An Overview on Multimodal Emergency Evacuation in an Urban Network

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Abstract

Emergency evacuation is important following natural disasters, terrorist attacks or other causes. This can put an enormous amount of pressure on our transportation networks as the generated traffic demand can significantly exceed those for routine travel conditions. Applying the best attributes of each mode of transportation is thus vital in such scenarios. Depending on the nature of the hazard and the population characteristics within the threat area, the implementation of evacuation models and simulations has the potential to save a vast array of lives by providing an effective path to safety for inhabitants. This paper aims to present an overview of approaches to emergency evacuation in an urban network, their features and findings. Key findings show a deficit of research in models incorporating other modes such as pedestrians and public transit, synergising different evacuation strategies for efficient evacuation and realistic travel behaviour.

1. Introduction

Natural disasters, failures in technology, and terrorist attacks have consistently put large populations at risk worldwide. Emergency managers have the big task to plan for such risk by developing strategies to alleviate damage and protect lives. When prevention is not possible, strategic emergency management is the next best option. While sheltering-in-place provides an option for protecting people from harm in many situations, often an evacuation is the only emergency management technique available to ensure a population's safety (Vanlandegen, 2010). In an evacuation of a major metropolitan area, large numbers of people must be moved to safety in a safe and timely manner. For some hazards, like hurricanes, this can often involve the movement of several million people over distances in excess of 160 kilometres, with elevated demand conditions lasting for several days. (Naghawi & Wolshon 2012). For some hazards like chemical spill or earthquake mass evacuation on foot within a few kilometres may be preferable (Ercolano, 2008). Likewise, multimodal evacuation could be advantageous in many situations (Abdelgawad & Abdulhai, 2010). Therefore, the challenge of prompt multimodal evacuation of dense urban areas has made evacuation demand management an essential priority in planning for emergency situations.

This paper reviews approaches for emergency evacuation in an urban network within the past 10 years considering three modes - auto, pedestrian and transit. It is to be noted that this overview does not aim to be complete and exhaustive, but rather to explore features and findings of some recent models for emergency evacuation in an urban network. In the next section, we investigate relevant literature and provide a key summary statement of recent studies on emergency evacuation with focus on different modes of transport. Conclusions are then presented including a summary of key findings and a discussion of their implications for future research.

2. Literature review

A large body of literature consider car as the main mode of transport for evacuation (Pel et al. 2011). Dynamic traffic simulation modelling tools have frequently been implemented for representing the movement of vehicles within transportation networks. They are particularly useful in evacuation traffic analyses because they allow the development and the comparison of different evacuation plans under a variety of hypothetical emergency situations to assess and forecast traffic conditions and duration of evacuation (Yuan et al. 2006). The choice of the model is usually a trade-off between the accuracy level and the cost, data requirements, and time required for the simulation. Recently, common practices have been to use well established dynamic traffic simulation models in PARAMICS, VISSIM, CORSIM etc. It is also interesting to note that the driving behaviour parameters like headway, acceleration, reaction time are adjusted for the evacuation and that the model structure and parameter settings are typically not changed (Tu et al. 2010).

Public transit has proved to be an effective way of evacuation during large scale evacuations (Scanlon, 2003), due to the large volume of people it can facilitate (Vuchic, 2005). In addition, rail transit is typically included into existing evacuation plans (e.g. Chicago Police, 2007). Despite this, little work has been conducted for modelling rail transit in evacuations. Simulation based tools have been developed to study the feasibility and performance of transit evacuation plans. Elmitiny et al. (2007) performed a simulation to evaluate evacuation plans using bus depots. Different evacuation strategies were evaluated including traffic diversion, bus signal optimisation, access restriction, different destinations, and evacuation of pedestrians. Some researchers have converted transit demand to passenger car traffic for studying evacuation (Liu et al. 2008). A heuristic approach was developed by Mastrogiannidou et al. (2009) for integrating the micro-simulation software package VISTA with transit based emergency evacuation models. The approach involved assigning vehicles to pick-up points based on the shortest time criterion and then evaluating the impact of different numbers of available buses on routing strategies.

