Australasian Transport Research Forum 2017 Proceedings
27 – 29 November 2017, Auckland, New Zealand
Publication website: http://www.atrf.info

Emergency Evacuation Modelling using Traffic Simulation: A Case Study of Auckland

Mujaddad Afzal[1], Prakash Ranjitkar[1], Seosamh B. Costello[1], Nirojan Jayananthan[1], Sithika Jayasinghe[1]

[1]Department of Civil and Environmental Engineering, University of Auckland, New Zealand

Email for correspondence: mafz774@aucklanduni.ac.nz

Abstract

This paper reports on the development of a prototype decision support system for use by emergency planners in developing contingency plans for emergency evacuation of a city. A case study is conducted for mass evacuation of Auckland city in the event of volcanic eruption centred at high density land use area in Central Auckland. A 5km radial zone from the centre of the simulated volcanic eruption was considered as evacuation zone. A traffic simulation model is developed using AIMSUN traffic simulator to model emergency evacuation of the city. The worst-case scenario (day time scenario) was investigated out of three different scenarios: two night-time and one day-time scenarios. Results from the early prototype model indicate that the clearance time under the worst-case scenario (during day-time) might exceed the proposed warning time for evacuation. Although this research is still in its early stage and the model needs further refinement including calibration under normal traffic conditions however, this study can be useful to improve and update mass evacuation planning for the city.

Keywords: emergency evacuation, planning, modelling, volcanic eruption, network clearance time, traffic simulation, AIMSUN.

1. Introduction

Auckland is the economic and social hub of New Zealand. The region generates 37 percent of the country's GDP and houses 33.4 percent of country's population. It is also the home to 66 percent of the country's top 200 companies. The Auckland port handles 32 percent of the country's exports by value, and 61 percent of its imports. Auckland is an international gateway with more than two million people visiting the city annually (Statistics New Zealand, 2013; New Zealand Trade and Enterprise, 2016).

Auckland city is built on top of the Auckland Volcanic Field (AVF), which covers 360km^2 area and is the youngest basaltic field in the world on which an urban area is established (Searle, 1964; Kermode, 1992). Geographically, Auckland is an isthmus resulting in a limited north-south transportation corridor, which can be a challenging factor given the threat of a volcanic eruption if the city need to be evacuated. Hence, it is important to estimate the total evacuation time to better plan the emergency mass evacuation prior to such eruption in the future. The total evacuation time includes four overlapping components: initial warning time, evacuees' preparation time, network clearance time and evacuation verification time (Sheffi et al., 1980). The focus of this study is on the network clearance time. The main contributions of this paper can be listed as follows:

- Develop a traffic simulation model of Auckland city to model evacuation of the city in case of emergency;

- Develop evacuation scenarios;
- Estimate vehicle demand under different evacuation scenarios based on census date and identify the worst-case scenario;
- Evaluate network performance in case of emergency evacuation for the worst-case scenario; and
- Identify bottleneck locations in the road network.

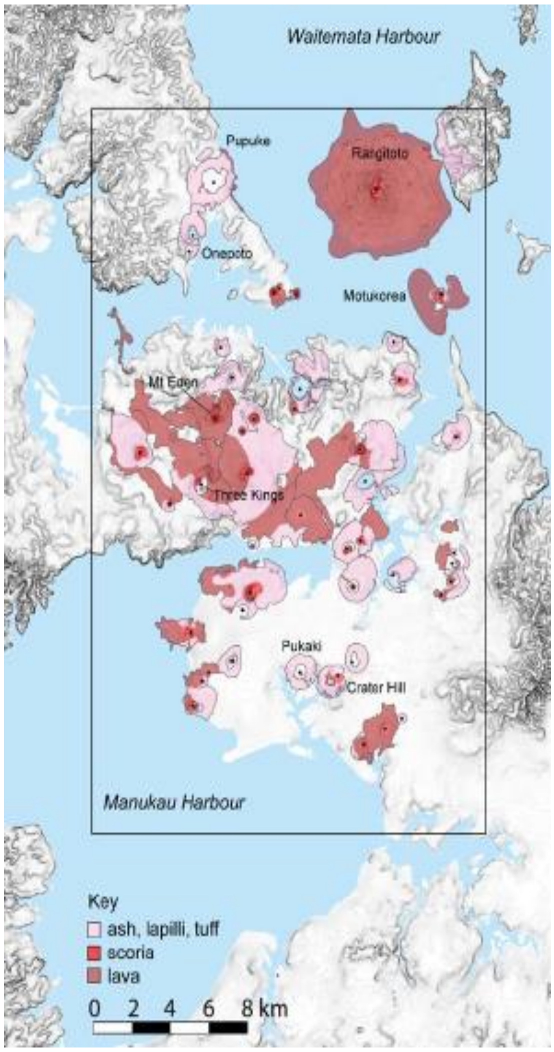
The rest of the paper is organised as follows. A brief history of AVF, eruption scenarios, study area and software used in evacuation modeling is discussed in Section 2. Section 3 provides an overview of the methodology and an estimate of vehicle demand for three evacuation scenarios. Section 4 explains the results of network clearance time and in section 5 concluding remarks are discussed.

