# Hurricane Evacuation Traffic Model

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***Abstract*—In response to severe natural disasters, cities and regions may need to evacuate people from potentially dangerous or flooded regions. This paper gives an overview of a model for traffic during regional evacuations due to hurricanes, using queueing theory to describe traffic congestion. Other methods of modeling traffic are also evaluated. A simulation of a hurricane evacuation in Massachusetts was created, and the simulation was used to identify congested and potentially vulnerable regions. The model was validated against navigation predictions from other software. The results of the model indicate that Boston and the bridges to Cape Cod are particularly vulnerable to congestion, and that some people remain on the road many hours after the beginning of the evacuation. A visualization for the model was also designed to present the simulation in a visually accessible way to both experts and the general public.**

***Index Terms*—agent-based modeling, queueing analysis, traffic congestion, hurricanes, evacuation, data visualization**

## I. Introduction

In recent years, it has been theorized that the frequency and severity of natural disasters have been exacerbated by climate change. Coastal cities, which account for 60% of cities with a population over 5 million, are particularly at risk from rising sea levels and related natural disasters [5]. When disasters are severe enough, such as in hurricanes with widespread flooding, it can be necessary to evacuate a city or region. Such evacuations create unique traffic conditions, which can make evacuations difficult to predict and plan.

The importance of evacuation planning is evident through studying historical examples, such as Hurricane Katrina and Hurricane Sandy. During Hurricane Katrina, there were still 100,000 to 300,000 people that were trapped inside the city [9]. In this case, vulnerable populations with limited mobility or from congested regions of the city could have been better served through government assistance and modified evacuation planning. In New York during hurricane Sandy, only 49% of people evacuated during the mandatory evacuation order because many people underestimated the risk of staying behind [1]. The rates of evacuation could have been improved through communicating information to the public in a more visually compelling and accessible way.

However, for most cities there is very little empirical data to guide evacuation planning. This project simulates traffic during a regional hurricane evacuation in Massachusetts, and uses the results of the simulation to identify vulnerable regions. Furthermore, the visual display of the model presents the findings in a clear and useful way to both experts and the general public.

## II. Concepts

This project models traffic using an agent-based model that implements queueing theory, and extends the generic traffic model to a hurricane evacuation scenario. Two other models for traffic were also considered and are evaluated here.

### *A. Traffic Flows*

Traditionally, traffic has been modelled by approximating the movement of traffic to fluid flow. This model is fairly accurate at low traffic density, where the model predicts uniform movement along roads. However, this model becomes less accurate when modeling congestion, where traffic jams occur intermittently, so it no longer behaves as a simple fluid. While there are methods to model congestion using shock waves [3], these modifications were determined to be unnecessarily complex for the purposes of this project.

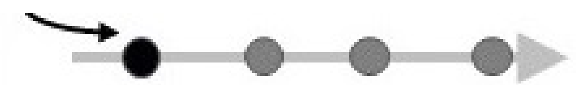
### *B. Agent-Based Microscopic Decisions*

Agent-Based Modeling is commonly used in social modeling and treats each agent as a separate entity with distinct behavior. As agents follow simple rules that govern interactions with other agents, patterns begin to emerge in the system. In a traffic model, each car would be represented by a separate agent that controls its individual acceleration based on the distance to the car in front of it, the curvature of the road, and control mechanisms in intersections [4]. While this type of model gives a very accurate description of individual decisions and how they contribute to overall behavior, it is very computationally intense for a regional evacuation model, and too complex for the scope of this project.

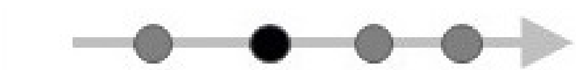
### *C. Queueing Theory*

Queueing theory is a method of mathematical modeling that describes waiting, and it is a less computationally intensive form of agent-based modeling. It is generally used in systems where the rate of agents entering a queue is different from the rate at which agents exit the queue. This can be easily applied to modeling traffic, where each link (road) is treated as a ”queue” of agents (vehicles). For traffic, a First In First Out (FIFO) model is used, where vehicles that enter the road first will leave before vehicles that arrive later [7].

