Transportation Research Part E 48 (2012) 715–729

Contents lists available at SciVerse ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

# Shelter location and transportation planning under hurricane conditions

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ARTICLE INFO

Article history:
Received 27 July 2011
Received in revised form 9 November 2011
Accepted 25 November 2011

Keywords:
Hurricane evacuation
Shelter location
Bilevel programming
Stochastic programming
Dynamic traffic assignment
Heuristic

ABSTRACT

This paper develops a scenario-based bilevel programming model to optimize the selection of shelter locations with explicit consideration of a range of possible hurricane events and the evacuation needs under each of those events. A realistic case study for the state of North Carolina is presented. Through the case study, we demonstrate (i) the criticality of considering multiple hurricane scenarios in the location of shelters, and; (ii) the importance of considering the transportation demands of all evacuees when selecting locations for public shelters.



## 1. Introduction

The task of moving tens or even hundreds of thousands of people from a wide geographic area in a few days or hours under uncertain and dangerous conditions and getting them to safe locations is a complicated process. As Hurricane Katrina made abundantly clear, the stakes are high. Hurricane response requires coordination of many organizations, including a range of local, state, federal and non-governmental organizations, each of which must make a series of inter-related decisions. In the long-term, they must identify the facilities as possible shelters and prepare them for that role, establish evacuation routes, and plan for the decisions that will be made as each hurricane event unfolds. In the short period immediately before a hurricane makes landfall, they must decide which shelters should be opened and how best to issue evacuation orders, which includes deciding who should evacuate, what level of evacuation it should be (e.g., voluntary or mandatory), and possibly where they should evacuate to.

This paper proposes a scenario-based location model for identifying a set of shelter locations that are robust for a range of hurricane events. Standard practice today is to focus on a small number of conservative representations of hurricane events to make the majority of these decisions with little understanding of the impact of these choices on the range of possible events. Using a small number of conservative events can lead to decisions that are effective against those particular events, but are not robust against the range of events that could occur. By representing a range of hurricane events explicitly and their associated probabilities of occurrence, it is possible to achieve the long-term benefit of shelter planning effort and to capture the hurricane-specific features, such as the areas that are no longer suitable for shelters with particular characteristics and the spatial distribution of population in "harm's way".

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doi:10.1016/j.tre.2011.12.004

A key element of the model developed in this paper is the explicit inclusion of drivers' route choice behavior to support predictions of congestion across the network in each hurricane scenario. This model addresses the two inter-related questions: (i) to what extent can different shelter locations influence drivers' route choice by exploiting the inter-dependence between the shelter location plan and the dynamic traffic patterns? (ii) given a certain predictive model for drivers' route choice behavior, how should the facility planner choose a set of shelter locations, which together with the induced traffic pattern, is optimal with respect to a specific criterion? The shelter location and route choice decisions are made by two different decision makers, i.e. a facility planner who manages the shelter facilities and a set of network users who try to minimize their travel times on the network. This is a class of problem that can be represented as a bilevel programming problem or a Stackelberg leader-follower game in game theory, where the leader (upper-level decision maker) is the facility planner, and the follower (lower-level decision maker) is the set of network users. In this paper, the traffic dynamics is included by assuming the route choice behavior of network users follows dynamic user equilibrium (DUE), where any individual user chooses a route that dynamically minimizes his or her travel time along the route to the destination.

This paper makes the following methodological contributions. First, this model is the first attempt, to the best of our knowledge, to incorporate user equilibrium-based traffic dynamics into the optimization of shelter locations under uncertainty. In the proposed model, the decision of shelter selection is based on a suite of hurricane events and their associated occurring probabilities so this decision is robust for long-term shelter planning. This model accounts for the influence of shelter location decisions on congestion-related travel times and drivers' route choice behavior which is described through DUE. Second, the applicability and efficacy of the model are demonstrated through a large-scale real world example for the state of North Carolina. The problem scale contains nearly 100,000 origin-destination (OD) pairs and 15,000 network links for 33 hurricane scenarios with about 6,500 binary location variables. The results illustrate the importance of understanding the relationship between shelter locations and traffic congestion.

The remainder of this paper is organized as follows. Section 2 gives an overview of the related literature. The model formulation and solution algorithm are presented in Sections 3 and 4, respectively. Section 5 describes a case study for the state of North Carolina and discusses the computational results. The last Section concludes this paper and recommends future research opportunities.

## 2. Literature review

There is a vast amount of literature on the development of simulation and optimization models to support evacuation decisions (e.g., Chiu et al., 2008; Cova and Johnson, 2003; Dunn and Newton, 1992; Franzese and Sorensen, 2004; Hobeika and Kim, 1998; Sbayti and Mahmassani, 2006; Yamada, 1996). Yazici and Ozbay (2007) studied the impact of roadway capacity changes on shelter capacity requirement and average travel times during evacuation. The shelter locations were assumed to be known and the impact of each shelter on the performance of evacuation was evaluated by eliminating one shelter at a time. Very few evacuation models to date have considered shelter locations as decision variables and sought the optimal locations that minimize total system cost. Sherali et al. (1991) assumed that a central authority had the power to control the evacuation flow (a system optimal approach) and considered an evacuation planning problem by jointly optimizing traffic flow distribution and the selection of shelter locations from a set of given candidate sites. However, it is not practical for emergency planners to precisely direct traffic flows to links when drivers are generally free to select their own travel routes to their destinations (Cova and Johnson, 2003). They also represented traffic not destined for shelters as "constant" background traffic and therefore did not allow this traffic to be re-routed based on the shelters selected. Kongsomaksakul et al. (2005) also considered the impact of shelter locations on evacuation traffic and developed a bilevel shelter location model where the upper level problem was a location problem which minimized the total network travel time and in the lower level problem, the evacuees simultaneously decided which shelter to use and the route to take under static user equilibrium. They did not consider traffic bound for other destinations in addition to shelters. A similar problem was formulated in Ng et al. (2010) where the shelter allocation was optimized in the upper level problem rather than a choice made by the evacuees in the lower level problem as in Kongsomaksakul et al. (2005). They adopted the same representation as Sherali et al. (1991) for traffic not destined for shelters. All these shelter models (Sherali et al., 1991; Kongsomaksakul et al., 2005; Ng et al., 2010) focused on a given hazard scenario and hence the selected shelters may not be robust across the full range of hazard scenarios. They also all employed a static traffic assignment which assumed steady state for time-varying OD demand. Further, all of these papers either did not represent traffic not bound for a shelter or assumed that traffic was constant. The study in this paper extends the previous studies on shelter locations in the following ways: (i) instead of a single evacuation scenario, the decision of shelter selection is based on a suite of hurricane events and their associated probabilities of occurrence; (ii) we focus on the situation where drivers are free to select the routes based on their own preferences and DUE is used to describe their behavior; (iii) we account for not only the total travel time in the objective function, but also a penalty for failing to meet the shelter demand due to limited budget or staffing; (iv) computational experience illustrating the efficacy of the modeling is provided for large-scale applications; and (v) we explicitly represent traffic not bound for shelters allowing the optimization model to understand how all traffic will adapt to changes in shelter location decision.

The field of optimal investment that considers traffic dynamics is very new. When dynamic traffic assignment (DTA) is considered in the decision making to optimize investment strategies (e.g., network design, facility location modeling), the