2. Literature Review

2.1 Auckland Volcanic Field

The AVF has over 50 eruptive centres (vents) and has erupted over 55 times in the past 250,000 years (Loughlln et al., 2016), with the most recent eruption, 550 years ago, witnessed by early indigenous Maori (Lindsay, 2010). The rectangle box in Figure 1 shows the AVF (Lindsay et al., 2010). Most of AVF vents are monogenetic, which means they erupt only once and the next eruption will be at a new location within the field. Despite considerable scientific effort, no spatial or temporal patterns have been identified. Indeed, the oldest (Pupuke) and the youngest (Rangitoto) vents are located next to each other. As such, it is completely unknown where or when the next eruption will be. The size of the next eruption is also difficult to predict, as the last eruption, Rangitoto, accounts for nearly half of the erupted volume of the field. It is also unclear that whether this eruption is an anomaly or signals a change in the eruptive behaviour of the field (Loughlln et al., 2016).

Figure 1: Auckland Volcanic Field (Lindsay et al., 2010)



GNS Science is continuously monitoring the AVF though Auckland Volcanic Seismic Monitoring Network (Lindsay, 2010). If any activity is detected by this network, warning communications will be in accordance with the National Civil Defence Emergency Management Plan Order (2005), which outlines the responsibilities of GNS Science, Ministry of Civil Defence and Emergency Management (MCDEM), Auckland Civil Defence and Emergency Management Group (ACDEMG) and MetService in regard to the emergency situation (Auckland Council, 2013).

There had been no significant AVF or other volcanic activity evacuations in New Zealand in recent times and as such, local data was not available for research and study purposes (Cole et al., 2005). Therefore, the New Zealand government ran Exercise Ruaumoko in 2008, to test New Zealand's nationwide arrangements for responding to a major disaster resulting from a volcanic eruption in Auckland. The Mt Ruaumoko scenario was selected because it would affect the infrastructure severely (Deligne et al., 2015).

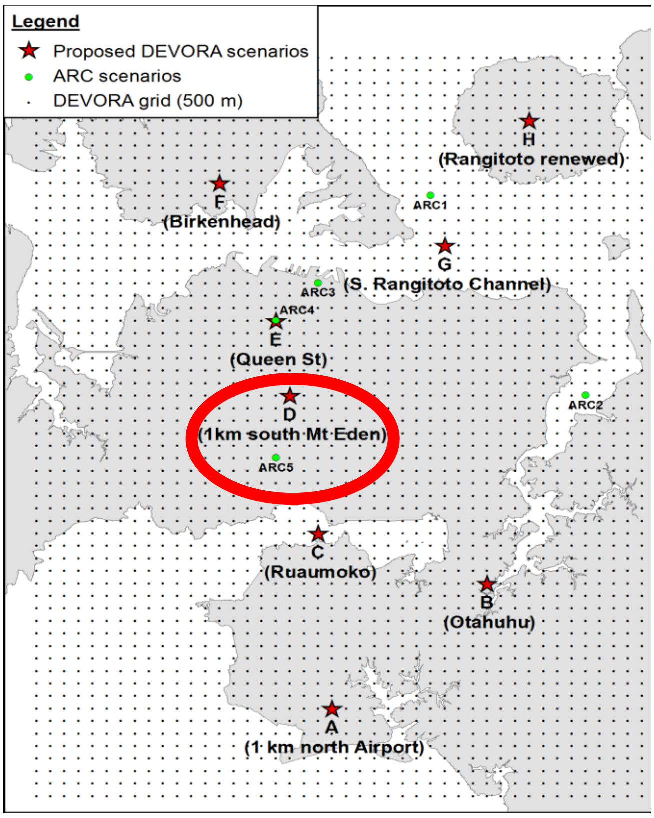
The Mt Ruaumoko Scenario spans a 10 week period (6 February – 14 April 2008) (Deligne et al., 2015). Research on Mt Maugataketake was used to explain surge severity and range. It was assumed that there would be complete destruction with in 2.5km radius of eruption, sever damage to most structures and complete damage to weak structures from 2.5-4km and some damage to weaker structures from 4-6km (Brand et al., 2014).