The largely ignored mode of evacuation is the pedestrians. Mass pedestrian evacuation is a vital mode of escape during an emergency situation when the street and highway network is close to or at gridlock. Likewise, since most of the people are transit dependent for their travel to dense urban areas, the dependency on evacuation by foot also becomes vital when the transit systems are close to or at gridlock conditions or inoperative. Recognizing that pedestrian evacuation will be the first step and/or last resort when it comes to escape

from a sudden catastrophic event, transport agencies around the world are now working on the development of emergency plans for pedestrians (Ercolano 2008). Interestingly, much of the work on pedestrian evacuation is limited to indoor scenarios such as buildings, stadiums and transit station rather than urban transport networks. There has been development of microscopic and macroscopic models to understand pedestrian crowd behaviour in general and emergency situations (Shiwakoti et al. 2008, Shiwakoti et. al. 2011) but very little research has been conducted to model mass pedestrian evacuation in an urban network (Shiwakoti, 2006). Mass evacuation of pedestrians is believed to be faster than vehicular evacuation within a 2 km region (Ercolano, 2008); however more rigorous research is necessary.

Recent emphasis has been on multimodal emergency evacuation as multimodal evacuation is still largely missing in most emergency evacuation studies (Transportation Research Board, 2008). The focus has been mostly on the minimisation of evacuation travel time, network clearance time, total travel time and total waiting time. Abdelgawad et al. (2010) proposed a multimodal optimization framework combining vehicular traffic and mass transit for emergency evacuation. A prototype implementation of that conceptual framework for a hypothetical medium-size network in a downtown urban area in Canada showed that considering only the travel time in emergency evacuation significantly underestimates the waiting time of evacuees especially in the case of non-notice evacuation. Also, for mass transit, when considering fleet cost, an increase of 13% in network clearance time for transit evacuees was observed with a decrease of 12% in fleet size. A multimodal study by Thomas et al. (2010) calculated the evacuation time estimates for an evacuation of Washington, D.C. Various available travel modes, including the metro lines, under a no-notice emergency scenario were considered in the analysis. However very little detail was provided on the simulation or the parameters considered in the study. Instead, the focus was predominately on what evacuation modes would be used and who would use them. Naghawi & Wolshon (2012) conducted a simulation-based assessment of the performance of the multi-modal evacuation traffic network. The results showed that buses were able to increase the total number of people evacuated from the threat area. However, when buses were routed to heavily utilized freeways, it led to significant delays and congestion while the additional vehicles had minimal impact when routed exclusively to arterial evacuation routes.

Table 1 provides a summary of recent studies on emergency evacuation including the level of detail (micro, meso and macro), mode considered (auto, pedestrian, transit) along with features and findings. It is apparent that all observed models, in one way or another, contain some deficit of analysis and knowledge. Commonly, this is in the form of neglecting whole modes of evacuation with specialized focus on specific modes (methods) and representation (scope) as well as lacking realistic assumption of travel behaviour.

Table 1: Key summary statement of recent studies on emergency evacuation in urban networks.

Reference	Representation			Model(s)	Mode			Features	Findings
	Macro	Meso	Micro		Auto	Pedestrian	Transit		
Naghawi & Wolshon (2012)			×	CAEP	×		×	Trade-offs of routing options and effects of ordering evacuation with varying levels of urgency. Ability to add specific vehicles to routes.	Microsimulators can be used to identify where and when bottlenecks occur. Buses were able to increase the total number of people evacuated from the threat area while adding average queue length on some interstate freeway segments.
Abdelgawad et al (2010)		×		MDTCPD-VRP & OSTE	×		×	Optimal spatiotemporal evacuation (OSTE) formulation is presented for auto evacuees while a multiple-depot, time-constrained, pickup and delivery vehicle routing problem (MDTCPD-VRP) is proposed for transit vehicles.	Mass transit was shown to provide latent transportation capacity that is needed in evacuation situations.
Chan (2010)	×			SSCFLP			×	Two-stage model for carless evacuation including a location problem that aims at congregating the carless at specific locations and a routing problem with the objective to pick up the carless.	Giving priority to idle buses to visit evacuation sites over other buses performed better than sending idle buses directly to the closest available safe locations.
Wang et al. (2010)		×		TransCAD	×			Probable maximal flood case evacuation of riverside communities in Massachusetts. Evacuates people in a progressive order (order of affected). Using the four - step model together with altered inputs, an analysis is conducted to identify when and where the traffic problems will be the most severe	People can evacuate to shelters given 2 hours notice. The four-staged evacuation is able to represent the dynamic development of the flood (from where the dam breaks to where the flood reaches the downstream end of the inundation area) and generates reasonable results.
Sayyady (2010)		×		Dynasmart-P	×		×	Disaster plan using mixed-integer linear program is developed for transit-dependent citizens during no-notice disasters. Includes optimal evacuation routes with the objective to minimize the total evacuation time and the number of casualties.	Model can be used in process of planning for a disaster, or during disaster response. Can identify the number of public transit vehicles needed to evacuate all transit-dependent citizens as well as identify paths for vehicles that minimise the number of casualties, evacuation time; and maximise the vehicle utilisation.