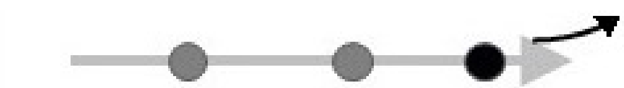
With this type of model, in every time step, cars can enter the road at the end of the queue of cars already on the road. (Figure 1a). Vehicles must stay on their current road for long enough to travel the entire length of the road (Figure 1b), and that time is calculated based on the length of the road and the speed limit [6]. As cars from the beginning of the queue move onward (Figure 1c), the other cars increase their position in the queue, and thus move along the length of the road.



(a) Cars “get in line” at the end of the road.



(b) Cars move along the road in order.



(c) When cars get to the front of the line, they move on the the next road

Fig. 1: Steps of movement in the queueing model.

This method inherently models congestion, because cars can only move onto the next road if that road has enough empty space in the queue to accept more cars. However, if a road reaches its capacity for cars, then it will no longer accept more cars from the roads feeding into it. Therefore, the cars are forced to remain on nearby roads, which causes those roads to reach their capacity, thus spreading congestion around a region. The ability to model congestion is crucial to modeling evacuation situations, where a high traffic volume inherently causes large amounts of congestion.

Queueing theory is the most appropriate type of model for regional evacuations, because it describes congestion fairly simply and accurately without being computationally intense.

## III. Implementation

The model uses previously collected geospatial data for roads, population, and hurricane inundation zones. Based on the data, two main classes in the model are created. Cars control path-finding between their origin and destination. Roads control the movement of cars using the queueing model.

### A. Data Sources

This model is built by combining information from three geospatial data sets, published by government organizations. Census population data was overlaid onto hurricane inundation zones to create an appropriate number of agents at the corresponding locations. The agents are added onto a network of roads, created from another geospatial data set with major roads in Massachusetts. A visualization of just the roads and the population centers is given in Fig. 2.

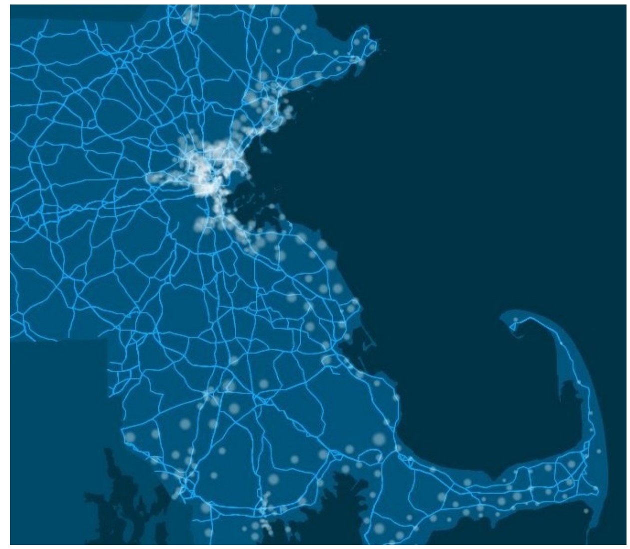


Fig. 2: Visualization of Massachusetts roads (blue lines), overlaid with the population origin points (white circles).

### B. Navigation

In this model, the car objects calculate the optimal route from their origin to destination. Each agent is created at its origin based on the locations of people that need to evacuate. The agents then choose a destination by randomly selecting between nearby cities outside of inundation zones, because cities have the highest potential for absorbing an influx of people.

The road network is represented as a graph, where roads are the edges and nodes are the intersections. Path planning is performed using Dijkstra’s algorithm, which finds the shortest path between nodes of a graph [2]. Rather than weighting each link purely by distance, the algorithm instead finds the route with the shortest time, calculated from the speed limit, number of lanes, and length of the road.

