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An agent-based modeling system for travel demand simulation for hurricane evacuation

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ABSTRACT

This paper presents an agent-based travel demand model system for hurricane evacuation simulation, which is capable of generating comprehensive household activity-travel plans. The system implements econometric and statistical models that represent travel and decision-making behavior throughout the evacuation process. The system considers six typical evacuation decisions: evacuate/stay, accommodation type choice, evacuation destination choice, mode choice, vehicle usage choice, and departure time choice. It explicitly captures the shadow evacuation population. In addition, the model system captures pre-evacuation preparation activities using an activity-based approach.

A demonstration study that predicts activity-travel patterns using model parameters estimated for the Miami-Dade area for a hypothetical category-4 hurricane is discussed. The simulation results clearly indicate the model system produces a distribution of choice patterns that is consistent with sample observations and existing literature. The model system also identifies the proportion of the shadow evacuation population and their geographical extent. About 23% of the population outside the designated evacuation zone would evacuate. The shadow evacuation demand is mainly located within 5 km of the coastline. The output demand of the model system works with agent-based traffic simulation tools and conventional trip-based simulation tools.

1. Introduction

Hurricane evacuation is a highly complex and dynamic process, which is generally modeled using optimization and simulation-based tools (Pel et al., 2012). Simulation abstractions of the evacuation process require accurate representations of evacuation demand, which is governed by many factors, such as the hurricane trajectory, warning system, and household characteristics (Baker, 1991; Gladwin et al., 2001; Murray-Tuite and Wolshon, 2013; Urbina and Wolshon, 2003). This paper presents an agent-based model system that captures household evacuation travel decisions and converts them into activity plans.

During an evacuation, households encounter a series of related decisions: whether to evacuate, when, to where, and by which mode, among other decisions. These decisions lead to the ultimate evacuation trips which constitute a large proportion of the evacuation demand. However, the demand also includes trips derived from pre-evacuation preparation activities,

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which can span several hours or days (Wolshon et al., 2009). These activities generate local traffic that was ignored in most previous evacuation simulation studies, which generally assumed no pre-evacuation activity travel, possibly due to data unavailability. However, before they leave, households usually make purchases (e.g., fuel and food) for their evacuation trips, which generate local traffic that contributes to overall congestion. In the no-notice context, preparation activities (e.g., family gathering) have a significant effect on evacuation time and traffic patterns (Liu et al., 2014; Murray-Tuite and Mahamassani, 2004) and some such effects are anticipated for hurricane evacuation as well (although at a lower magnitude). Therefore, pre-evacuation activity travel should be considered in the demand representation. Furthermore, incorporating the activities allows assessment of the implications of supply shortages, such as the gas stations running out of fuel.

Agent-based modeling and simulation (ABMS) is a useful approach to represent the complicated evacuation decision-making process. ABMS employs autonomous agents that can interact with the artificial surrounding environment (North and Macal, 2007). An agent has a set of attributes and behavioral characteristics. The attributes define an agent's identity and the behavioral characteristics define what an agent does (North and Macal, 2007). When a household is modeled as an agent, typical attributes include household size, number of children, and number of senior citizens. Agents' behavioral features can include decision rules to select actions, adaptation capabilities to learn from experiences, perceptual capabilities to sense surroundings, and optional internal mechanisms to project decisions' potential consequences (North and Macal, 2007). For evacuation decision modeling, the behavioral characteristics can be constructed using econometric models and other findings from evacuation behavioral studies.

The advantages of the ABMS framework over conventional trip-based demand modeling approaches in evacuation modeling are threefold. First, the households have different characteristics which lead to different behaviors. Even if the households have identical characteristics, they may choose different actions due to unobserved taste (preference) variation (Train, 2002). The agent is a useful abstraction capable of handling such behavior, especially for capturing shadow evacuation, largely due to households' different perceptions of risk. However, an aggregate demand modeling technique, usually applied in trip-based simulation models, generally fails to recognize taste variation. Second, ABMS can capture the evacuation decisions and preparation activity travel in a consistent and integrated manner. Households, the agents, are the actual entities that make evacuation decisions and they are also the trip-makers that conduct pre-evacuation travel and the ultimate evacuation trips. In comparison, the analysis units of conventional trip-based simulation models are individual trips generated at the level of traffic analysis zones (TAZs). This discrepancy renders coherent modeling of decision-making and trip-making behavior difficult, if not impossible. Finally, agents can interact with the external environment, such as hurricane characteristics. The external environment abstraction in the ABMS framework allows incorporation of these aspects of the evacuation process. Therefore, the ABMS framework is particularly suitable for simulating households' behaviors and exploring emergent collective phenomena in evacuation (Zhang et al., 2009).

In prior evacuation ABMS studies, the agent assumed different appearances in different transport simulation applications. Some studies (e.g., those using the microscopic simulation package VISSIM) defined agents as cars that follow a certain car-following logic (PTV, 2011). Adopting this convention, Chen et al. (2006) evaluated various evacuation scenarios for the Florida Keys using VISSIM. They generated evacuation demand at the level of evacuation zones. Other studies that considered cars as agents focused on evacuation route choice. For example, Handford and Rogers (2011) considered agents' familiarity with local routes. Zhang et al. (2009) explicitly dealt with the risk-taking preference for evacuees in route choice by categorizing the households as "normal" and "greedy" agents in hurricane evacuation.

A few studies considered decision-making entities as agents, an alternative to defining cars as agents. Notable examples include Wolshon et al. (2009), Montz et al. (2011), and Montz and Zhang (2013) who applied the ABS package TRANSIMS (Ley, 2009) to hurricane evacuation. Though the households were modeled as agents, the households' decisions and behavior were still treated at the aggregate level. A simplifying assumption was made regarding the evacuation trips and departure time- the departure time distribution was not associated with evacuees' characteristics, rather departure time was assigned based on a zone-level sequential logit model (Montz et al., 2011). A similar approach was used with regard to destination choice and they did not consider pre-evacuation preparation activities explicitly.

ABMS has also been used in pedestrian evacuation (e.g., Lämmel et al. (2010), Liu et al. (2008)). Santos and Aguirre (2004) provided a comprehensive review of the simulation-based evacuation models for pedestrian evacuation in buildings. Though the applications of ABS to hurricane evacuation have been limited, ABS has received attention in general transportation planning for daily commutes (e.g., Balmer et al., 2006; Balmer et al., 2009).

This paper applies the ABMS approach to develop a model system that generates evacuation demand, including pre-evacuation preparation activities in addition to a series of evacuation decisions. This paper makes the following contributions:

- The proposed system is among the first comprehensive agent-based evacuation demand model systems. It differs from previous TRANSIMS applications in that it relies on stochastic simulation with agents completely characterized by household-level behavioral models and findings. It flexibly represents evacuation decisions by allowing different behavioral model specifications and modeling orders.
- It explicitly captures shadow-evacuation demand, leading to a more realistic representation of the evacuate-stay choice.
- It statistically considers the choice of the number of evacuation vehicles through explanatory factors.
- It explicitly models pre-evacuation trips using an activity-based approach. The incorporation of the pre-evacuation trips enhances the accuracy of the demand representation.