In the Mt Ruaumoko Scenario, it was assumed that evacuation would be called on 12th March, when volcanic gas was detected. Tomsen at al. (2014) simulated the scenario in TransCAD and suggested that real evacuation would take longer than estimated during exercise Ruaumoko.

2.2 Eruption scenarios and study area

After the Ruaumoko exercise Determining Volcanic Risk in Auckland (DEVORA) brings together more than 40 researchers on board from various research organizations including GNS, RiskScape, Auckland Council, University of Auckland and Massey University. DEVORA proposed 7 more eruption scenarios to study in detail, while recognizing that the next eruption could be anywhere in the AVF. Out of those 7 scenarios "1 km south of Mt Eden" scenario was selected for this study, which is encircled in the Figure 2.

Figure 2: Eight Proposed Eruption Scenarios (Source: Leonard et al., 2016)

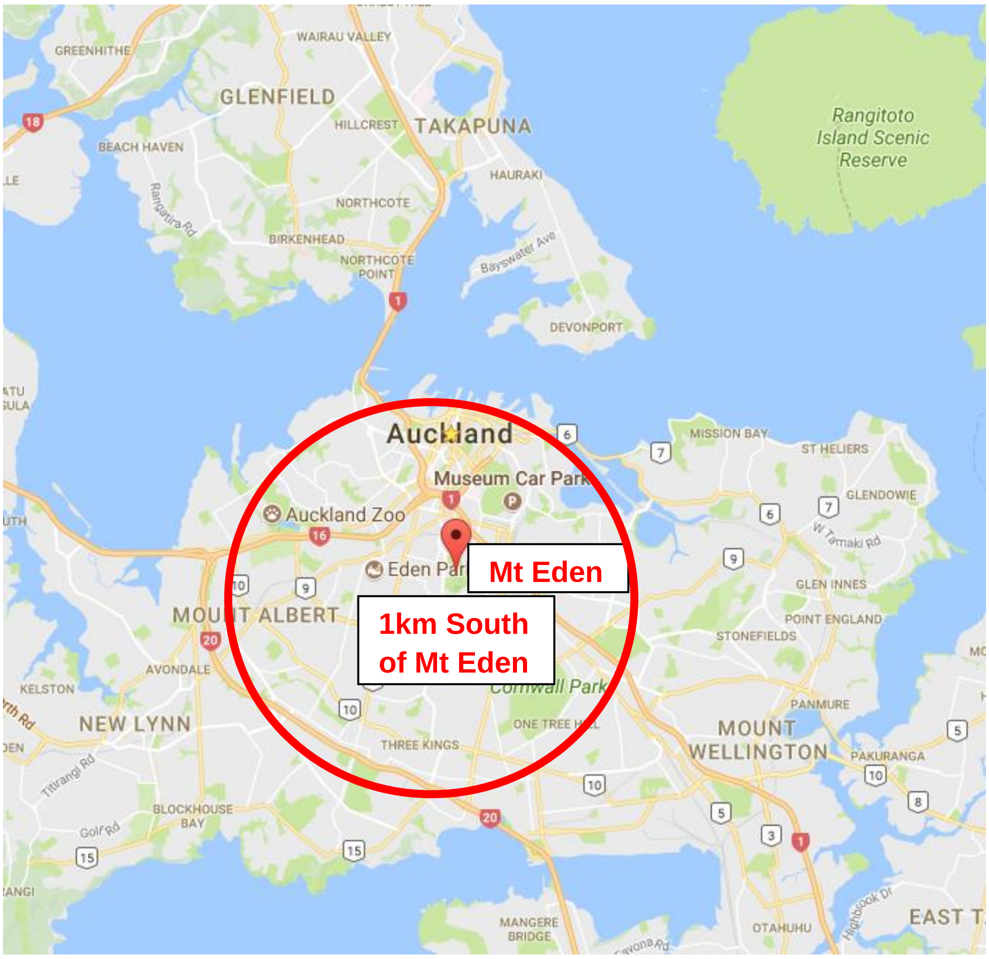


Extent of spread of the initial estimated hazard zone is vital in terms of estimating number of evacuees. The overall hazard zone is made up of two sub-zones; primary and secondary (Smith & Allen, 1993). These zones exist to represent the level of danger associated with the eruption and essentially provide a required evacuation area.

According to Auckland Council (2016), the primary hazard zone (3km radius) represents a high risk area, in which base surges, volcano formation, shockwaves, earthquakes and lava flow may occur. Severe injuries, fatalities and infrastructure damage is more than likely within this zone. The secondary hazard zone (2km radius) surrounds the primary zone and represents a moderate risk area. People, animals and infrastructure are likely to be effected and evacuation is strongly advised.

Therefore, a 5km radial hazard zone from the centre of the "1 km south of Mount Eden" was chosen which covers the most populated area of Auckland city including the Central Business District (CBD). Figure 3 illustrates the 5km radial study area which includes 3km primary and 2km secondary hazard zones.

Figure 3: Study Area (Eruption Scenario, 1 km South of Mt. Eden)



2.3 Modelling evacuation