Mastrogiannido et al. (2009)			×	VISTA			×	Assign vehicle(s) to pick-up points based on the shortest time criterion. They also study the impact of different numbers of available buses on routing strategies.	Successfully modelled transit evacuating from facilities in urban areas using the micro-simulation based integrated tool.
Klunder et al. (2009)	×			INDY	×			6 different evacuation strategies analysed specifically for flooding disaster in Randstad, West of the Netherlands.	Final strategy has substantially shorter evacuation times (44hrs) compared to the reference scenario. However, it is based solely on theoretical calculations with restrictive assumptions, not taking into account possible chaotic behaviour of the people, road blockages by incidents and bottlenecks outside the evacuation area.
Noh et al. (2009)		×		DynusT	×			Estimation process for short-notice evacuations. The method uses on-hand data models for trip generation, trip distribution, and travel time generation for these trips, considering a staged evacuation.	Merit in using existing metropolitan travel demand tools. Inferior to other methods that require more detailed data or more sophisticated modelling techniques where activity-based models could be used to help estimate demand in such short-notice disasters.
Ercolano (2008)		N/a		N/a		×		Summarises the latest state-of-the-art information and best practices for pedestrian disaster preparedness and emergency evacuation planning.	The paper analyses and gives recommendations for short, mid and long term management approaches, albeit neglecting other evacuation modes.
Liu et al. (2008)	×			GIS module		×	×	Terrorist attack emergency evacuation system for Washington, D.C. Accounts for critical issues associated with planning and real-time operations; including the integration of data from multiple sources, network decomposition, network-level traffic routing, contraflow design, staged evacuation and optimal signal timing.	GIS module allows operators to assess the impact of the emergency incident, specify preliminary control plans, identify TAZ-based evacuation demands, allocate evacuation routes, and revise the evacuation plans that have been implemented. Does not include optimal assignment of bus pickup points, emergency bus routing, pedestrian routing, travel time estimates for users.
Balarkrisna et al. (2008)		×		DynaMIT	×			No-notice event assessment with train response personnel and traffic management centre operators providing decision support and assistance. Incorporates unhindered access to first responders.	Addresses contraflow, signal priority and staged release of evacuation demand. Future work to demonstrate its ability to interface with surveillance and incident detection systems.

Chen & Zhan (2008)		×	Paramics	×		Inability to model individual vehicle movements by network flow models is taken into account dynamically through Agent Based Modelling (ABM) to build group behaviour. Examines simultaneous and staged evacuation strategies by ABM using node-link networks.	Employs agent-based simulations to show, for conditions employed, that staged evacuation had no advantage over simultaneous evacuation except for a theoretical high-density population grid network.
Elmitiny et al. (2007)		×	VISSIM		×	×	Assessments of surrounding traffic network, traffic diversion, bus signal optimisation, access restriction and multi-destinations.	Number of buses used had equal clearance time, despite affecting overall network. Peak-hour traffic best evacuated by pedestrians. ITS technologies may greatly support traffic management in an emergency situation.
Murray-Tuite (2007)	×		DYNASMART	×			Post impact emergency evacuation for a terrorist attack - mathematically modelling how households react to the evacuation conditions, and describes how a terrorist may select links to target. Includes unanticipated activity behaviours of evacuees that delay or even head into danger to collect household members.	Incorporating household activity chains in an evacuation leads to different traffic patterns from those during peak conditions. The most important evacuation link with multiple exit route options is not necessarily one of the roads leading out of the network; however the most important link may be one that leads to a location where family members without vehicles are.
Williams et al. (2007)		×	CORSIM	×			Lane reversal plan for Interstate 40 to facilitate hurricane evacuation of residents and tourists in south-eastern North Carolina	Utility of simulation modelling in examining the viability of transportation systems using I-40 lane reversal was quantified although, vigorous research is needed in evacuee behaviour.
Mitchell & Radwan (2006)		×	INTEGRATION	×			Generic test with regression model with an input/output (I/O) analysis performed to establish a theoretical baseline clearance time estimate (CTE).	Analysis showed that the I/O method underestimated simulated CTE as a function of network size, with a correction factor range of 1.09 to 1.19. Needs further research.
Shiwakoti (2006)		x	n/a		x		Mass evacuation of pedestrians is explored via micro simulation in a small hypothetical urban network.	Increase in population, blockage of certain links in the network, increase in desired speed of pedestrians were found to be significantly affecting the total evacuation time.

