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Hurricane evacuation planning using public transportation

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ABSTRACT

Just before a hurricane is predicted to strike an urban area, millions of people evacuate from impact zones to safer regions. This paper provides a mass-evacuation strategy using public transportation before the strike of a hurricane. The assumptions made are that the evacuation zones, shelter locations, and the time of strike of the hurricane are pre-determined. The evacuation operations commence when the warnings are issued and end when the hurricane strike is predicted to occur. We propose a multi-stage approach. At the first stage is the planning framework, where pickup locations are determined and assigned to shelters, and an initial set of routes is generated along these locations. This is done by weighing each location based on the accumulated demand, and favoring multiple routes to pass through a location with higher demand. In the next stage, each route is assigned a trip number such that 1) routes with higher demand require more trips, and 2) two successive trips to a route are spaced evenly. A simulation tool has been developed to model the dispatching of the given number of buses, stochastic arrival of evacuees, queueing effects at the pickup locations, and the transportation of evacuees to the safety regions. The results from the simulation presented in this paper serve as an evaluation tool for a route design, and a local search heuristic is proposed to effect positive changes in the route design.

1. Introduction

Hurricanes, typically characterized by spiraling rain bands, strong winds and severe flooding, are the one of the deadliest of natural disasters. They originate over large water bodies of relatively warm temperature and strike coastal regions with very high wind speeds. Hurricane Patricia (2015) recorded a maximum wind speed of 165 mph, the most intense among all major Pacific hurricanes known till date. Coastal flooding triggered by a hurricane is as destructive as the wind, as it poses a severe threat to life and property along the coastline. For instance, the net property loss due to Hurricane Katrina (2005) is estimated to be around $125 billion [18] and that due to Hurricane Sandy (2012) is around $71.4 billion [5]. Hurricanes in the past have also left behind exorbitant damage to human existence. Hurricane Mitch (1998) resulted in a death toll of over 11,000 along the coasts of Caribbean Sea [21], and hence known to be the most destructive hurricane in the recent past.

Technological advances in satellite imagery, radar imagery and aircraft reconnaissance have ensured that sound forecasting models exist today. With accurate forecasting tools, it is possible to determine the timeline of a hurricane landfall about 3–5 days in advance, although the exact location of landfall is still difficult to be predicted early. The benefit of time must be effectively used to provide information to residents living in areas categorized into risk-based zones and more importantly, to setup an evacuation infrastructure where it is deemed necessary.

The objective of this research is to provide a framework for utilizing existing public transportation resources, namely buses, to administer efficient evacuation operations to evacuate people from high-risks zones to shelters located in safe zones. The motivation behind this research is multifold and is as follows.

1.1. Pre-disaster evacuation over post-disaster evacuation

When a hurricane makes landfall, the extreme winds and flooding cause damage to the transportation infrastructure in the affected areas. Such damage would constrain the evacuation capacity drastically if the roads are affected, and when aerial and water-based support are the only possible modes of evacuation. In addition to that, post-disaster demand surge would lead to delays in the evacuation operations, thereby imposing the additional

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burden of providing essential relief materials for those who are stranded. Hence, evacuating the maximum number of people possible before a hurricane is of dire importance, and is the primary objective of this research.

1.2. Addressing carless population

In a recent study conducted by the University of Michigan Transportation Research Institute [27], it was found that 9.22% of all households in the United States do not own a car. This number is much higher in urban areas where public transportation is the primary mode of daily commute. As of 2012, 56.5% of the households in New York City and 37.9% of the households in Washington D.C. do not possess a single car. In the context of a pre-hurricane scenario, the definition of what constitutes carless population would also extend to people who own a car but are not able to (or willing to) use it for evacuation purposes. This can be due to fuel shortages, disability, temporary illnesses, etc. Therefore, it becomes essential to utilize public transportation resources to cater to these population groups.

1.3. Reducing congestion

In addition to catering to the carless population groups, public transportation is also expected to reduce congestion on the road network. Existing research on pre-disaster traffic assignment problems focus on increasing link capacities by contra-flow traffic assignment, dynamic signaling protocols to allow uni-directional flow of traffic, providing alternate routes for travelers, etc. From the network utilization perspective, the approach of this research is on demand reduction, as opposed to capacity augmentation. Not only does this approach guarantee a reduction in congestion on roads, but will also induce a reduction in vehicle fuel demand, which tends to become scarce during times of demand surge.