NETVACL, designed by Sheffi et al. (1980), was the first to model evacuation at macroscopic level. They used this software to estimate the network clearance time for area surrounding nuclear power plant sites. With the passage of time, lot of other macroscopic traffic simulation software were developed and used to analyse evacuation studies. Oak Ridge Evacuation Modeling System (OREMS), Dynamic Network Evacuation (DYNEV), and Evacuation Traffic Information System (ETIS) have been used in various evacuation plans for areas surrounding the nuclear power plants (Moriarty et al., 2007), EMME/2 has been used to prepare evacuation plan for area in the vicinity of the Koeberg nuclear power plant, South Africa (Jones et al., 2007). TransCAD has been used to prepare evacuation plan for the Auckland city (Tomsen, 2010).

Mesoscopic models have been used in evacuation planning to cover congestion conditions and temporal effects better than macroscopic models, while still covering a larger geographic region. Cube Avenue, TRANSIMS and TransModeler are examples of commercially used mesoscopic models (Hardy et al., 2008).

Microscopic models provide more details than macroscopic and mesoscopic models, as they consider individual driver behaviour, vehicle characteristics and detailed road geometry. Such software are usually used to undertake operation analysis, but these can also be used for evacuation planning. AIMSUN, CORSIM, Paramics, DYNASIM, Sim Traffic and VISSIM are example of commercially used micro simulation software (Hardy et al., 2008). TRANSIM was used for evacuation analysis of the Gulf of Mexico (Zhang et al., 2013) and New Orleans (Naghawi and Wolshon, 2010) in the case of hurricanes. VISSIM has been used for analysis of Evacuation of Galveston Island and Florida Keys, USA in case of hurricanes (Chen et al., 2006; Chen, 2008).

In this study AIMSUN is used, as it provides integration of macro, meso and micro models in one package. Moreover, the New Zealand Transport Agency and Auckland Transport use AIMSUN for their various projects. Therefore, it will be beneficial and easy to integrate into future models.

