PLANNING FOR EMERGENCY EVACUATION: ARE LARGE CANADIAN CITIES READY?

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Abstract

This paper addresses the essential elements and strategies that should be in place for large-scale evacuations under emergency situations, particularly in densely used networks such as in Toronto, Ottawa, Vancouver and Montreal to name a few. Some questions that possess some indispensable information to achieve that goal are proposed. A novel framework that addresses these questions is proposed and applied to evacuate the entire City of Toronto as a case study.

A large-scale evacuation model is developed for the evacuation of the City of Toronto in cases of emergency. A demand estimation model is first designed to accurately quantify the evacuation demand by ***mode*** (drivers vs. transit users), over ***time*** of the day when the crisis begins and over ***space*** (location). The output of the demand estimation model is then fed into two optimization platforms; (1) an Optimal Spatio-Temporal Evacuation (OSTE) model that synergizes evacuation scheduling, route choice, and destination choice for vehicular traffic; and (2) a model based on a new variant of the Vehicle Routing Problem (VRP) to optimize the routing and scheduling of mass transit vehicles. The study concluded that OSTE can clear the City of Toronto *four* times faster than the do-nothing strategy.

Introduction and Background

Canada's history of man-made disasters and natural threats mimics that of the United States but as a distorted reflection. While emergency evacuation and management systems in Canada have not experienced the frequency or the severity of the United States events, emergency management in Canada has drawn significant experience from the events and developments in the United States emergency management systems.

To date, ***Flooding*** has been the most expensive hazard in terms of property damage in Canada. Spring thaw can cause severe flooding; for example, the 1997 Red River flood in Manitoba resulted in huge losses that are estimated to be $815 million. ***Transportation accidents*** have been significant in Canada; for example, the ***Halifax explosion*** in 1917 has led to launching the first initiative for academic research in disaster management. It was also considered the largest loss of life (estimated 1960 deaths) in a single event in Canada. Fortunately, Canada has been spared the large scale acts of ***terrorism*** that has been recently experienced by other countries. Nevertheless, Canada experiences some acts of violence such as the 1989 killing of 14 women at École Polytechnique in Montreal. Also, the most significant event that shaped the development of Canada's emergency management plans was the FLQ kidnappings in 1970 (Lindsay, 2009).

The following paragraphs chart the events that are somewhat relevant to planning for emergency evacuation from a transportation perspective and to the extent possible shed the light on the lessons learned from them.

In 1954, ***Hurricane Hazel*** blew up from the Caribbean, crossed North Carolina, went through Washington DC and New York State, and then the storm is intensified to hit the Toronto area bringing 110 kph of winds and 285 millimeters of rains. The management system was limited in responding to this storm and the Humber River flooded resulting in 30 deaths and 14 homes on Raymore Drive were washed away, this brought the total losses to 81 lives and a damage that was estimated to be $ 1 billion.

In 1979, a huge explosion is caused by a ***Train Derailment in Mississauga***, Ontario. Most of the train cars were carrying hazardous material that could be a potential for a toxic cloud of chlorine, a thread that led officials of the city to order the largest *peacetime* evacuation in Canada. Despite that 225,000 people were evacuated the city while there were no deaths; this event resulted in renewed interest in proper planning for emergency evacuation.

In 1998, an ***Ice Storm*** struck Ontario causing significant losses in people lives and the nation capital. The death of 28 people, the chaos of 600,000 evacuees, and the declaration of over 250 communicates a state of emergency made it the Canada's largest disaster.

In 2005, the Atlantic coast of the Unites States was hit by ***Hurricanes Katrina*** and ***Rita***. In hurricane Katrina, out of the 1.4 million inhabitants in the hazard areas, 200,000 to 300,000 people did not have access to reliable personal transportation. In hurricane Rita an estimated 3 million people evacuated the Taxes coast, creating 100-mile-long traffic jams. After some drivers crawled 30 miles in severe congestion, some drivers decided to return back home (Litman, 2006). Numerous lessons were learned from the consequences of these two hurricanes; most notably is the poorly integrated public transportation services in Katrina and the lack of communication and the excessive dependence on automobile evacuation in Rita.

Motivation

Developing proper regional evacuation plans is paramount for public safety in the case of man-made disasters and natural disaster threats. However, planning for emergency evacuation in densely populated cities is challenging. The main objective is to move people from potential hazard zones to safe destinations in the quickest and most efficient way. Given the drastic consequences of large-scale emergencies, proper development of emergency evacuation plans is essential. Also, given the typical diverse demographic characteristics of most communities, an efficient evacuation strategy should integrate multiple modes to particularly aid transit-dependent people who have no access to automobiles at the time of evacuation or at all.