With this motivation, we construct a heuristic multi-step procedure. The rest of the paper is organized as follows. In Section 2, we review some of the key literature in the areas of Operations Research and Management Sciences (OR/MS) that were useful in this research. In Section 3, we discuss the discrete optimization models used to identify pickup locations and assigning them to shelters, and also heuristic methods to generate good candidate routes and a dispatch sequence. In Section 4, we describe the simulation tool built to replicate a realistic evacuation operation, where we explicitly consider stochasticity in the arrival of evacuees and queuing effects at pickup locations. Section 5 demonstrates the planning methodology by employing it on a real-world case study based on Hurricane Sandy, with a target evaluation area selected as Brooklyn, New York. In Section 6, we provide a few concluding reflections on this research and considerations for future work.

2. Literature review

We separately review literature in the general area of hurricane evacuation planning and in bus-based evacuation modeling. This collective literature is relevant to our work. We note that our major contribution to the literature is the provision of a *planning framework* using public transportation for hurricane events.

2.1. Literature in hurricane evacuation planning

We first review some of the existing work covering diverse aspects of modeling the evacuation processes of mass-scale disasters. Evacuation modeling falls into the broader set of problems in Disaster Operations Management (D.O.M.). A 2013 study by Galindo and Batta [12] found that a majority of research work published in OR/MS journals focus on the mitigation, preparation and response to a disaster, as opposed to recovery after the disaster, which was the same trend compared to a 2006 study by Altay and Green [2]. They also found that some of the assumptions used in the models in D.O.M. were limited or unrealistic, and models that encapsulate challenges in both the pre-disaster preparation and the post-disaster recovery stages are more in need.

In the context of evacuation planning, Murray-Tuite and Wolshon [23] categorized evacuation models based on the following: evacuation warnings and information dissemination, zoning, demand modeling, route selection and traffic assignment, and strategies for evacuation efficiency improvements.

Effective communication of evacuation orders/warnings from the government bodies to the evacuees is critical, and often, there is little consistency in the terminology in the warning messages used. A recent study by Wolshon [31] found that legally unclear terms such as ”Mandatory” and ”Voluntary” were the most commonly used phrases. Warnings are not just intended to make evacuees to take the road, but also necessary to provide useful information about the right departure time and the routes to take. Taaffe et al. [29] examined the role of communications during hurricane evacuations in South Carolina and concluded that after the Hurricane Hugo landfall in 1989, the communication infrastructure has improved a lot, with the pervasive use of cell phones and the Internet playing a vital role.

Dividing the study area into geographical zones is crucial for customized delivery of communication orders, and also for modeling demand at the aggregate level. Wilmot and Meduri [30] report that zoning for hurricanes is currently done based on personal judgment to some degree. They suggest that additionally, uniform elevation and homogeneous land use, and crossing political boundaries must be also considered.

Modeling evacuation demand before a hurricane involves determining the number of people evacuating and spreading them temporally. Many studies have been conducted on identifying the variables that influence whether an evacuee decides to evacuate or not. Recent work like Hasan et al. [16] used a mixed logit model to capture the heterogeneity in the effect of parameters such as voluntary evacuation notice, work requirements, and the number of children in the household. Sorenson [28] first published in 2000 that the time spent in responding to an early warning often follows an S-curve, and many evacuation models have been based on cumulative departure S-curves. An analysis of traffic count data from

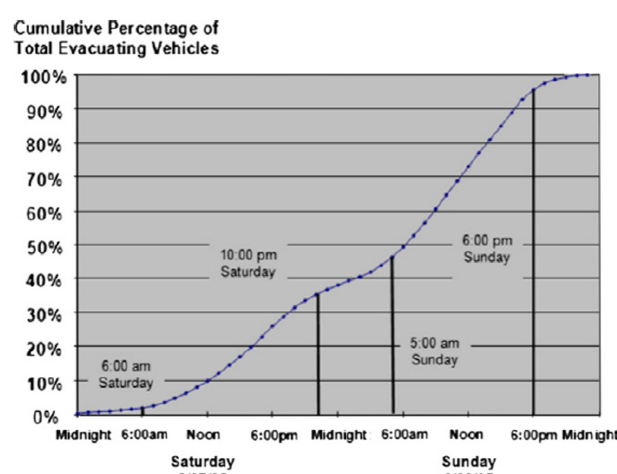

Fig. 1. Cumulative evacuation traffic during Hurricane Katrina. *Source: Murray-Tuite and Wolshon* [23].

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