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An Integrated Approach to Earthquake Evacuation Modeling: Incorporating Risk Analysis and Stochastic Route Choice Effects

Umma Tamima[1]
Luc Chouinard[2]

Abstract: Emergency response for an earthquake disaster occurring in a metropolitan area is extremely challenging due to the co-existence of multi-priority groups in a network. There is a necessity of quick arrival of some priority evacuees to safe zones and prioritized routing treatment for these evacuees. This study develops a scenario based stochastic route choice model of emergency vehicles to assess the performance of transportation network for post-earthquake emergency situation. The model calculates travel time for each evacuee to reach desired destination based on stochastic user equilibrium based principle. A scaled multinomial logit model is applied to estimate the probability of choosing emergency routes by multi-priority emergency vehicles. This study also compares the computed travel time between deterministic user equilibrium based model and stochastic user equilibrium based model. In this model, origin-destination demand of emergency vehicles is loaded to determined route of a transportation network to estimate travel time. HAZUS Canada 2.1 is applied to estimate the origin-destination demand of evacuation vehicles. Oak Ridge Evacuation Modeling System (OREMS) is used to estimate travel time for deterministic user equilibrium based model. The method is demonstrated with downtown Montreal road network. The results shows that evacuation time for downtown Montreal is 55 min for all evacuation vehicles and major parts of Sherbrooke Street have worst speed (<30Km/hr) in the network. Stochastic Route Choice Model identifies links with critical volume for priority evacuees (ambulances, fire trucks etc.). The study provides valuable insights for first responders of earthquake disaster to take necessary actions for efficient evacuation in a metropolitan area.

Key words: Earthquake Evacuation, stochastic route choice model, scaled multinomial logit model, HAZUS Canada 2.1, OREMS.

1. INTRODUCTION

Emergency evacuation for earthquake disaster in urban areas is challenging due to the uncertainty associated with estimating emergency traffic demand and co-existence of multi-priority group in the transportation network. The area-wide traffic demand, after an earthquake, is different than the traffic in normal condition. Damaged building and critical facilities, time of earthquake such as day and night time, weather condition, ethnic distribution influence the traffic demand after an earthquake.

The evacuees and emergency vehicles (i.e. ambulance, fire trucks etc.) generate additional trips aftermath an earthquake disaster. For example, some evacuees want to leave the Emergency Planning Zone (EPZ), while emergency vehicles try to reach to affected areas quickly. The complexity of

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[1] PhD Student, Department of Civil Engineering and Applied Mechanics
McGill University, Montreal, Quebec, Canada

[2] Associate Professor
Department of Civil Engineering and Applied Mechanics
McGill University, Montreal, Quebec, Canada

simultaneous mobilization of these multi-priority groups is aggravated when all of these emergency traffic flows interact with existing traffic at the urban road network with limited capacity and redundancy. One group can not devise a mobilization strategy without interacting with other groups (Chiu and Zheng, 2006). Interaction of emergency traffic with regular traffic, during simultaneous mobilization, may cause traffic delay of emergency response vehicles. This may result in the amplification of evacuation related casualties and property damage.

A mobilization strategy for evacuation traffic is essential in order to ensure an efficient earthquake evacuation planning. However, it is critical to ensure ingress and egress of emergency response vehicles and to manage queues and delays (Chang et al. 2012). The prioritized-routing treatment or segregation of emergency vehicles can contribute to the reduction of evacuation delay. This can minimize the evacuation related casualties and property damage.

The objective of this paper is to develop a scenario-based stochastic route choice model of emergency vehicles to assess the performance of transportation network after an earthquake event. This paper is organized as follows. Section 2 discusses on the related works and relevant models of emergency evacuation. Section 3 formulates a methodology to model route choice of emergency vehicles or High Priority Vehicles (HPV). Section 4 and 5 describes the numerical example and results obtained from stochastic route choice model, followed by concluding remarks.