It is important to note that these calculations are performed before congestion occurs. Future work should adjust for dynamic congestion, where agents chose alternate routes based on existing congestion.

### C. Traffic Model

The model and visualization were both implemented in processing, an open source platform built off Java. The implementation of queueing theory in this model is a fairly standard implementation of general queueing models for traffic, described in Section II-C. Each road object controls the movement of cars using queueing theory.

Each road object stores two lists of cars: the queue of cars on the road, and a wait-list of cars waiting to enter the road. Each road also stores information about its capacity and speed limit. In every time step, each road processes cars by the following algorithm, adapted from Simon, Esser, Nagel [6]:

1) Allow cars into the main queue from the waitlist. Only accept cars until the road reaches capacity.
2) For every car in the main queue, check whether the car has been in the queue for long enough to reach the end of the road.
    - IF the car has not reached the end of the road: Increase the time the car has spent on the road.
    - ELSE add the car to the waitlist of the next road. *Note: The car remains on its current road until it is accepted off the waitlist of the next road. While it remains on the current road, congestion builds up.*

### D. Validation

The congestion model was difficult to validate because there is little empirical data for past evacuations. However, the model was validated for free-flow conditions by comparing it to the prediction from Google Navigation around midnight, which is assumed to have no traffic. This validation is shown in Fig. 3, with comparisons for six different cases.

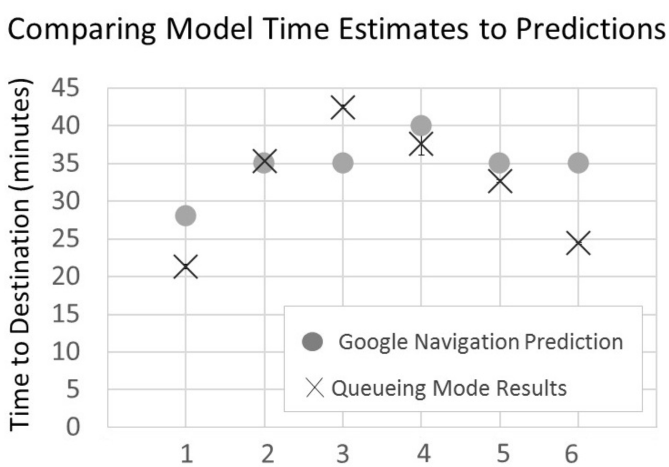



Fig. 3: Comparison of model results to Google navigation predictions for non-congested conditions. Each case is a different set of origin and destination points.

The model's predictions were within 20% of the Google prediction. The model was least accurate for cases 1 and 6, which were primarily city routes, because the model was built for a regional scale and does not include traffic lights or city conditions. The model was most accurate in purely highway routes: cases 2 through 5, where the simulation was within 6% of the predicted time. The main source of inaccuracy in case 3 was because the navigation algorithm of the model calculated a different route than Google navigation.

Although validation for this model in congestion conditions was not possible, , because of the lack of historical evacuation data, the general queueing model has been accepted as a good approximation for congestion. In Woensel and Vandaele, a queueing model is validated against empirical data for different traffic conditions [8]. Since the implementation of queueing theory in this model is similar to other validated models, this congestion model is expected to show similar accuracy.

### E. Visualization

In order to make the results accessible to the general public, the simulation must be visualized in an intuitive way. The geospatial data is displayed on a screen using the Mercator projection, and includes zoom and pan functionality.

Each agent represents multiple cars, and is represented by a grey circle that moves along the roads. The color variation between the agents is randomized in order to visually distinguish between adjacent agents, as shown in Fig. 4.

