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Transportation network reliability in emergency response

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ABSTRACT

Distribution of humanitarian supplies is vital in saving lives during disasters. Investment in retrofitting critical transportation links reduces casualties as intact links improve flow of relief supplies. In finding critical links, link importance values are derived using the concept of network reliability. A network improvement problem is then solved to minimize death toll. To increase practicality, a heuristic algorithm is proposed to solve real size problems. Results show that initial incremental investments in network improvement are more profound in reducing the death toll than higher budget increments. Moreover, higher relief inventories reduce the death toll when the network is reliable.

1. Introduction

1.1. Background

Natural disasters, earthquakes in particular, claim many human lives and damage major lifelines such as transportation networks. When an earthquake strikes, buildings lacking adequate structural stability collapse and humans either die or need immediate help. To further exacerbate the situation, failure of transportation networks may delay assistance. This delay was consequential in the Haiti earthquake of 2010 where vital infrastructure such as air, sea, and land transport facilities were damaged including the control tower of the L'Ouverture International Airport (Lipton, 2010) and the Port-au-Prince seaport (Branningan, 2010). The roads were no better than air or sea. A 10 days long blockage of the major roads after the earthquake severely hampered the emergency response operations (Fraser, 2010). Hence, an action effective in disaster mitigation in large metropolitan areas is to reinforce transportation infrastructure to ensure they are operational to carry emergency supplies during disasters (Holguín-Veras et al., 2014; Miller-Hooks et al., 2012).

Having a reliable transportation network is critical at times of disaster when the transportation network provides crucial access to disaster-hit areas (Aksu and Ozdamar, 2014). Despite the importance of emergency-based network reliability, the majority of research focuses on operations during non-emergency with reliability measures based on travel time, connectivity, consumer surplus, and traffic flow. Among the current available research, some may argue that connectivity reliability is the same as emergency reliability as a more connected network enhances distribution of relief supplies to the disaster-hit areas (Novak and Sullivan, 2014). However, the use of the connectivity measure in the emergency context may be misleading in the presence of sufficient relief supplies at the vulnerable zones. In such cases, the vulnerable zones would be

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self-sufficient (in terms of attending to the zone's vulnerable population) and there would be no need for inter-zonal distribution of humanitarian supplies. In such circumstances, connectivity of the network would be less critical and the network would still be considered reliable during disasters even if all the links have failed. On the other extreme of the spectrum, a completely connected network after an earthquake will do little to help for the disaster response phase if there are not enough relief supplies to be distributed. Thus, study of a more appropriate emergency-based reliability measure requires an in-depth understanding of the emergency response operations including relief distribution.

At the onset of an earthquake, buildings lacking sufficient structural stability are susceptible to collapse and residents are at risk of getting injured and requiring medical attention and humanitarian supplies. An emergency response plan is one which dispatches humanitarian supplies (e.g., water, food, medical supplies, and survival equipment) to the affected regions. One key factor in having an efficient emergency response plan is timeliness as human survival is dependent on travel time for emergency supplies to arrive where needed. The arrival time of humanitarian supplies is dependent on the condition of the transportation network. The network consists of links which have independent failure probabilities. It is necessary to retrofit certain critical links to promote a reliable network during times of disaster.

Upon identification of critical links, a decision maker (such as the local or provincial government) has a choice of retrofitting the links. It is reasonable to assume that the decision maker can also choose the intensity of retrofitting which will influence the failure probability of a link (Ball et al., 1995). If a link is retrofitted then its failure probability diminishes, whereas if a link is not retrofitted, its failure probability remains the same. Generally, the decision maker does not have the resources to retrofit every link. Hence, identification of critical links and selection of the appropriate retrofitting intensities is required.

The main objective of this paper is to introduce a new reliability measure, called the Emergency Response Reliability, which considers humanitarian logistics (e.g. inventory and distribution of relief supplies) network connectivity and travel time reliability. The paper then describes a method to find the optimal set of links to retrofit for maximizing the ERR measure. Methods for selecting and evaluating level-of-service are discussed and a new heuristic is proposed for dealing with larger size problems. In order to build the groundwork for the contributions of this paper, a literature review is provided in the Section 1.2 and the contributions of the paper are discussed in Section 1.3.

1.2. Network reliability

The concept of network reliability has been extensively studied under the contexts of connectivity and performance (Li et al., 2010). Performance-based network reliability can be further divided into travel time reliability and capacity reliability. Travel time reliability is generally defined as the probability that a trip between two nodes takes less time than some threshold value[3] (Taylor et al., 2006) and capacity reliability is defined as the probability that the network capacity can accommodate a certain volume of traffic demand at a required level-of-service (Chen et al., 2013). Compared to performance-based reliability measures (i.e. capacity and travel time reliability), connectivity reliability is defined as the probability that nodes of a network remain connected. According to Konak and Smith (2006), connectivity reliability measures can be further classified based on the number of nodes the measure covers into (i) two-terminal reliability (the probability of the existence of a path between two specified nodes), (ii) all-terminal reliability (the probability that each node of the network is connected to every other node), and (iii) k-terminal probability (the probability that every two nodes in a subset K are connected).

The use of performance-based or connectivity-based network reliability for disasters requires defining specifically which phase of the disaster is of interest. Disaster-reliability can be defied for both pre-disaster and post-disaster phases (Chen and Miller-Hooks, 2012). Disaster phases can include (i) the evacuation process at the onset and prior to the disaster, (ii) relief distribution after the disaster, or (iii) post-disaster recovery (Altay and Green, 2006; Galindo and Batta, 2013). Each phase is distinguished based on the nature of demand. In the evacuation phase, a reliable network renders a platform for people to travel from their origin locations to shelters. During relief distribution, a reliable network allows humanitarian supplies to be transported from inventory locations to the disaster-hit regions in time. Post-disaster recovery requires a reliable network so that individuals can return to their daily activities. The majority of the research on disaster-based network reliability is dedicated to relief distribution although simple modifications can be made to the available models to tailor them for the evacuation phase as well. This study is concerned with relief distribution reliability.

Among performance-based and connectivity-based reliability measures, the latter has been applied more extensively in the study of relief distribution during disasters. In this context, one of the major questions of interest has been "Given a budget, which links should be retrofitted in a network in order to maximize network connectivity reliability?" In answering this question, Moghtaderi-zadeh and Kiureghan (1983) determine the survivability of links (i.e. which links will fail and which will survive) based on the distance of the link from the earthquake epicenter for a specific magnitude earthquake. The authors then determine critical links in the network that would substantially reduce the connectivity reliability if they fail. An incremental investment plan is then proposed to retrofit the critical links. Nicholson and Du (1997) define critical links in a network as those whose absence significantly reduces the reliability of the network. Identification of critical links helps to act preventively to increase the reliability of the network in advance of natural disasters. Chang and Nojima (1998) measure the performance of the transportation network when an earthquake strikes. They introduce several performance measures

[3] In the literature, this threshold value is referred to as the level-of-service.