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Risk-based spatial zone determination problem for stage-based evacuation operations

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ABSTRACT

This study seeks to determine risk-based evacuation subzones for stage-based evacuation operations in a region threatened/affected by a disaster so that information-based evacuation strategies can be implemented in real-time for the subzone currently with highest evacuation risk to achieve some system-level performance objectives. Labeled the evacuation risk zone (ERZ), this subzone encompasses the spatial locations containing the population with highest evacuation risk which is a measure based on whether the population at a location can be safely evacuated before the disaster impacts it. The ERZ for a stage is calculated based on the evolving disaster characteristics, traffic demand pattern, and network supply conditions over the region in real-time subject to the resource limitations (personnel, equipment, etc.) of the disaster response operators related to implementing the evacuation strategies. Thereby, the estimated time-dependent lead time to disaster impact at a location and the estimated time-dependent clearance time based on evolving traffic conditions are used to compute evacuation risk. This time-unit measure of evacuation risk enables the ERZ concept to be seamlessly applied to different types of disasters, providing a generalized framework for mass evacuation operations in relation to disaster characteristics. Numerical experiments conducted to analyze the performance of the ERZ-based paradigm highlight its benefits in terms of better adapting to the dynamics of disaster impact and ensuring a certain level of operational performance effectiveness benchmarked against the idealized system optimal traffic pattern for the evacuation operation, while efficiently utilizing available disaster response resources.

1. Introduction

An evacuation operation is necessary to relocate the affected and/or potentially threatened population to places of safety to avoid the immediate or impending dangers due to a disaster. To proceed with an evacuation operation, disaster response operators need to identify the locations to be cleared and the associated evacuation demand. In practice, the total evacuation demand is assumed to be pre-specified in a planning context as the population within an "evacuation zone". This evacuation zone, also labeled the emergency planning zone (EPZ), contains the locations which are vulnerable to a certain level of disaster impact potential. Thereby, in current practice, an affected region is recognized as the EPZ by applying simple principles; for example, locations within a 10-mile radius of a nuclear power plant or a 100-year flood plain in urbanized areas

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(Sorensen et al., 1987). Wilmot and Meduri (2005) propose a criteria-based procedure for hurricane evacuation planning to examine the locations in a potentially threatened region and determine if each of them should be evacuated under the potential hurricane impact. Their criteria are developed based on a review of the hurricane evacuation literature, insights from actual events, and expert opinions.

The current approaches to determine an EPZ and identify the corresponding total evacuation demand can be insufficient to address several issues that arise in an operational context: (i) An EPZ is pre-determined based on historical data and expected disaster impact. However, for disasters characterized by high spatial randomness in occurrence location, such as terror attacks and hazardous material spills, there may not be adequate data to support EPZ determination *a priori*; (ii) Except for some rare cases (Sorensen et al., 1992), in most current practice, the disaster response operators identify a single EPZ which encloses the entire affected region. However, in an operational context, the level of the disaster-induced danger may vary spatially and temporally within this EPZ. The spatial and temporal variation of the disaster-induced danger has implications for operational priorities, and consequently the allocation and coordination of resources (for example, personnel to enforce right-of-way control at roadway intersections). Resource allocation has been recognized as a critical issue for evacuation problems (Wolshon et al., 2005; Parr et al., 2012). Ignoring these spatio-temporal variations of the disaster-induced danger may lead to disaster response inefficiencies in that adequate resources are not allotted to the population that is currently under greater threat; (iii) An EPZ in general is determined by only considering the potential of disaster impact. However, the demand pattern and the transportation network structure over the affected region are also key factors that characterize the complexity of evacuation operations from a traffic management perspective. For example, between two locations under the same level of disaster impact potential, the location with higher population and less transportation capacity/connectivity leads to greater traffic management challenges in clearing the population of that location to safe areas; and (iv) In an operational context, the disaster characteristics, traffic demand pattern, and network supply conditions (link capacity and topology) may be continuously evolving throughout the evacuation operation period. Hence, evacuation operations can be significantly characterized by the time-dependency of these factors. For example, the intensity of a storm varies along its trajectory, and the spread of hazardous materials may be affected by varying wind directions. Also, the demand–supply interactions of the transportation system evolve with time and manifest as the traffic flow dynamics. In summary, the determination of evacuation strategies based on a pre-specified EPZ cannot factor the dynamics of both the disaster characteristics and traffic conditions, resulting in reduced performance effectiveness and resource allocation efficiencies.

To bridge the aforementioned gaps for the operational context, this study proposes a Risk-based Spatial Zone Determination Problem (RSZDP) within a stage-based framework for evacuation operations. The time horizon of the evacuation operation is discretized into time stages. The evacuation operation is implemented for each stage so as to capture the dynamics of the evacuation network in terms of the evolution of the disaster and the network traffic. The RSZDP determines an Evacuation Risk Zone (ERZ) for each stage of the evacuation operation so that the operators can deploy information-based evacuation strategies, evacuation recommendation and evacuation route guidance, to the ERZ in that stage to achieve some system-level objectives. The ERZ is a spatially bounded subzone that encompasses spatial locations in the affected region containing the population currently with the highest evacuation risk, where evacuation risk is a measure based on whether the population at a location can be safely evacuated before the disaster impacts it. The ERZ for a stage is calculated based on the evolving real-time disaster characteristics, traffic demand pattern, and network supply conditions subject to the resource (such as personnel and equipment) limitations of the disaster response operators related to implementing the evacuation strategies.

The proposed ERZ-based approach has several elements that are synergistic with the operational needs for deploying information-based evacuation strategies. First, the use of an ERZ reflects the spatio-temporal variability of evacuation risk across the affected region. Second, the consideration of the locations with the highest evacuation risk in an ERZ enables prioritization of the allocation of limited resources by operators within the operational framework. Third, the approach uses a time-unit measure to assess evacuation risk that can be seamlessly applied to different types of disasters. This enables the methodological framework to be generalized relative to the disaster type and its characteristics, and represents a key departure from most of the existing approaches in this domain that are specific to a disaster type. Fourth, it factors the time-dependent effects of disaster impact and transportation network to prioritize locations in terms of when their populations should be recommended to evacuate to mitigate the substantial impact of a large demand impinging on a finite transportation capacity in a short duration as is common under a mass evacuation scenario. Thereby, the ERZ-based strategies seamlessly integrate time-dependent demand, supply and disaster characteristics to foster a generalized evacuation operational framework. Fifth, the use of a ERZ paradigm is consistent with the stage-based deployment, thereby enabling operational computational tractability.

The remainder of the paper is organized as follows. Section 2 describes the characteristics of RSZDP and highlights its benefits for stage-based evacuation operations. It also introduces the proposed evacuation risk concept, which represents a key modeling aspect. Section 3 describes the RSZDP mathematical formulation and proposes a solution method. Section 4 discusses numerical experiments to analyze the performance of the ERZ-based deployment for evacuation operations. Finally, concluding comments and practical implications are presented in Section 5.