2. LITERATURE REVIEW

The conventional evacuation studies mainly focus on estimation of evacuation time, network performance during or after the disaster events and impact of evacuation strategy on road network. Southworth (1991) defines regional evacuation modeling as a five step-process, similar to the four-step urban transportation modeling system (Meyer and Miller, 1984; Cova and Johnson, 2002). The simulation of emergency traffic is the first step of evacuation modeling. Oak Ridge Evacuation Modeling System (OREMS), DYSNEV, MASSVAC, NETSIM, CLEAR, Paramics, SLAM II, DYNAMART-X, MATSim, MCEVEC, cell transmission model are frequently applied by evacuation planner for simulating emergency traffics as it is difficult to count the emergency traffic during or after the disaster events (Cova and Johnson, 2002; Pal et al., 2002; Song et al., 2010; Zhao et al., 2012).

OREMS is used for a number of evacuation studies to calculate and evaluate evacuation times, to develop traffic management and control strategies, bottlenecks and to determine best route choice (ORNL, 1991; Pal et al., 2003; Chiu and Zheng, 2007; Song et al., 2010). OREMS is based on the principle of System Optimal (SO) and can be applied for a variety of disasters. Some recent dynamic traffic assignment (DTA) based traffic estimation and prediction models such as DYNASMART-X, ATIS/ATMS (Mahmassani, 2001; Hawas, 2000) or DynaMIT (Ben-Akiva et al., 2010) have the potential to be utilized for the real-time emergency response. These models have the capability of dynamic network modeling (Chiu and Zheng, 2007). Cell transmission is used to obtain the actual travel time at each time-interval (Zhao et al., 2012).

Edara and others (2010) apply the VISSIM model to estimate total evacuation time and evaluate the traffic performance during emergency period. Chang (2010) applies Deterministic User Equilibrium (DUE) and Dynamic Traffic Assignment (DTA) models to calculate the travel cost for delay and traffic congestion after the occurrence of an earthquake. The same study uses the integrated simulation models to analyze the travel demand because of infrastructure damage.

A good number of studies deal with route choice behavior of evacuees and its impact on evacuation time estimates (Chiu and Zheng 2007; Chang et al. 2012; Xing et al. 2012; Fang and Edara, 2013;) Although many evacuation studies apply Deterministic User Equilibrium (DUE) principal for route choice model (Sheffi et al. 1980, Sherali et al. 1991, Franzese and Han 2001) the principal is criticized due to the assumptions of perfect knowledge of network travel times and inability to know all possible routes in the network. Stochastic user equilibrium (SUE) model is used for evacuation study because it can simulate optimal egress problem during the earthquake (Talebi and Smith, 1985).

SUE model assumes that the utility function of route-choice, the generalized cost of each path, is stochastically distributed. Probabilities of route choice are calculated with scaled multinomial logit model. This study also integrates trip generation, mode choice and route choice model forming a nested multinomial logit model.

3. METHODOLOGY

Evacuation modeling of earthquake is a five step process - traffic simulation after an earthquake event; O-D matrix modification; trip distribution; mode choice and route choice. Trip generation step includes traffic simulation and O-D matrix formulation or modification. One of the challenges, associated with earthquake modeling, is trip generation phase. Trip generation depends on number of variables such as magnitude of earthquake, local site effect, depth of hypocenter, distance of earthquake epicenter, building density and building code, spatial variation of population, weather condition and so on. The following section describes the methodology to model earthquake evacuation.

3.1 Earthquake scenario

The study develops a scenario-based methodology to model earthquake evacuation. A hypothetical earthquake is chosen for the study area of Montreal to estimate building damage, people require shelters, casualty, number of fire trucks and ambulance. For this study; a hypothetical earthquake of magnitude 7.0Mw; location (X, Y) 45.521429, -73.56481; hypocentral depth 10km is chosen. Ground Motion Prediction Equations (GPMEs) has significant impact on damage estimates. Atkinson and Boore (2006) or AB06 attenuation function is chosen because is it one of the most robust attenuation relationships among three GPMEs, that is AB95, AB06, AB08 (Atkinson, 2008).