Numerous notable emergency evacuation planning models have been developed over the past few decades. They propose and investigate the effect of one or more strategies that have the potential to improve the performance of the evacuation process. Approaches in the literature use various modeling and optimization techniques. However, these studies are typically focused on automobile-based evacuation using a certain strategy (e.g. evacuation scheduling) without considering other modes of transportation or attempting to simultaneously synergize several other possible strategies such as destination choice optimization, route selection optimization etc. In addition, the absence of accurate representation of the spatio-temporal distribution of the population makes estimating evacuation demand difficult and hence renders the interpretation and the conclusions of the methods themselves questionable. Furthermore, the lack of quantifying mode-specific populations (e.g. transit-dependent) magnifies the vulnerability of those people to threats in cases of large-scale emergencies, a major drawback of existing planning models.

Building on the lessons learned from the previous disasters/threats and the published articles in the field of emergency evacuation planning and modeling, this paper is geared toward proposing few indispensable questions (milestones) for proper planning and modeling of emergency evacuation of large cities such as Toronto, Vancouver, Ottawa, to name a few. To address the proposed questions, we introduce our integrated framework for multimodal evacuation of large-scale evacuation.

Are Large Cities Ready for Emergency Evacuating Planning?

Although planning for emergency evacuation accentuates the consideration of policy oriented issues such as coordination across jurisdictions, public awareness, evacuation type, education/involvement of the transportation engineering community, interagency communication and data sharing (Wolshon *et al.*, 2005); the discussion in this paper is geared toward the modeling side of the problem, i.e. the authors make no attempt to address all the policy oriented question, but rather provide set of tools and modeling procedures that can help decision makers addressing most of these issues.

To illustrate the essential requirements for modeling and planning of large-scale regional evacuation scenarios, the following discussion is structured in a *question* format; each question forms a building block in the presented framework (described in the next section) in which these questions will be addressed.

- Question 1: Are there accurate assessment and representation of the transportation infrastructure, especially for the roadway and public transit network (i.e. transportation supply)?
- Question 2: Is there an accurate estimation of the spatial and temporal distributions of the population (i.e. transportation demand)?
- Question 3: Is there an accurate identification of the available modes and captive population to certain modes?
- Question 4: Is there an integrated framework that simultaneously considers various evacuation strategies (such as evacuee scheduling, route choice and destination choice)?
- Question 5: Is there a multimodal evacuation strategy that synergizes the effect of multiple modes?
- Question 6: Is there an accurate representation for the background traffic or noncompliant evacuees (i.e., the percentage of travelers not following the evacuation plan)?

While the aforementioned questions constitute separate modeling, analysis, optimization and operational tasks, they are closely interrelated. Each is indispensable for the design and implementation of an effective emergency evacuation plan. The remainder of the paper is geared to address these questions in one framework that is structured to plan for realistic large-scale multimodal emergency evacuations.

Emergency Evacuation Planning Framework

The presented framework is designed to account for the former proposed questions. A demand estimation model is designed to accurately quantify the evacuation demand by ***mode*** (drivers vs. transit users), over ***time*** of the day when the crisis begins and over ***space*** (location). The output of the demand estimation model is then fed into two optimization platforms; (1) an Optimal Spatio-Temporal Evacuation (OSTE) model that integrates and synergizes evacuation scheduling, route choice, and destination choice for vehicular traffic (Abdelgawad and Abdulhai, 2009; Abdelgawad *et al.*, 2010); and (2) a model based on a new variant of the Vehicle Routing Problem (Multiple Depots, Time Constraints Pick and Delivery VRP, MDTCPD-VRP) to optimize the routing and scheduling of mass transit vehicles (Abdelgawad *et al.*, 2010; Abdelgawad *et al.*, 2010). The presented framework integrates the two modules, OSTE and the MDTCPD-VRP. OSTE is achieved through optimizing the evacuation scheduling problem and the destination choice problem simultaneously in a Dynamic Traffic Assignment (DTA) environment while solving the optimization problem using Evolutionary Algorithms (EA). The MDTCPD-VRP is formulated with additional supply, demand, and time constraints to better mimic the evacuation situation; therefore, constraint programming (CP) and neighborhood search techniques are simultaneously used to solve a constraint satisfaction problem (CSP) and an optimization problem. The presented emergency evacuation planning model is coupled with 1) accurate representation for the transportation supply and 2) accurate estimation of the transportation demand.

