Transportation Research Part B 72 (2015) 146–163

Contents lists available at ScienceDirect

Transportation Research Part B

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

Compromising system and user interests in shelter location and evacuation planning

Vedat Bayram *, Barbaros Ç. Tansel †, Hande Yaman

Bilkent University, Department of Industrial Engineering, Bilkent, 06800 Ankara, Turkey

ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 23 November 2014
Accepted 24 November 2014
Available online 26 December 2014

Keywords:
Evacuation traffic management
Shelter location
Traffic assignment
System optimal
Constrained system optimal
Second order cone programming

ABSTRACT

Traffic management during an evacuation and the decision of where to locate the shelters are of critical importance to the performance of an evacuation plan. From the evacuation management authority's point of view, the desirable goal is to minimize the total evacuation time by computing a system optimum (SO). However, evacuees may not be willing to take long routes enforced on them by a SO solution; but they may consent to taking routes with lengths not longer than the shortest path to the nearest shelter site by more than a tolerable factor. We develop a model that optimally locates shelters and assigns evacuees to the nearest shelter sites by assigning them to shortest paths, shortest and nearest with a given degree of tolerance, so that the total evacuation time is minimized. As the travel time on a road segment is often modeled as a nonlinear function of the flow on the segment, the resulting model is a nonlinear mixed integer programming model. We develop a solution method that can handle practical size problems using second order cone programming techniques. Using our model, we investigate the importance of the number and locations of shelter sites and the trade-off between efficiency and fairness.

1. Introduction

There has been a significant increase in the number of disasters over the past decades; from fewer than 50 disasters per year reported in 1950 to more than 400 disasters in 2010 (EM-DAT, 2013). Consequently, the number of people affected and the economic damages caused by disasters increased. International Federation of Red Cross and Red Crescent Societies (IFRC, 2011) defines disasters as "serious disruptions of the functioning of a community through widespread losses that exceed the community's capacity to cope with using its own resources". IFRC classifies disasters as naturally occurring physical phenomena caused either by rapid or slow onset events which can be geophysical, hydrological, climatological, meteorological or biological and as technological or man-made hazards that are caused by humans and occur in or close to human settlements. Federal Emergency Management Agency (FEMA) reports that 45–75 disasters require an evacuation annually (TRB, 2008). Whether it is made by the Military or Civil Emergency Management authorities, evacuation planning for large scale disasters such as earthquakes, hurricanes, floods, tsunamis or CBRN (Chemical, Biological, Radiological and Nuclear) consequences of ballistic missile attacks is of critical importance for disaster management.

Various traffic management problems arise during disasters; evacuation of the disaster region being one of the most important. In 1999 hurricane Floyd (CNN.com, 2001), and in 2005 hurricanes Katrina and Rita (TRB, 2008) required millions

* Corresponding author.
E-mail addresses: bayram@bilkent.edu.tr (V. Bayram), hyaman@bilkent.edu.tr (H. Yaman).
† Deceased.

http://dx.doi.org/10.1016/j.trb.2014.11.010
0191-2615/

of people to evacuate creating largest traffic jams in the U.S. history. Since disasters have different peculiarities, the evacuation objectives and decisions faced by a disaster management agency may differ. Most frequently used objectives in evacuation models are minimizing the total or average evacuation time, minimizing the clearance time, minimizing the maximum latency and maximizing the number of people who reach safety in a given time period. Clearance time is the time that the last vehicle in the network leaves the danger zone and reaches safety while latency is defined as the total time it takes a vehicle to complete its trip on a given route. The total evacuation time, i.e., the sum of the evacuation times of all vehicles, which is the focus of this paper, is a measure of how long the vehicles stay in the area at risk.

The time to evacuate a disaster region depends on the locations of shelters and on the traffic assignment. Shelters serve as safe facilities to provide the evacuees with food, accommodation and medical care. But the primary goal of sheltering before or after a disaster hits is to protect the population from possible dangers. Sherali et al. (1991) point out at their study that one of the greatest tasks in developing a hurricane evacuation plan is to determine where evacuees should seek shelter in order to retreat from the storm's damaging power. In their study Liu et al. (1996) emphasize that improving the local warning system will be effective only if people at risk can be evacuated to safe shelters. And secure shelters are a means to increase evacuation rates (Litman, 2006). Even though the decision of where to locate the shelters from among potential alternatives is of critical importance to the performance of an evacuation plan (Sherali et al., 1991; Kongsomsaksakul et al., 2005; Kulshrestha et al., 2011), few evacuation models in the literature decide optimally on the number and location of shelters. The aim of this study is to provide an evacuation planning tool that simultaneously optimizes the shelter locations and the allocations of evacuees to shelters and to routes.

