Scalable evacuation routing in a dynamic environment☆

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ARTICLE INFO

ABSTRACT

In emergency management, tools are needed so we can take the appropriate action at different stages of an evacuation. Recent wildfires in California showed how quickly a natural disaster can affect a large geographical area. Natural disasters can create unpredicted traffic congestion or can temporarily block urban or rural roads. Evacuating a large area in an emergency situation is not possible without prior knowledge of the road network and the ability to generate an efficient evacuation plan. An ideal evacuation routing algorithm should be able to generate realistic and efficient routes for each evacuee from the source to the closest shelter. It should also be able to quickly update routes as the road network changes during the evacuation. For example, if a main road is blocked during a flood, the evacuation routing algorithm should update the plan based on this change in the road network. In this article major works in evacuation routing have been studied and a new algorithm is developed that is faster and can generate better evacuation routes. Additionally, it can quickly adjust the routes if changes in the road network are detected. The new algorithm's performance and running time are reported.

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1. Introduction

How to plan a large-scale evacuation is a serious and an important research question. However, this question is not entirely answered. Currently we have the required computational power and good quality geospatial data to produce evacuation routes for large geographical areas. Furthermore, the advent of mobile platforms and smart cars have made it possible to reach out to individuals in seconds with life-saving news as might happen during a disaster. The missing element is the ability to generate efficient evacuation routes at large scale. Such a system should be able to monitor the evacuation and update the routes in case some of the initial conditions have changed.

Imagine there is a wildfire in Southern California. Fig. 1 shows a map of Southern California with major roads and historical wildfire incidents. The responsible agency generates evacuation routes to convey residents from each threatened neighborhood to specific shelters. These routes can be communicated with each neighborhood via a mobile or car app. Assuming none of the initial conditions change, everyone will get to a shelter in a reasonable and predictable time. The problem of generating these evacuation routes while minimizing the traffic congestion is what we call static evacuation routing. As the evacuation is happening, a number of things can change in the environment: (1) there could be background

traffic that were not initially considered; (2) automobile accidents can temporarily affect the traffic flow; (3) changes to the road network such as a damaged bridge, a partially blocked road, or a flooded underpass can affect the road network; and (4) there could be more cars leaving one or more neighborhoods than we anticipated. Each of these situations can affect the evacuees. The public safety agency can learn about these changes either via the same mobile app (crowd sourced) or with the help of onsite public safety personnel. Updated evacuation routes could then be generated and pushed to affected motorists. The problem of generating and maintaining evacuation routes in a dynamic environment is called dynamic evacuation routing.

In this article, we propose a new solution to the dynamic evacuation routing problem. We focus on solutions that can be scaled to large geographical areas at least the size of a city. The remainder of this section provides an overview of the broader evacuation planning process with an emphasis on evacuation routing challenges. We then lay out the contribution and scope of our solution with respect to the evacuation planning problem. Section 2 reviews related work on evacuation routing. Section 3 formally defines the problem and explains the solution. Section 4 presents the experimental results. Section 5 offers conclusions.

1.1. Background

The evacuation problem can be decomposed into four phases: (1) mitigation; (2) preparedness; (3) response; and (4) recovery (Cova, 1999).

The **mitigation and preparedness** phases refer to the time before the incident actually happens. Since the nature of the disaster is not known at
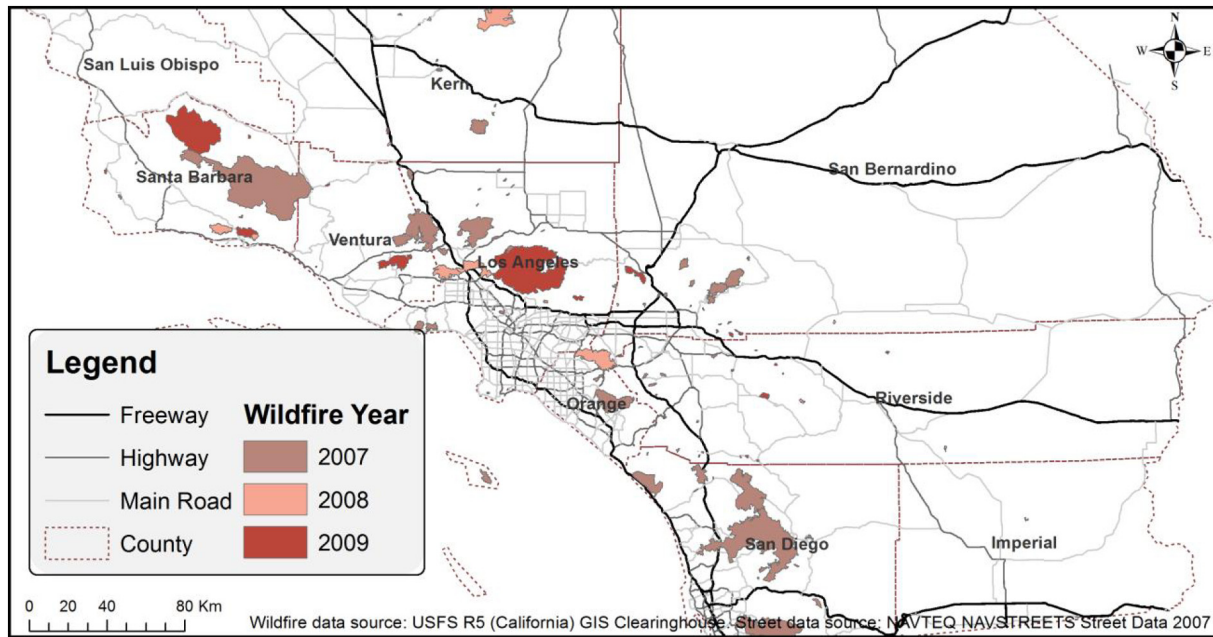
Fig. 1. Map of historical wildfires in southern California with major roads.