Site condition significantly affects the amplitude of ground motion (Yu, 2011). The inclusion of soil amplification factor, based on Vs30 (Shear Wave Velocity of first 30m soil), in the attenuation function is important to estimate the ground motion parameters such as; Pga, Pgv, Sa (0.3s) and Sa (1.0s). A microzonation map of Montreal developed by Chouinard and Rosset (2011) is used to estimate ground motion. Potential Earth Science Hazard (PESH) data, building data and demographics data are collected from McGill University researchers, Ville de Montreal and Census Canada. This study applies HAZUS Canada 2.1 to estimate damage, total number of evacuees and number of emergency vehicles.

3.2 Trip generation and trip distribution

HAZUS Canada 2.1 provides output for each census tract of the study area. One of the assumptions of this study is that earthquake will hit during winter season and evacuees will be evacuated by car. Mass transit ride during evacuation is converted to Passenger Car Unit (PCU) to estimate trip generation, although one third of the Montreal households do not have car at all (STM, 2012). Another constrain of this model is to determine the evacuation time. The prediction of evacuation time, by the evacuees, is uncertain as the earthquake is a no-notice disaster. For the simplicity, this model assumes the evacuees will evacuate right after the earthquake hit due to the fare of aftershock and power outage.

Origin-destination (O-D) matrix after disaster is an essential input for this study. Shinozuka et al. (2005) estimate the post-earthquake demand matrix by modifying the pre-earthquake OD data. Nojima and Sugito (2000) propose Modified Incremental Assignment Method to obtain the post-earthquake O-D matrix (Chang et al. 2012). This study modifies pre-earthquake O-D data by adding up the number of evacuees and High Priority Vehicles (HPV).

This study applies the Gravity model to estimate the trip distribution by evacuees and HPV among the selected emergency zones. Trips are assumed to be attracted to the zone where shelters and hospitals are located. On the other hand, trips are generated from the zones having fire stations and damaged buildings.

3.3 Mode choice and route choice

For this study three types of modes are considered i.e. car, fire trucks and ambulances. Trip assignment or route choice is widely used approach to model traffic flow over the road networks. System Optimal based principle is applied to estimate network travel time after earthquake that is considered as a base case and compared with Stochastic User Equilibrium (SUE) based model.

The levels of decisions are considered in the evacuation model: trip generation, mode choice and route choice. These three models are linked to each other by the composite cost forming the nested multinomial logit model. For each one of these levels, the model estimates disutilities, and these in turn, form the basis for the calculation of probabilities. Probabilities are calculated with scaled multinomial logit models. The probability that trip makers of category *s* choose path *p* when travelling from *i* to *j* by mode *k* is given by the Equation 1.

[1] $$P_{ijp}^{ks} = \frac{\exp(-\gamma^{s} c_{ijp}^{ks})}{\sum_{p} \exp(-\gamma^{s} c_{ijp}^{ks})}$$

c_{ijp}^{ks} is the scaled and overlapped generalized cost of travel, and γ^s is the dispersion parameter in the logit path choice model. If c_{ijp}^{ks} represents the resulting overlapped generalized cost of each path, as described above, then the scaled disutility of a path can be expressed by Equation 2.

[2] $$c_{ijp}^{ks} = \frac{c_{ijp}^{ks}}{(\min_{p}(c_{ijp}^{ks}))^{\theta_{s}}}$$

Where θ_s sets the degree of scaling in the utility function. The composite travel disutility c_{ijp}^{ks} ~ from *i* to *j* by mode *k* to trip makers of category *s* is estimated by aggregating over all paths in Equation 3.

[3] $$c_{ijj}^{ks} = -\frac{\ln pg^{ks}}{\gamma^{k}} \left(\min_{p}\left(c_{ijp}^{ks}\right)\right)^{\theta_{s}}$$

Where Pg^{ks} is defined as a series in Equation 4.

[4] $$pg_{ks} = \sum_{p} G_{p} \prod_{h=1}^{p-1} \left(1 - G_{h}\right)$$

where function *Gp* is the numerator of the logit model of equation 1.

[5] $$G_{p} = \exp\left(-\gamma^{s} c_{ijk}^{ks}\right)$$

TRANUS software is used to estimate the emergency traffic flow. It is also possible to assign weight of various operators i.e. fire trucks and ambulances by assigning monetary value of time. Another field of scaled logit model is travel cost in terms of money, the value is null for evacuation model as no operator consider travel cost during emergency.