The existing models used for assigning evacuees to routes are mostly based on three traffic assignment models, namely, the user equilibrium (UE, also known as User Optimal or Nash Equilibrium), the system optimal (SO) and the nearest allocation (NA) models. These models differ in assumed driver behaviors. In accordance with the UE principle, travelers' aim is to minimize their individual travel times. While a user equilibrium satisfies the drivers, it does not necessarily minimize the total evacuation time in the system. From the evacuation traffic management authority's point of view, the desirable goal is to explicitly minimize the total evacuation time by computing a system optimum. Under SO conditions some travelers may travel longer than they could to the benefit of the overall system. In the NA model, each evacuee uses a shortest path based on geographical distance or free flow travel time to reach the nearest shelter. Clearly, such a traffic assignment may lead to poor system efficiency.

The UE approach is not realistic to plan an evacuation during a disaster for the following reasons. In the UE model, it is assumed that the evacuees have full information on travel times on every possible route and they are able to find the optimal routes. Disasters and evacuations are rare events with unusual traffic demand resulting in different from normal traffic conditions. As a result, evacuees do not have the opportunity to learn from the past experience which routes minimize their evacuation time (Pel et al., 2012). It is unlikely for an equilibrium that distributes demand evenly across the evacuation routes to emerge (Lindell and Prater, 2007). Galindo and Batta (2013) and Faturechi and Miller-Hooks (2014) also state that the assumption that evacuees have perfect information about the road network and the traffic conditions is unrealistic, since it takes a while to state the traffic conditions. Such knowledge hardly exists for emergency evacuation for which the evacuees will have very limited if any prior experience regarding the travel patterns (Yazıcı, 2010).

On the other hand, the SO model, in which a central authority assigns evacuees to routes to minimize the total evacuation time, may route some evacuees on paths much longer than the ones they could take if they had a choice. In a disaster, where the aim of an evacuee is to leave the endangered zone as soon as possible and to reach safety at a shelter point, people may not show conscientious behavior to accept routes that are much longer than the shortest ones they would take. It is likely that some may not abide by the evacuation rules imposed on them; instead they may choose routes to reach the closest shelter site as quickly as possible without considering the adverse affects of their choice on others.

Barrett et al. (2000) classifies destination choices of evacuees as nearest safe destination, soonest safe destination and easiest safe destination. A similar classification is made by Southworth (1991). In a disaster situation, where there is limited information on the road network and congestion levels, evacuees show selfish behavior, as people do even under normal daily traffic conditions (Roughgarden, 2002; Jahn et al., 2003; Schulz and Moses, 2003; Correa et al., 2005, 2007; Schulz and Stier-Moses, 2006; Olsthoorn, 2012) and they tend to select routes that take them to the nearest shelter site, as proposed and implemented by Yamada (1996), Cova and Johnson (2003), Alçada-Almeida et al. (2009), Coutinho-Rodrigues et al. (2012) and Sheu and Pan (2014).

To develop a route guidance system, Jahn et al. (2005) propose to honor the individual needs by imposing additional constraints to ensure that drivers are assigned to "acceptable" paths only. Such a traffic assignment model is referred to as constrained system optimal (CSO).

Our aim is to propose a CSO model that optimally locates shelter sites and that assigns evacuees to the nearest shelter sites and to shortest paths to those shelter sites, shortest and nearest within a given degree of tolerance. As our model already considers fairness among evacuees by assigning them to close shelter sites, we use the overall system performance in our objective and minimize the total evacuation time. We note here that our model generalizes both SO and NA traffic assignment models, as these correspond to the cases of infinite and zero tolerance levels, respectively. The solution of the model evacuates the disaster region as quickly as possible, with a "fair" assignment of evacuees to shelters and to routes. To this end, we propose a nonlinear mixed integer programming model and solve practical size problems in reasonable times by representing the nonlinear objective function with second order cone programming. In addition, we present a sensitivity analysis by changing the level of tolerance and the number of shelters to open and make a comparison of the results of SO,