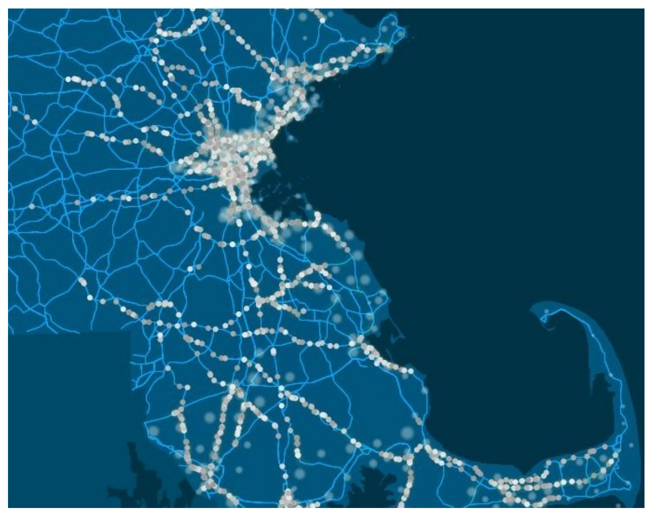


Fig. 4: Visualization with agents (cars) shown as white and grey circles.

## IV. Results

It is possible to use the results of the simulation to understand metrics about the evacuation. In order to identify vulnerable areas, a heat map of congested regions is created over the course of the simulation. As the roads stay congested for a longer time, the color in that area becomes more red and opaque, building up a heat map of vulnerable areas shown in Fig. 5. The map indicates that the Boston area takes longest to evacuate because of the high population density. The bridges to Cape Cod and a few other congested regions along the coast are also vulnerable, especially because those congested areas are in hurricane inundation zones. These regions take longer to evacuate, so planning and interventions should be focused towards these areas.


Fig. 5: Visualization with a heatmap to indicate regions that are vulnerable to congestion. More red and more opaque colors indicate a longer amount of time spent congested.

The evacuation can also be evaluated based on how long it takes each car takes to get from its origin to one of the destination cities. Each car individually calculates its own time spent on roads, and those values can easily be aggregated into a distribution of times. Fig. 6 contains a histogram of the length of travel time during a category 2 hurricane. The shape of the distribution under different circumstances could be another metric for understanding the impact of policy interventions.

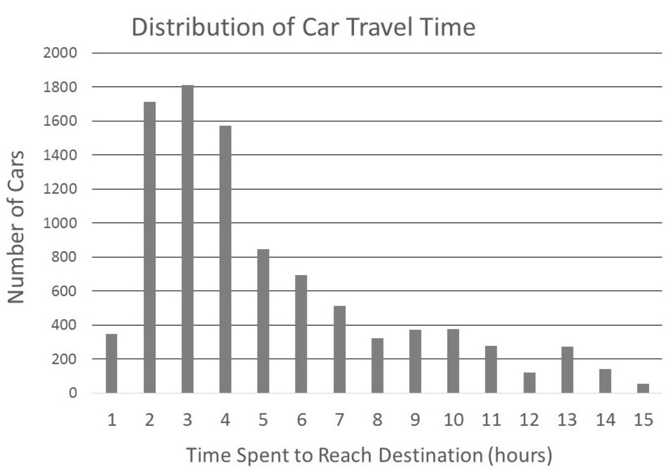



Fig. 6: Histogram showing distribution of travel time for cars over evacuation period.

Using the validated baseline model, we can analyze evacuations under different conditions. The metrics of congestion and car travel time can be used to quantify the efficiency of simulated evacuations, thereby presenting a model that can evaluate the effect of policy interventions. Furthermore, the visual interface for the model allows for intuitive presentation of the results to both experts and non-experts.

## V. Conclusion

This project implemented a queueing model for traffic in Massachusetts in the context of hurricane evacuations. The model was validated in free-flow conditions, and the main area for future improvement is creating a more realistic navigation algorithm. However, more work is needed in order to validate the model in congestion conditions. Given these limitations of the model, it can still be used to qualitatively identify regions that are vulnerable to congestion, and measure the distribution of travel times of evacuating cars. The data used in the model is also widely available for other cities, so this model could easily be adapted to other locations.

Future work for this model would include implementing and evaluating possible interventions to improve the time-frame and congestion of the evacuation. Such interventions could include evacuating vulnerable regions early, modeling public transportation, or evaluating different methods of government assisted transportation.

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