4. NUMERICAL EXAMPLE: MONTREAL

Montréal Island is located in the Western Québec Zone, which experienced at least three significant earthquakes since 1732. According to Natural Resource Canada, 1732-earthquake (magnitude 5.8) caused destruction of 300 houses and 185 dwellings in Montréal because of aftershock fire. Furthermore, based on population, structure, infrastructure and regional seismic hazard, Montréal is ranked as the second for seismic risk after Vancouver in Canada (Chouinard and Rosset 2007). Downtown Montreal is highly vulnerable for earthquake disaster because of the high density of population and building. Transporting refugees to shelters is a challenge for Montreal Island due to extra traffic flow during earthquake emergency and distance from origin to shelters (Tamima and Chouinard, 2012). This study considers four municipalities (Ville Marie, Plateau, Westmont and Outremont) of Montreal for estimating evacuation time and level of service of road network in case of emergency. The input data required for network performance evaluation are: geometric characteristics of road network, capacity, volume, O-D data, location of structures such as; hospitals, shelters, fire stations.

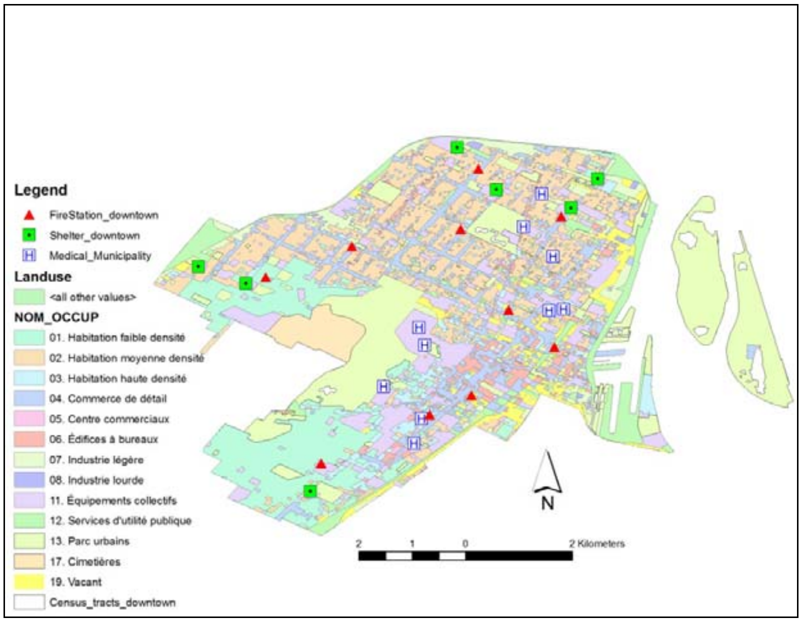


Fig.1: Emergency facilities and land use of Montreal (downtown and its surroundings)

5. RESULTS

5.1 Trip generation from Emergency Planning Zones (EPZs)

HAZUS Canada 2.1, risk assessment software, estimates the trip generation. Trips generate from vulnerable zones such as moderate or high building damages, fire exposed zones, hospitals and fire stations. Total number of vehicular trips is 9579 and hospital traffic constitutes less than 1%. HAZUS Canada 2.1 estimates 29 ignition points and to suppress fire at the ignition points, Montreal city requires 150 trucks.

5.2 Evacuation time and network performance evaluation

Evacuation time for the study area is estimated based on System Optimal principle. OREMS software is applied to estimate evacuation time after the earthquake. Evacuation time for downtown Montreal is 69 minutes for all evacuation vehicles and major part of Sherbrooke Street has worst speed (<30Km/hr) in the network. The percentile distribution of evacuation time, calculated by OREMS, explains that 50% evacuees and emergency vehicles need 25 minutes to travel the desired destinations. A total 40 minutes travel-time is required by 75% evacuees and emergency vehicles, while 55 minutes travel-time is required by 95% of the same vehicle groups (Fig. 3).