Han & Yuan (2005)		×	VISSIM	×		Nuclear accident evacuation using dynamic traffic assignment (DTA) in a no-notice scenario including most desirable destinations (MDD) in a transient traffic network.	58% reduction in overall evacuation time was achieved when DTA and MDD were implemented. Detailed the steps involved in preparing necessary data for the proper representation of the transportation network.
Wolshon et al. (2005)	×		DYNEV	×	×	Command and control strategies, types of evacuations used, implementation and enforcement criteria, methods of building public awareness, evacuation of low mobility and special needs groups, and use of public transit for hurricane evacuation.	Contraflow freeways deemed effective for hurricane evacuations, however it poses challenges to supervising agencies and evacuating drivers. Many of the findings are applicable to multi-hazard evacuation planning.
Kwon & Pitt (2005)	×		Dynasmart-P	×		Evaluating effectiveness of alternative strategies for evacuating traffic in a large urban network downtown Minneapolis, under hypothetical emergency situations.	Managing traffic conditions at the outbound freeway links during the evacuation period and the access capacity from the downtown area to those outbound freeway links are the critical factors affecting the evacuation operations.
Jha et al. (2004)		×	MITISLab	×		Laboratory-like setup evaluates the Los Alamos National Laboratory with diverse scenarios including no evacuation. Includes full/partial closures of various roads, limited access to some special facilities, and security delays at specific locations.	Total time to achieve a complete and partial evacuation in which the population within certain areas is at risk, and the percentage of the population in affected zones as a function of time was developed.
Cova & Johnson (2003)		×	PARAMICS	×		Optimal lane-based routings plans in a complex network used to generate routing plans that trade vehicle travel-distance against merging, while preventing crossing-conflicts at intersections.	Channelling flows at intersections to remove crossing-conflicts decreases network clearing time by 40% over the no-routing plan; however the study implements unrealistic assumptions.

3. Discussion and Conclusions

Emergency evacuation in urban network has been widely investigated in the literature considering both notice and non-notice natural and man-made disasters. Diverse issues have been explored such as traffic network optimization, demand management, evacuee behaviour, mode of transport, multiple objectives, spatial and temporal distribution of evacuee to highlight a few. Nevertheless, recent emphasis has been on capturing the demand and supply dynamics during emergencies, utilizing the available modes and modelling/formulating multiple objectives to create a framework that could simultaneously optimize the multi-objective multimodal evacuation process. As experimentation in a real system is very costly, simulation models have proved to very helpful and insightful.

The limitations of static assignment models have prompted researchers to use dynamic traffic assignment models to evaluate evacuation strategies. Some of the relevant strategies in the planning for emergency evacuation has been evacuation scheduling (simultaneous and staged evacuation), destination choice (predetermined destination, relaxing predetermined destination), traffic routing and control strategies (user equilibrium, system optimum, multiple users class assignment). The challenge is in synergising all or some of these strategies to improve the efficiency of the evacuation process. Moreover, with public transit evacuation, insight on the relationship between the rate of passengers arriving at stations and the transit capacity need to be explored in greater detail. Examining the potential service breakdown would provide valuable information on the reliability of the transit based evacuation. Also some of the common assumptions such as the evacuees being present at the pick-up locations as soon as the evacuation begins, buses operating in a fixed route mode is unrealistic in a real-world scenario suggesting the need for a real-world case study.

One of the modes that has been greatly neglected is the pedestrian. As mass pedestrian evacuation is a vital mode of escape, especially within a few kilometres, there is need for robust quantitative models that can predict the behaviour of pedestrians in an urban network. Although the long term planning (streetscape design, sidewalk/crosswalk capacity, regulations etc.) is important, proper understanding of mass pedestrian evacuation at operational level is vital to develop design solutions in the longer term. Nevertheless, the increasing research in past decades on understanding crowd behaviour during emergency evacuation in confined spaces such as buildings, stadiums, stations is a positive step in this direction. This is also relevant to multimodal evacuation as travel behaviour during an emergency situation is not well represented or assumed realistically in model formulation. To assess the suitability of these behavioural assumptions, it is important to acknowledge the findings from the multidisciplinary literature on crowd behaviour where many studies have acknowledged that people react according to how they perceive the situation. Rather than telling people what to do, it is imperative to look at what people actually do and plan for that. Having said that, it is also important to consider people who are disabled, hospitalised, institutionalised, homeless, in nursing homes, child day care, senior centres etc. leading to the need for public transit based evacuation including bus and rail. Robust tools for understanding multimodal urban network evacuation is thus vital.

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