The overall system attempts to optimize the use of multiple modes during emergency evacuation. Figure 1 illustrates the steps toward achieving this goal by utilizing both OSTE and MDTCPD-VRP in one platform. We start by estimating the evacuation demand using a regional demand survey (e.g. TTS) and a representation for the traffic analysis zones. The output of which is an accurate representation of the spatial and temporal distribution of population and their modes of travel. We then generate OSTE plans for the vehicular demand using genetic algorithms as a global optimization technique and a dynamic traffic assignment tool. OSTE generates optimal evacuation schedule, optimal destination choices if requested and optimal routes to destinations. It also produces link travel times that are used as input for the optimal routing and scheduling of transit vehicles. The routing and scheduling problem of transit vehicles is then solved using constraint programming. The auto OSTE plan and the transit optimal routing and scheduling plan are finally combined for dissemination to evacuees. It is to be noted that currently we do not loop back from the transit assignment component to the traffic assignment component, a potentially worthy step that we defer to future research. However, while extracting the travel times from the DTA model to form the input to the MDTCPD-VRP, the most congested travel times are used as a worst case for buses while travelling through the network. Although it might overestimate the travel times for buses, but it may compensate for the uncertainty of travel times for such heavily utilized transit vehicles; i.e. if the process errs it does that on the conservative side. The next section describes a large-scale implementation of the presented approach to evacuate the entire City of Toronto, Canada.

Large-Scale Application: Evacuation of the City of Toronto

In this section we demonstrate the application of the presented framework to optimally evacuate the entire city of Toronto in case of emergency. The City of Toronto is a typical example of fairly large North American cities with a population of 2.37 million. The City of Toronto is located in the center of the Greater Toronto Area (GTA) as illustrated in Figure 2.

Evacuation Demand Estimation: The output of the demand estimation method is the temporal distribution for the total number of people in the City of Toronto for a 24 hour clock (400-2800) that starts at 4 AM on the trip day to 4 AM the next day (DMG, 2003). Three groups of people are considered in case of emergency evacuation: people who commute with the *Drive* mode, people who commute with the *NonDrive* mode, and people *Resident* at home. In total, the number of people in Toronto peaks at 108% of the City's population (residents at 4:00 AM). This increase is attributed to the high concentration of economic activities in the City of Toronto and particularly the business and financial district. The peak demand is found to be 2.56 M people and occurs at the 11:30 AM- Noon interval, which constitutes the worst case scenario for evacuating City of Toronto.

