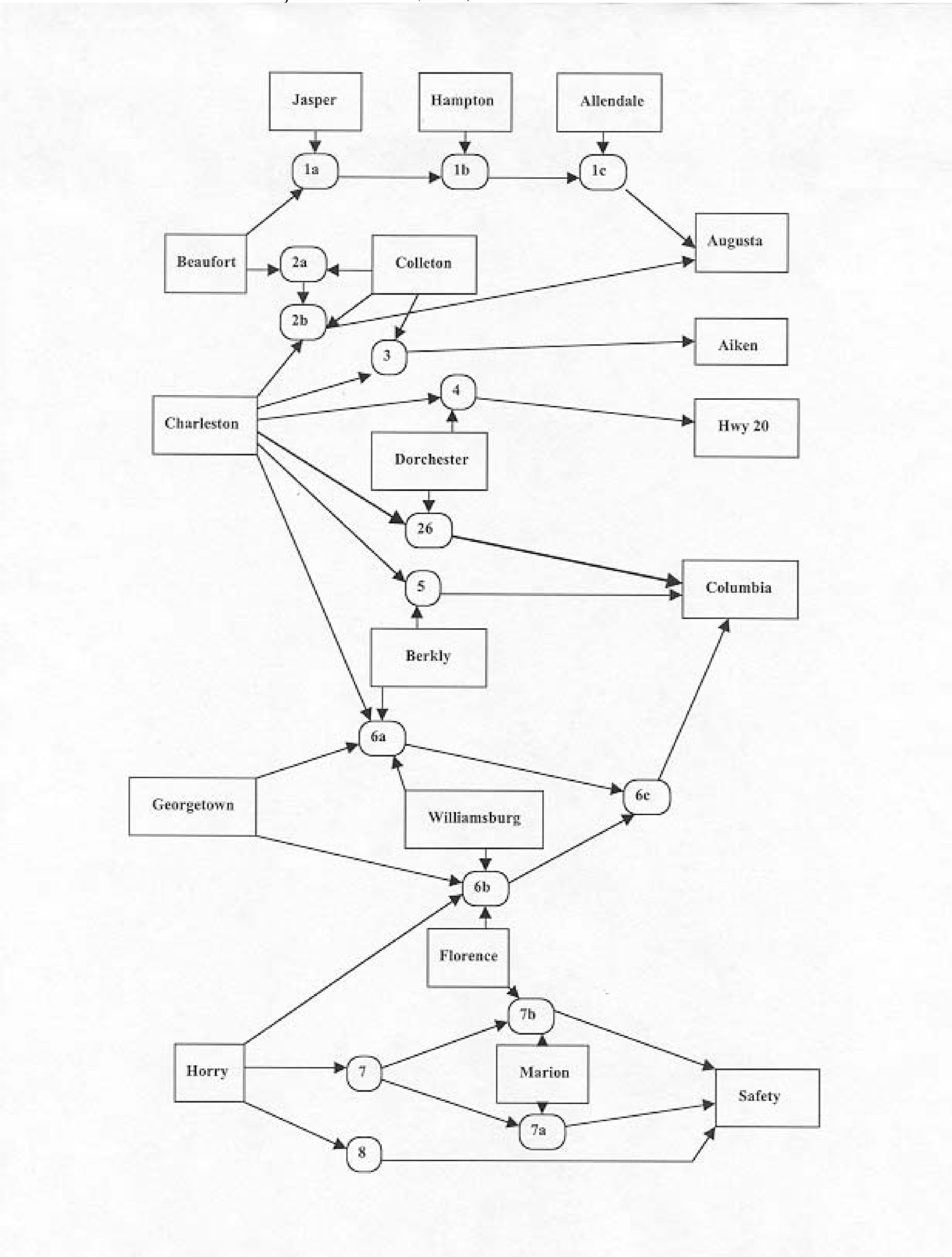

Figure A1. Abstracted flow model.