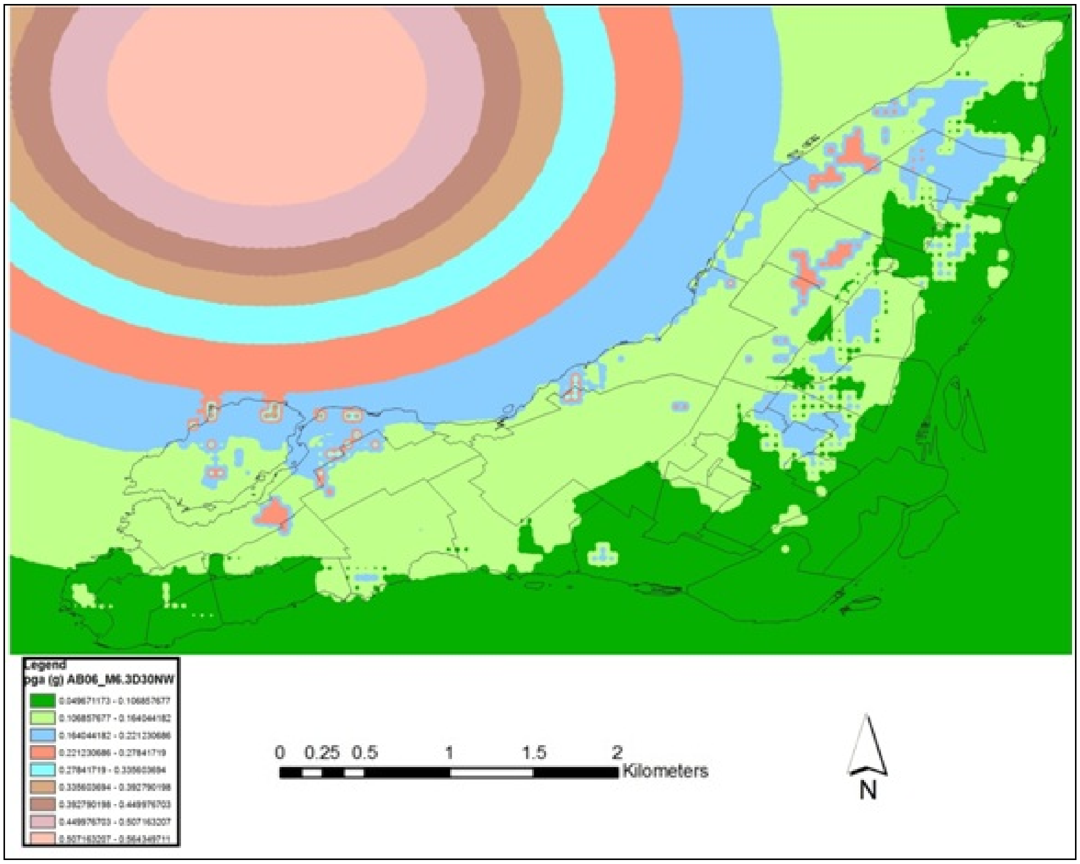
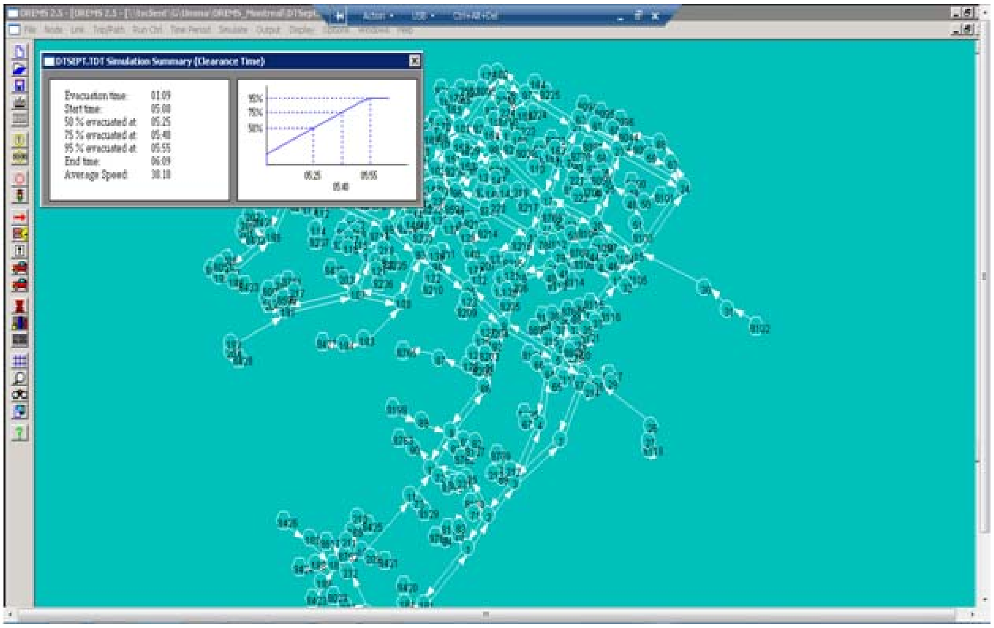


