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Model and a solution algorithm for the dynamic resource allocation problem for large-scale transportation network evacuation

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ABSTRACT

Allocating movable resources dynamically enables evacuation management agencies to improve evacuation system performance in both the spatial and temporal dimensions. This study proposes a mixed integer linear program (MILP) model to address the dynamic resource allocation problem for transportation evacuation planning on large-scale networks. The proposed model is built on the earliest arrival flow formulation that significantly reduces problem size. A set of binary variables, specifically, the beginning and the ending time of resource allocation at a location, enable a strong formulation with tight constraints. A solution algorithm is developed to solve for an optimal solution on large-scale network applications by adopting Benders decomposition. In this algorithm, the MILP model is decomposed into two sub-problems. The first sub-problem, called the restricted master problem, identifies a feasible dynamic resource allocation plan. The second sub-problem, called the auxiliary problem, models dynamic traffic assignment in the evacuation network given a resource allocation plan. A numerical study is performed on the Dallas–Fort Worth network. The results show that the Benders decomposition algorithm can solve an optimal solution efficiently on a large-scale network.

1. Introduction

Efficient transportation of evacuees during emergencies has long been recognized as a challenging issue. Effective evacuation plans play an important role in improving the evacuation throughput, and reduce clearance time and property losses. In the evacuation literature, some studies focus on modeling traffic flow characteristics and dynamics during evacuation (see reviews in Murray-Tuite and Wolshon (2013) and Dixit and Wolshon (2014)). Other studies focus on improving the ground transportation performance during an evacuation through network design, mainly including: (i) network topological design, such as expanding link capacity (Patil and Ukkusuri, 2007; Ng and Waller, 2009), planning lane reversal strategies (so-called contraflow or counterflow) (Tuydes and Ziliaskopoulos, 2006; Kalafatas and Peeta, 2009; Xie et al., 2010), or enhancing link functionality reliability (Peeta et al., 2010); (ii) intersection design, such as reducing crossing and merging conflicts by restricting the right-of-way at intersections (Cova and Johnson, 2003; Xie and Turnquist, 2011); and (iii) traffic management strategies, such as investigating shelter location and the associated routing guidance to the shelter (Sherali et al., 1991;

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Kongsomsaksakul et al., 2005; Ng et al., 2010), signal timing to favor evacuation traffic (Lo, 2001; Chen et al., 2007), stage-based traffic flow control using behavior-consistent information (Hsu and Peeta, 2014a,b), and law enforcement personnel deployment strategy (Jabari et al., 2012). These strategies relevant to evacuation network design and management primarily deal with the optimal distribution of limited resources, such as budget, personnel, and traffic control devices, in the evacuation process. Among most existing evacuation network design studies, resource locations (or design patterns) are fixed, namely, they do not change over time during the evacuation process. Resource allocation in a dynamic model has been addressed in large-scale disasters, for instance, earthquake (Bakuli and Smith, 1996; Fiedrich et al., 2000). Because time and the quantity of the resources are limited, emergency management agencies need to find an optimal schedule for assigning resources in space and time to the threatened areas to enable a timely evacuation.

This paper investigates the dynamic resource allocation of well-trained personnel and movable devices to different intersections to route the evacuation traffic as efficiently as possible through these intersections. In this context, the personnel could be used to control traffic through an intersection to preclude, for example, turning movements that can reduce capacity under saturated conditions. Similarly, movable message signs could be used to disseminate real-time route guidance information towards safe zones. Allocating these movable resources dynamically can enable management agencies to further improve the system performance in the evacuation process. The study seeks to generate movable resources allocation plans to support evacuation planning, especially on large-scale networks. When a disaster occurs, the management agencies can deploy the plans generated off-line based on the unfolding traffic conditions.

From a modeling standpoint, the dynamic resource allocation (DRA) problem has some similarity to the machine scheduling problem in the operations research domain, in which a number of known jobs (i.e., resources in our context) need to be assigned to variant machines (i.e., locations in our context), such that the obtained schedule leads to minimum costs (Thomas and Salhi, 1998). As the same resource can be dynamically allocated to different locations, the DRA model is characterized by the job-shop problem where a job (one resource/personnel) can be assigned to different machines (locations).

To establish a foundation for the DRA implementation, He and Peeta (2014) recently proposed a mixed integer linear programming (MILP) formulation for the DRA problem to support evacuation. It determines an optimal plan that dynamically assigns a limited number of moveable resources (e.g., trained personnel) to a set of intersections such that the total system travel time is minimized. The total system travel time includes the waiting time at origins and the travel times through the network to the safe zones. Incorporating congestion, or traffic flow dynamics using concepts of traffic flow theory, is a central component in the constraint set of the problem formulation. In this context, He and Peeta's DRA model is built upon the Cell Transmission Model (CTM) (Daganzo, 1994, 1995) to describe the traffic flow dynamics. In addition, the model includes a set of spatiotemporal constraints to enable realism in practice; for example, the time required to reallocate the resource from one location to another is subject to the feasible traversal time, the allocated resource at one location is subject to the minimum service time, and the gap between successive allocations of resources to the same location is subject to a minimum time span.

The major barrier to applying He and Peeta's MILP to large-scale evacuation management lies in the high computational cost due to the following analytical features. First, the embedded CTM discretizes the network into small pieces of cells and the time span of interest into small time steps. The model contains a large number of variables because each link is divided into cells at each time step. Hence, a network of even a modest size will create millions of variables. This makes the MILP difficult to solve especially when the network size and evacuation planning time period are large. Second, the existence of traffic backward propagation constraint in the CTM involves a parameter that is not 1, 0, or -1, and thus precludes the time-expanded network structure which is preferable for developing efficient network algorithms. As illustrated by Kalafatas and Peeta (2007), a model that maintains a time-expanded network structure can be solved more efficiently due to the inherent total unimodularity and acyclic properties. Third, the embedded CTM permits traffic holding at intermediate nodes that is unrealistic during evacuation. Fourth, the binary decision variables which determine the allocation of the moveable resources make the problem NP-hard. The number of binary variables would increase significantly if one attempts to increase fidelity of traffic dynamics by dividing cells at a smaller dimension. Fifth, He and Peeta (2014) use a heuristic algorithm to identify an approximate solution that does not guarantee optimality unlike the proposed study. Hence, there is a key need for a DRA model and an efficient solution algorithm to facilitate practical applications, especially for evacuation planning for large-scale networks.

This study addresses the DRA problem especially for large-scale transportation network evacuation in two aspects. First, from a modeling standpoint, we adapt the earliest arrival flow (EAF) model instead of the CTM to describe the system-optimum evacuation traffic flow pattern. The main difference between the EAF model and the CTM is the choice of how to model dynamic traffic flows in the constraint sets of the DRA problem. The CTM describes realistic traffic flow dynamics but destroys the graph-theoretic properties and makes the problem much harder to solve. Recently, Zheng et al. (2015) illustrate that the traffic flow component does not matter much for certain evacuation objectives, especially if route advisories and guidance can manage flows. They show that the EAF and the system optimum dynamic traffic assignment (SO-DTA) encapsulating CTM have the same total system travel time. Another advantage of using the EAF model is that the evacuation flow can be modeled on a much simpler link-node time-expanded network (without division of cells) without compromising the optimal solution. In addition, traffic holding can be precluded in the EAF model.

Second, to improve the computational efficiency, a solution algorithm based on the Benders decomposition scheme (Benders, 1962) is developed for the DRA problem. Decomposition is a common technique to solve large-scale optimization problems. In this paper, the DRA model has a separable structure, which leverages the benefits of using Benders