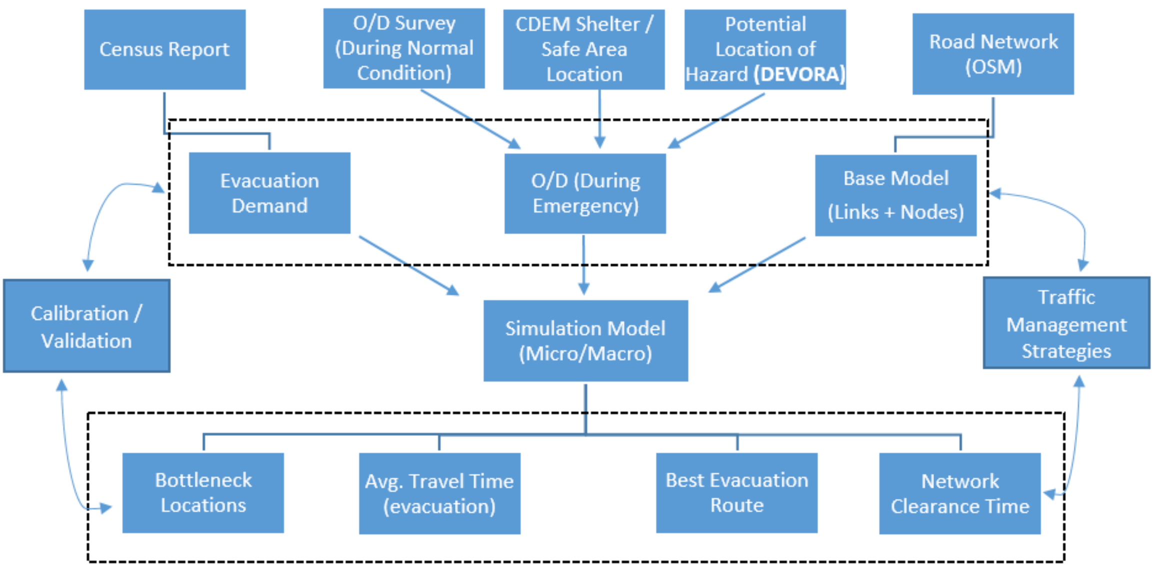
3. Methodology

The study area was modelled in traffic simulation software (AIMSUN). Simulation model entirely depends on the accuracy of inputted data. Data including but not limited to: population counts, number of vehicles per household, Origin and Destination (O/D) data, shelter locations, students enrolled in affected areas and day-time worker information were made available from NZ Statistics and Auckland Council.

A base model was prepared in AIMSUN using Open Street Maps (OSM). Road network attributes, such as lane number and configuration were identified using the most up-to-date images on Google Maps and GIS. Figure 4 shows an overview of the methodology for this study, which illustrates different components of research and their interrelationships.

Due to the limitations of the simulation software and computer hardware, the entire road

Figure 4: Overview of Methodology



network of the Auckland region was not modelled. However, a high degree of detail was preserved within the evacuation area, where all levels of roads on the hierarchy were retained except local roads. Outside the evacuation area, only the primary arterial roads and state highways were retained. This simplification assumed that drivers would travel on any road in the network initially (Moriarty et al., 2007), but once outside their locality, they would travel on the main / familiar routes (Lindell and Prater, 2007).

The simplification allowed comprehensive analysis of the network within the evacuation area and allowed reasonably reliable outcomes of the simulation. The road network was stored as Open Streets Maps (OSM) files and imported into AIMSUN software. The OSM template only produces a rough sketch of the road layout. Therefore, each road segment and intersection / interchange was checked individually to ensure network represents actual field conditions and was up-to-date. The main motorways, highways, arterial and main collector roads were included in this model. Local streets were not included and trips generated from these locations were distributed around the nearest modelled link / node.

After defining the road network, attributes of each segment of network were defined in detail. This includes the number of lanes of each link, turning bays, speed limits and give-way signs where applicable. All Intersections were checked and turning movements at each intersection were defined, also major and minor links were defined. Yellow box speeds were applied to each intersection, it means that approaching vehicles would avoid entering the junction if the preceding vehicle is moving slower than a previously determined speed. This reduced the likelihood of a network crash due to vehicles getting stuck within the node area.