Fig. 2: Peak Ground Acceleration Map (Mw 6.3NW)



Evacuation time: 01:09
Start time: 05:00
50 % evacuated at: 05:25
75 % evacuated at: 05:40
95 % evacuated at: 05:55
End time: 06:09
Average Speed: 30.10

Fig. 3 Evacuation network in OREMS

System Optimal base principle is considered as base-case scenario and compared with stochastic route choice model. Routes are assigned for each operator (mode) during the simulation phase of stochastic route choice model. The estimation of travel time varies depending on which route is assigned for what type of operator. Travel time of the network is the lowest when ambulances are assigned to designated routes (Fig.4) and other operators are freely accessible to other routes.

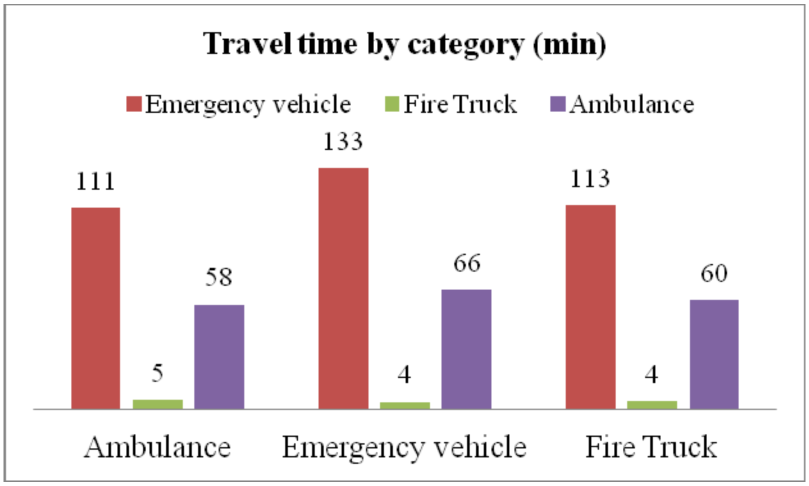


Fig. 4: Travel time by category (modes)

Evacuation time that is estimated by using system optimal based principle is 37.84% lower than the stochastic model. Moreover, it does not provide any estimate of travel time for different categories of mode. Critical volume of network is depicted in Fig.5, where part of Sherboooke, Saint Joseph, D'Iberville and Victoria Street shows critical road section when routes are assigned for ambulances. The critical volume of a segment of Sherbrooke Street, between Saint Laurent and Papineau Street, is highest as this segment is in close proximity of hospitals (Fig. 5). This link is also the part of shortest routes for the ambulance from and to the source of injured people.

HAZUS Canada 2.1 simulates the fire exposure in the close proximity to the Mont Royal Avenue, Ontario Street, Saint Laurent Street, Sherbrooke Street, Rene Levesque Street and Cote St. Catherine Street (Fig. 6). For this reason, parts of the Sherbrooke Street, Saint Joseph Street and Papineau Street have highest critical volume for fire trucks (Fig. 6).