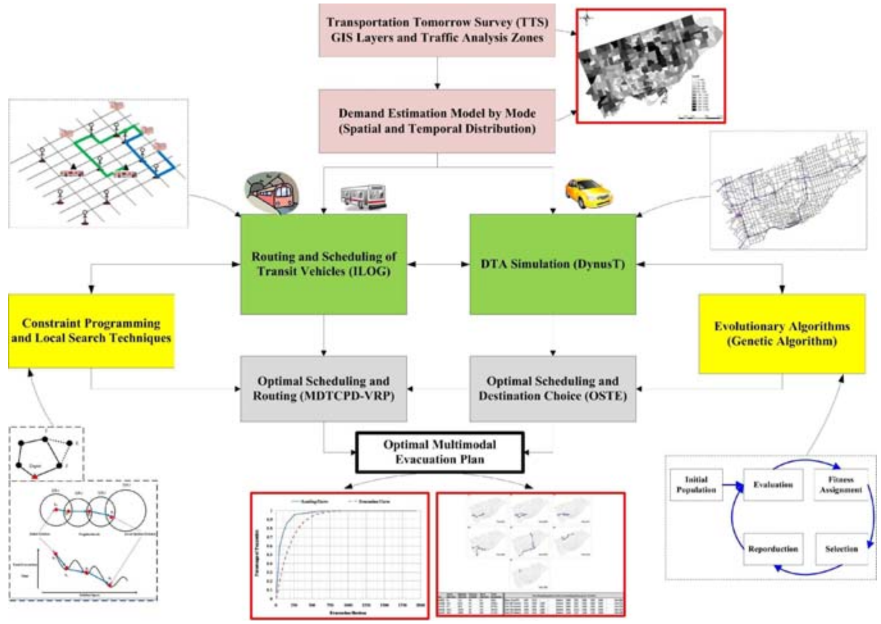

Figure 1 Framework for Optimization of Multimodal Evacuation

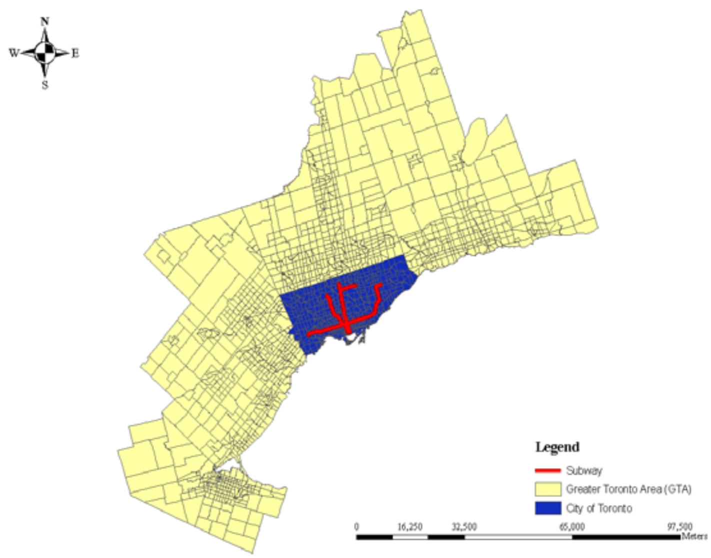

Figure 2 The GTA and City of Toronto Traffic Analysis Zones

In case of evacuation, it may be harder to persuade drivers to abandon their cars and take any other mode. Also transit users and non-drivers are captive to transit modes because their choices are limited. Therefore, it seems practical to assume that evacuees will use the same mode of transport while commuting to City of Toronto. This resulted in 1,216,886 evacuations trips by auto and 1,344,942 evacuations trips by transit. The auto trips form the input origin-destination matrix to the simulation-based DTA model; while the transit trips are distributed between buses and subway as they are the predominant mode for transit-captive travelers.

Representation of Noncompliant Traffic: To the best of the author's knowledge and based on the literature, evacuees' compliance to guidance is rarely modeled or reported. Although it is challenging to model evacuees' behavior, stated-preference surveys and post analysis surveys for certain evacuation scenarios may be plausible avenues to model such behavior. In the absence of past evacuation surveys in Ontario and in Toronto, we assumed that 25% of evacuees will not comply with the provided guidance and will seek their homes first. This assumed percentage has no scientific basis. It is only for illustration purposes until a better behavioral approach is available.

OSTE, Traffic Assignment Outputs: The output of the genetic optimization process (the optimal scheduling vector) is evaluated using the traffic assignment model. The mesoscopic representation of the traffic assignment simulation model provide sufficient details for the analysis of departure time, destination choice (shelters), and routing plan for each vehicle. The optimal loading and evacuation curves are extracted as shown in Figure 3.

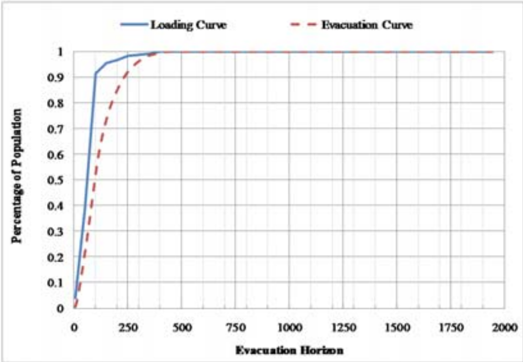

Figure 3 Optimal Loading and Evacuation Curves

Optimal Routing and Scheduling of Transit: The model generates the optimal routing and time table for each bus as it shuttles between pick-up points and nearest shelters. It is to be noted that buses are initially assigned to pickup points according to their location at the onset of the evacuation. After the initial pickup, buses shuttle to the nearest shelter then back into the system but not necessarily to the same pickup points. This means that each bus seeks the *best* pick-up point in order to achieve certain *objective function*. As shown in Figure 4 shuttle buses loop between the *optimal* pick-up points and *optimal* safe shelters until all the demand is exhausted and finally head back to safe shelters

Summary, Conclusions, and Future Directions

In this paper six questions were proposed that demonstrate the readiness of city planners and officials to plan for emergency evacuation. In case the answers for all the proposed questions are *yes*, then proper and realistic emergency evacuation plans can be designed; and hence provide meaningful results that can be potentially implemented or tested in case of emergency situations. While unavailability of data, lack of modeling rigorousness, and lack of information about transportation modes are sometimes unavoidable, the planner/modeler has to make some assumptions to overcome these limitations. The sensitivity and effectiveness of the plan to the assumed information varies greatly because of the multi-dimension nature of the problem. Therefore, special attention is required while modeling and planning for emergency evacuation situations due to its uniqueness compared to the traditional transportation planning models. To demonstrate how these questions and elements could be amalgamated in one framework, an integrated multimodal evacuation plan is presented. The framework is applied to evacuate the entire City of Toronto in case of a hypothetical evacuation scenario.

The results are found very encouraging in terms of system performance. One potentially critical dimension that needs further research is user equity, which may also have a direct bearing on compliance. Since evacuation scheduling, particularly for auto-based evacuation, implies holding back some evacuees and releasing others, the question remains who to let go first. Finally, further investigation is required to assess evacuee's potential compliance to the given recommendations. We defer researching these issues to a later stage when we can closely examine evacuees' behavior in general. Behavior can be potentially assessed via analyzing evacuees' behavior under past real evacuation scenarios, via stated preference surveys or through mix-reality simulations, exposing actual subjects to simulated evacuations in a virtual environment and watch their behavior.

Figure 4 Example of Routing and Scheduling for Transit Vehicle

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