After intersection movements were selected, a signalised traffic control was added. This traffic control operated under an actuated basis, meaning that phases would be given green time if the detector on that road section was occupied. The following parameters were set: minimum green time as 10 seconds, maximum cycle time as 120 seconds, minimum cycle time as 60 seconds for a T-intersection and 80 seconds for a Four-Way intersection.

A dynamic scenario was used to simulate evacuation behaviour as this is more realistic. The method is based on iterative algorithmic procedures that analyse vehicle loading and network density to re-route vehicles towards the path with the lowest calculated travel time. It should be noted that even with a dynamic assignment approach, vehicle paths are heavily restricted, as the limited network size means that there are few alternative routes available to the intended destination zone. As there is no evidence of how drivers will behave under evacuation conditions, default values were retained; that is reaction times of 1.2 and 1.6 seconds for stops and traffic lights respectively, and queue entry and exit speeds of 1 and 4 m/s respectively (AIMSUN, 2014).

3.1 Key assumptions

A realistic simulation of emergency evacuation is very challenging. For example, during emergency evacuation, unpredictable incidents can happen and driver behaviour can be different in panic situations. In addition, there is limited data available on emergency mass evacuation resulting in limited or no opportunity to calibrate such models. Therefore, the following assumptions are made to construct the initial model:

- Driver’s behaviour would not be reckless, and standard road rules would be followed by all road users.
- No background traffic exists on the road network during the evacuation period, this means that all roads would be used by evacuees only.
- Low mobility evacuees would use buses (with an average capacity of 30 passengers/bus) and the remainder would use private light vehicles (cars). Other modes of transport such as train, ferry, air ways and walking were not considered during evacuation.

- All signalised intersections were assumed to operate under actuated control.
- Evacuees would try to evacuate as early as possible.

3.2 Estimation of vehicle demand for evacuation scenarios

The evacuation call may be given during night time or day time. Therefore, for the initial simulations, three basis scenarios were assumed and mathematical models were developed to calculate vehicle demand during these three scenarios. All the notation used in the scenario models are illustrated as follows;

H_n = Number of households with n number of light vehicles
L = Number of households without access to light vehicles
P = Total population of the study area
W_i = Workers going into the effected zones
W_o= Workers going out of the effected zones
Oc = Occupancy rate of the private vehicles
M = Mode share of bus
E = Enrolments in the effected zones
S = Students living in the effected zones

The vehicle demand scenarios are described in the following section.

Night-Time Scenario (Single vehicle per household): This scenario assumes evacuees are based at home and use a single vehicle during evacuation. Lower vehicle demand is expected and hence results in better network performance. Vehicle demand is represented by Equation 1 below.

$$\text{Vehicle Demand} = \sum H_n + \frac{\frac{P}{(H+L)} * L}{30} \qquad (1)$$

In Eq. (1), the first component represents the quantity of cars (private vehicles) and the second component represents the quantity of buses (public transport).

Night-Time Scenario (Multiple vehicles per household): The second night-time scenario is similar to the previous but allows each household to use up to three vehicles during evacuation. Vehicle numbers were obtained through Census Data. Vehicle demand is represented by Equation 2 below.

$$\text{Vehicle Demand} = \sum_1^3 (H_n * n) + \frac{\left(\frac{P}{\sum_1^3 H_n + L}\right) * L}{30} \qquad (2)$$

In Eq. (2), the first component represents the quantity of cars (private vehicles) and the second component represents the quantity of buses (public transport).

Day-Time (Multiple vehicles per household): Day-time evacuation is the most challenging and the worst-case scenario. A much larger vehicle demand would result, as this scenario covers the schools, universities, work place and business centres traffic activities. There are extra incoming and outgoing trips in this scenario.

Uneven population density, especially in the central regions, will be a likely cause of congestion. Vehicle demand is represented by Equation 3 below.

$$\text{Vehicle Demand} = \sum_1^3 nH_n + \frac{\left(\frac{P-S}{\sum_1^3 H_n + L}\right) * L}{30} + \frac{(w_i + w_o) * (1-M)}{O_c} + \frac{(w_i + w_o) * M}{30} + \frac{E}{30} \quad (3)$$

Traditional census data in New Zealand reports the population according to their night-time residence but does not cover daytime population figures. We used business demographics data from Statistics New Zealand report (2008) and school enrolment data from Ministry of Education report (2009) to estimate Auckland's daytime population.