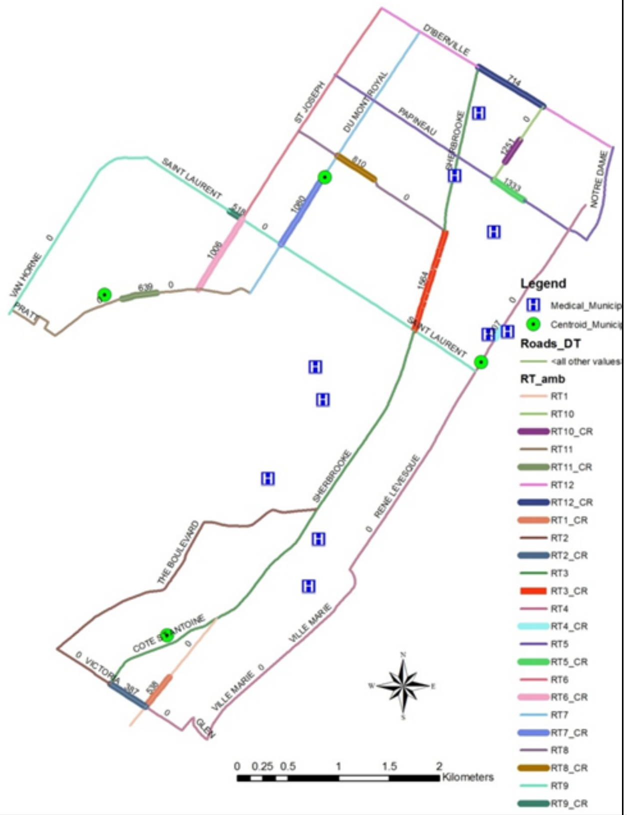


Fig. 5. Critical volume of ambulance routes

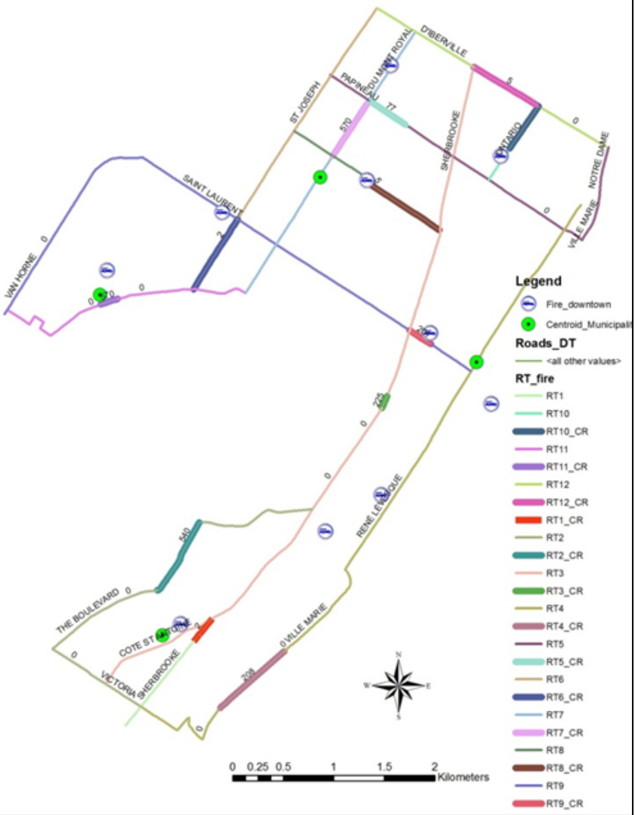


Fig. 6. Critical volume of fire truck routes

6. CONCLUSION

The study depicts seismic risk assessment methodology and evacuation modeling after an earthquake scenario. This study is unique because it integrates seismic risk assessment model with evacuation model. Moreover, evacuation model introduce a composite model that is a combination of trip generation, trip distribution and route choice model. The composite model can incorporate various operators such as; ambulances, fire trucks and so on and their priority in the road network. The study shows that High Priority Vehicles (HPV) face low speed (less than 30Km/hr) and poor level of service in terms of traffic flow per hour in many parts of the road network. Route assignment of HPV can be a solution that minimizes travel time of emergency vehicles. Although the method does not deal with real-time data of evacuation; it can be used for emergency shelter planning and route planning. Future research will include infrastructure damage of the network and evaluate network performance for the study area. As the study is based on number of assumption that ignores behavioral aspects of evacuees, future endeavor will incorporate behavioral aspects of evacuees in evacuation modeling.

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