this stage, solutions to this sub-problem are less about the execution details and more focused on the surrounding geography. For example, Church and Cova (2000) presented a model to detect overpopulated neighborhoods that might face traffic congestion during an evacuation.

The **post-disaster recovery** is the stage where emergency personnel care for the affected population, maintain shelters, and assess the damage. For example, Yi and Ozdamar (2007) proposed a solution for evacuation response and support coordination during an emergency situation. The proposed model considers the food distribution to shelters and transportation of wounded people to medical centers as a commodity distribution problem. They formulated and solved the problem with mixed-integer LP.

The **evacuation response** refers to what needs to be done from the moment we learn about a disaster up until the time at which all of the potentially affected population is secured in safe areas. At this stage the location and time of the disaster and the evacuees are the key information.

Disasters can be static or dynamic. Dynamic disasters are those with changing behavior, location, or severity. Disasters like tsunami or terrorist attacks are considered static because the affected area, once known, is static. Other disasters like hurricanes, wildfires, and floods are dynamic since they move from one place to another. Of course given the circumstances, any disaster can become dynamic.

The **evacuees** are those residents who leave voluntarily whereas others may choose to shelter in place. The locations of the evacuees may be gathered from a variety of sources. In the U.S., high resolution population data is available through the U.S. Census Bureau (e.g. U.S. Census Bureau, 2010). However, these sources refer to residential populations and would not reflect the population distribution during the day. The LandScan team at Oak Ridge National Laboratory presented a method to extract high-resolution population data from a combination of geospatial datasets including satellite imagery (Bhaduri, Bright, Coleman, & Dobson, 2002). Kobayashi, Medina, and Cova (2011) presented a dynamic population model to improve and visualize diurnal population density based on public transport data.

1.2. Contribution

In previous works the static problem has been studied and several algorithms exist that can efficiently solve the problem (e.g. Lu, George, & Shekhar, 2005; Shahabi & Wilson, 2014). In this article we propose a

routing solution for the dynamic environment. We formally define the problem and then develop a framework to solve both the static and dynamic versions of the problem.

Our main contribution is an iterative algorithm that can solve the evacuation problem in both static and dynamic environments. Our solution generates evacuation plans with better evacuation egress times compared to previous works. The secondary contribution is the ability to use a previously calculated evacuation plan to quickly find a new plan when a network change is detected.

2. Related work

The majority of the evacuation routing works in the literature can be divided into descriptive and prescriptive methods. Descriptive methods are those that visually simulate a given emergency situation. For example agent-based modeling (traffic simulation) visualizes what will happen during an emergency (Santos & Aguirre, 2004). Pel, Bliemer, and Hoogendoorn (2011) provided a thorough review of traffic simulation models for evacuation and looked specifically at the underlying formulation and psycho-behavioral assumptions of both commercial and academic traffic simulations. They categorized the models based on three choices: (1) evacuation participation and departure time; (2) destination choice; and (3) route choice. Prescriptive methods, on the other hand, determine the evacuation routing strategies to achieve some evacuation goal without necessarily performing a fine-scale simulation (Chiu, Zheng, Villalobos, & Gautam, 2007). In this section we briefly discuss major prescriptive evacuation routing methods.

Kwon and Pitt (2005) used the Dynasmart-P software (Mahmassani, Sbayti, & Zhou, 2004) to simulate the vehicular traffic for an evening event in downtown Minneapolis. They blocked different freeway ramps and observed the evacuation egress times. In one configuration they also implemented contraflow on freeways inside the study area. They concluded that it is feasible to study evacuation strategies using a dynamic network assignment model in a downtown-sized environment.

Xie, Lin, and Travis Waller (2010) defined and solved a new dynamic evacuation network optimization problem. In their work they considered both lane-reversal (contraflow) and crossing elimination jointly together and optimized the system for total evacuation egress time. The optimization was also conducted separately for network clearance