Transportation Research Part C 48 (2014) 339–359

Contents lists available at ScienceDirect

Transportation Research Part C

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

Behavior-consistent information-based network traffic control for evacuation operations

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ARTICLE INFO

Article history:
Received 21 July 2013
Received in revised form 5 June 2014
Accepted 30 August 2014

Keywords:
Evacuation operations
Behavior-consistent information-based control
Demand–supply interactions
Linguistic route guidance
Social equity

ABSTRACT

The evacuation operations problem aims to avoid or mitigate the potential loss of life in a region threatened or affected by a disaster. It is shaped to a large extent by the evolution of evacuation traffic resulting from the demand–supply interactions of the associated transportation network. Information-based control is a strategic tool for evacuation traffic operations as it can enable greater access to the affected population and more effective response. However, comparatively few studies have focused on the implementation of information-based control in evacuation operations. This study develops a control module for evacuation operations centered on addressing the demand–supply interactions by using behavior-consistent information strategies. These strategies incorporate the likely responses of evacuees to the information provided in the determination of route guidance information. The control module works as an iterative computational process involving an evacuee route choice model and a control model of information strategies to determine the route guidance information to direct evacuation traffic so as to approach a desired network traffic flow pattern. The problem is formulated as a fuzzy logic based optimization framework to explicitly incorporate practical concerns related to information dissemination characteristics and social equity in evacuation operations. Numerical experiments highlight the importance of accounting for the demand–supply interactions, as the use of behavior-consistent information strategies can lead evacuee route choices to approach the operator-desired proportions corresponding to the desired traffic pattern. The results also indicate that while a behavior-consistent information strategy can be effective, gaps with the desired route proportions can exist due to the discrete nature of the linguistic messages and the real-world difficulty in accurately modeling evacuees' actual route choice behavior.

1. Introduction

Evacuation traffic management primarily relies on strategies to physically adjust network capacity/supply or to route traffic flows using information-based control, thereby enhancing the efficiency of evacuation operations to move population from disaster-affected areas to places of safety. The strategies to adjust network capacity include using reversed lanes (Tuydes and Ziliaskopoulos, 2006; Kalafatas and Peeta, 2009), shoulders (Wolshon, 2002), or signal control/preemption/priority (Liu et al., 2008) which increases the capacity in outbound directions and eliminates crossing traffic flows at

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http://dx.doi.org/10.1016/j.trc.2014.08.025
0968-090X/

intersections to reduce the associated delays (Xie et al., 2010). Information-based control strategies can be implemented in the form of evacuation recommendation and evacuation route guidance to the affected population. The information can be disseminated to the public through multiple channels such as television, radio, variable message signs (VMS) and personal communication devices. Except VMS, other channels do not require additional field deployment of associated facilities in most situations (assuming communications infrastructure is not damaged). Hence, using information-based control strategies in evacuation operations allows disaster response operators more flexibility in attaining wider coverage and accessing larger population in the disaster-affected region under limited time and resources. However, comparatively few studies exist for the implementation of information-based control in evacuation operations.

Routing evacuation traffic using information-based control through route guidance entails robust modeling of traffic flow dynamics and evacuee behavior (Pel et al., 2011). Modeling traffic flow dynamics in an evacuation network has been broadly studied and addressed by using traffic assignment approaches, in both static and dynamic contexts (e.g., Hobeika and Kim, 1998; Alsnih and Stopher, 2004; Murray-Tuite and Mahmassani, 2004; Sbayti and Mahmassani, 2006; Chiu et al., 2007; Yazici and Ozbay, 2010; Songchitruksa et al., 2012). However, the behavioral aspects of evacuees have not been explicitly accounted for or are largely simplified in the related literature. This may restrict the validity of representing the realism of evacuation traffic. Evacuee behavior in terms of their likely responses to the disseminated information strategies is a fundamental factor for the efficiency of evacuation operations using information-based control.

Chiu and Mirchandani (2008) proposed an on-line closed-loop system for determining behavior-robust information routing strategies for mass evacuation. Their system regularly monitors network traffic conditions, and evacuee behavior is considered by excluding routes with longer travel times than desired. They also developed an evacuation route choice model based on a stated preference survey with respect to flooding scenarios. The model was primarily used for simulating evacuee route choice decisions to examine the deviation of realized traffic pattern from the control objective. However, it does not factor the effect of route guidance on evacuee route choice decisions. Furthermore, the determination of route guidance strategies is not reflective of the likely responses of evacuees, and vice versa. Pel and Bliemer (2008) developed an evacuation simulation model that contains behavioral components describing evacuation demand generation and evacuee route choice behavior. It allows modeling the effects of different types of information-based evacuation strategies, ranging from voluntary to mandatory, for evaluating evacuation plans. They presented a simple case study using the simulation model to illustrate the difference between the effects of voluntary and mandatory evacuation. Based on the developed simulation model, Pel et al. (2010) further developed an optimization model of traffic routing instructions while anticipating traveler compliance behavior. Nevertheless, the model was tested with different levels of compliance rates to the routing instructions, but the compliance rate in each analysis scenario is uniform across the studied population, which is not realistic in the real world. Also, their behavior models were primarily developed for planning purposes, but not incorporated in an on-line evacuation traffic management and/or control system.

In real-world operations, evacuees may not fully comply with the route guidance disseminated to them as prescriptive information. Without the accounting of evacuee responses to the information, there may be inconsistency between the objectives of the information-based control and the realized traffic flows resulting from evacuee responses. Motivated by the need to remove or mitigate such inconsistency, this study seeks to develop an evacuation route guidance paradigm that incorporates realistic evacuee behavior representation into the determination of information-based evacuation strategies.

The remainder of the paper is organized as follows. Section 2 introduces an operational framework for mass evacuation using information-based strategies to manage network traffic conditions. It describes the problem context for developing the evacuation route guidance paradigm. It also discusses in-depth the components in this framework relevant to developing the behavior-consistent information-based evacuation strategies. The associated behavior-consistent information-based control module is explicitly described and mathematically formulated in Section 3. A solution method is developed in Section 4, followed by numerical experiments to analyze the performance of the proposed control module in Section 5. Concluding comments and practical insights are presented in Section 6.

2. Modeling aspects of information-based control for evacuation operations

2.1. Operational framework for information-based control

The evacuation route guidance paradigm is constructed into a behavior-consistent information-based (BCIB) control module, which is the core of a stage-based operational framework for mass evacuation, as shown in Fig. 1. In the framework, the evacuation operation progresses along discrete time stages. In each time stage, to implement information-based control, the disaster response operators first identify whom information strategies should be disseminated to in that stage. An evacuation risk zone (ERZ) is determined which encompasses the affected people who sustain the highest evacuation risk (based on disaster characteristics and traffic conditions) in the current stage and need to be evacuated thereof (Hsu and Peeta, 2014). A recommendation to evacuate is made to the population in the ERZ. The demand-side responses of the ERZ population to the disseminated evacuation recommendation are predicted using an aggregate-level evacuation decision model developed by Hsu and Peeta (2013a). Accordingly, the evacuation demand in the ERZ for the current stage is forecasted as the aggregated decisions of the associated individuals in terms of whether to evacuate under the evacuation recommendation (indicated in Fig. 1 as the dashed line box). Based on this forecasted demand, adynamic traffic assignment