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Stochastic Multi-Objective Evacuation Model Under Managed and Unmanaged policies

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Abstract

Natural and man-created disasters, such as hurricanes, earthquakes, tsunamis, accidents and terrorist attacks, require evacuation and assistance routes. Evacuation routes are mostly based on the capacities of the road network. However, in extreme cases, such as earthquakes, road network infrastructure may adversely be affected, and may not supply their required capacities. If for various situations, the potential damage for critical roads can be identified in advance, it is possible to develop an evacuation model, that can be used in various situations.
This paper focuses on the development of a model for the design of an optimal evacuation network which simultaneously minimizes retrofit costs of critical links (bridges, tunnels, etc.) and evacuation time. The model considers infrastructures' vulnerability (as a stochastic function which is dependent on the event location and magnitude), road network, transportation demand and evacuation areas. Furthermore, the model evaluates the benefits of managed evacuation (system optimum) when compared to unmanaged evacuation (user equilibrium).
The paper presents a mathematic model for the presented problem. However, since an optimal solution cannot be found within a reasonable timeframe, a heuristic model is presented as well. This heuristic model is based on evolutionary algorithms, which also provides a mechanism for solving the problem as a multi-objective stochastic problem.
Using a real-world data, the algorithm is evaluated and compared to the unmanaged evacuation conditions. The results clearly demonstrate the advantages of managed evacuation, as the average travel time can be reduced by 5% to 30%.

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1. Introduction

Natural and man-created disasters, such as hurricanes, earthquakes, tsunamis, accidents and terrorist attacks, require evacuation and assistance routes. As of today, most research on emergency response operations focuses on evacuation problems from the perspective of transportation modelling such as network design and traffic assignment. In that context, transport networks are lifelines which support essential services, and need to be preserved in their functionality in case of disruptions caused by events which originate within (e.g. traffic accidents and technical failures) or outside the transport system (e.g. debris-flows, floods, earthquakes, storms, etc.).

Although evacuation is a stochastic process, most current evacuation models treat the problem in a deterministic way, while some of the models incorporate distribution laws to treat the randomness of human actions and decision inputs (Cuesta, Abreu, & Alvear, 2016). Evacuation routes are mostly based on the capacities of the roads network. However, in extreme cases, such as earthquakes, roads network infrastructure may have adversely affected, and may not supply their required capacities. If this can be identified in advance, it is possible to develop an evacuation model that can be used to recommend the construction of new road segments, retrofit and improve critical links, locate shelter locations, etc.

While disasters, such as earthquakes, cannot be predicted, it is possible to plan evacuation routes in advance, and provide the information to the population.

This paper focuses on the development of a model for the design of an optimal "in advance" evacuation network which simultaneously minimizes retrofitting critical links costs and evacuation time. The model takes into consideration the infrastructures vulnerability associated with the retrofitting road segment (as a stochastic function which is dependent on the event location and magnitude), road network potential structure, transportation demand, and evacuation areas' capacities. Also, in order to investigate evacuation when it is possible to control the flow (advanced notice evacuation and the availability of rescue teams or not (sudden onset disaster), the model evaluates the benefits of managed evacuation (system optimum) when compared to unmanaged evacuation (user equilibrium).

Furthermore, a chance constraint is used to provide the decision maker the means to assess the solution based on different risk levels. Due to the overall complexity of the model (multi-objective and stochastic), an optimal solution cannot be found within a reasonable timeframe and therefore a heuristic algorithm has to be developed and used.

2. Literature Review

Evacuation model planning usually refer to network design and traffic assignment (Chilà, Musolino, Polimeni, Rindone, Russo, & Vitetta, 2016; Heydar, Yu, Liu, & Petering, 2016; Zimmerman, Brodesky & Karp, 2007).

There are several different decisions that should be considered while developing an evacuation models (Cuesta et al., 2016): (1) Selection of Evacuation Routes. Usually more than one escape route is required for the same group of people in order to manage the possible evacuation routes. (2) Introduction of delay times that act as a mechanism for avoiding possible congestion and bottleneck problems in overlapping routes, by delaying evacuation movement of a group of people. (3) By dividing the evacuation route into several parts, it is possible to control the speed of evacuation when the available safe egress time of each piece of a route is known.

The effectiveness of an evacuation operation is dependent on various factors, such as: (1) The availability of resources, such as transit vehicles, volunteers and medical staff that should be optimally allocated. (2) The risk of exposure to disaster impact, which is proportional to the waiting time at pickup locations, and therefore a common objective in this case is minimizing evacuation time. (3) The vulnerability of different locations within the evacuation zone and their proximity to disaster sites. Ignoring any of these characteristics can reduce the performance of the evacuation system (Dhingra & Roy, 2015).

While the evacuation network model presented in this paper takes into consideration infrastructures vulnerability, according to Reggiani, Nijkamp, and Lanzi (2015), the vulnerability concept still lacks a consensus definition, and it depends on the application context (El-Rashidy & Grant-Muller, 2014; Mattsson & Jenelius, 2015). The authors of this paper, in past works (Hadas et al., 2015), adopted the risk theory framework to represent degraded scenarios as a