We must regulate the pre-merge flows to prevent congestion and allow for maximum post-merge flow.

If the density of merging traffic is large enough, we set aside one or two lanes for merging for about a mile prior to the merge point. We investigate whether this is possible without lowering the pre-merge flows A and B, and when this strategy is physically possible and beneficial.

Does shifting main-road traffic left to open a merge lane(s) increase the main road's flow (before merge traffic is added) and thus increase its contribution to post-merge flow? If so, then the post-merge flow would be

$$(A + \text{increase}) + B = (C + \text{increase}).$$

But we fixed $C = A + B$ as the maximum flow, so A or B or both must decrease. Is this reduction really a concern?

Recall that $F = ks$, where F is flow, k is density, and s is speed. Let N be the number of cars on a one-mile stretch and L be the number of lanes in the direction of concern. The total flow of the road is the product of the lane flow and the number of lanes:

$$Lks = L(N/L)s = Ns.$$

To shift one lane left, we must move N/L vehicles to $L-1$ lanes, adding $\frac{N/L}{L-1}$ vehicles to each non-merge lane, thus giving a new lane population of

$$\frac{N}{L} + \frac{N/L}{L-1} = \frac{N}{L} \cdot \frac{L}{L-1}.$$

So the new flow is

$$(L-1)\left(\frac{N}{L} \cdot \frac{L}{L-1}\right) s = Ns.$$

No change! We do not have to reduce pre-merge flows to add a merge lane (assuming that the merge lane modification is physically possible). The same argument confirms that pre-merging works for shifting two lanes.

When are these shifts physically possible? Let $m = N/L$, and let q be a lane's carrying capacity per mile, which is a function of s for fixed h_t. Then for clearing one merge lane to be physically possible, we need

$$\frac{m}{L-1} \leq q - m.$$

If two lanes need to be shifted left, the same process yields the requirement

$$\frac{2m}{L-2} \leq (q - m).$$

Moving everything to the right side of the inequalities gives two functions that are greater than or equal to 0, each a function of L and m. We fix $L = 2$, 3, and 4 lanes and graph the functions to see when they are within the constraints.

Figure A2 shows valid and invalid ms given four lanes (two lines for two possible shifts, single or double). We have $q = 309.83$, the carrying capacity for a mile-long lane with $s = 50$, and $h_t = 3$ seconds. The function must lie on or above the horizontal axis for creation of a merge lane.

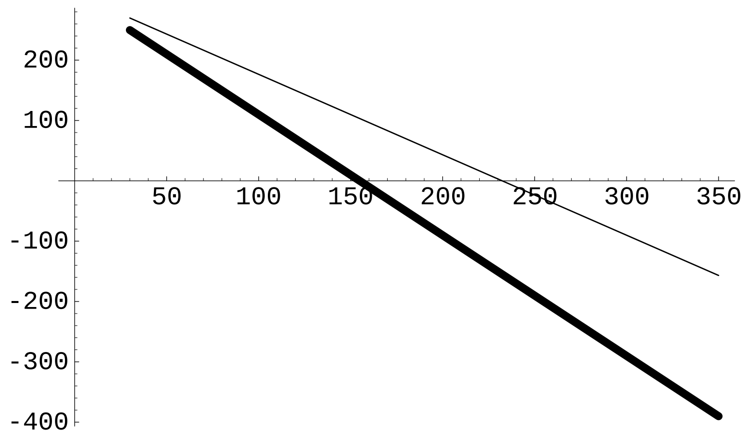

Figure A2. Feasibility functions for one lane (thin line) and two lanes (thick line), as a function of the number of cars per mile ($m = N/L$).

The merge patrol officer can determine q by multiplying the number of cars counted in one minute by $6/5$. If the ratio of merging traffic to main-road traffic is higher than $1:20$, there may be enough disruption that merge efficiency could benefit from a merge lane(s). With this ratio, and 90% flow, there would be one car merging every minute.

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