The vehicle demand was calculated for three scenarios and the worst case vehicle demand with maximum number of evacuees would be selected to simulate the clearance time.

Vehicle Demand: Vehicle demand (private vehicle) was calculated according equation 1, 2 and 3. The vehicle demand (private vehicle) for these three scenarios is illustrated in Table 2.

Table 1: Vehicle Demand for Each Scenario

S.N.	Scenario	Trips Generated
1	Night-Time (Single vehicle per household)	76,239
2	Night-Time (Multiple vehicles per household)	130,110
3	Day-Time (Multiple vehicles per household)	169,226

Table 2 shows that the vehicle demand for scenario 2 is almost doubled the vehicle demand for scenario 1. The vehicle demand for scenario 3 is more than twice of the demand of scenario 1. Vehicel demand for the scenarios 2 and 3 may be over estimated because low mobility population usually have strong social connections and they may share rides with other persons. The Scenario 3 was used to calculate clearance time in AIMSUN.

Origin / Destination: Due to software and hardware limitations, only the zones within the Auckland region were entered in the model. Each suburb in Auckland was considered as an individual zone, which means that there are 411 zones according to the shapefile from Auckland City Council. The zones within the evacuation area were considered as origin zones and outside the evacuation area were considered as destination zones. Therefore, there were 66 origin zones and 347 destination zones in Auckland.

3.4 Traffic loading rate

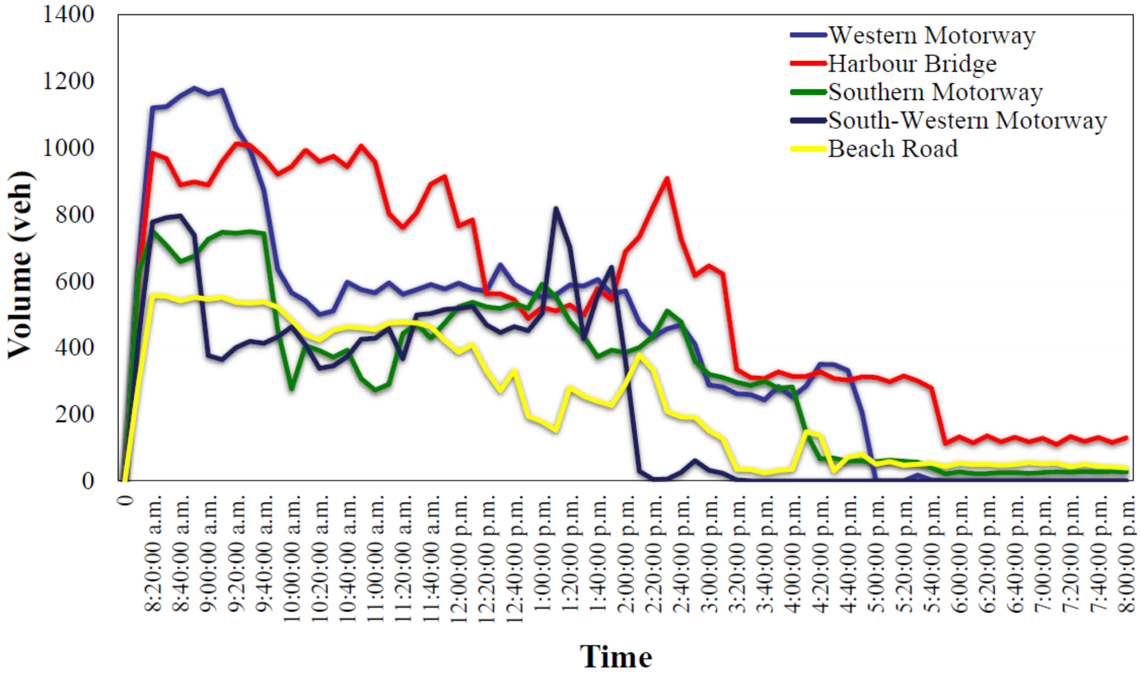
There are two leading types of traffic loading rate curves, which are being used in evacuation studies, such as late response curve and as soon as possible (ASAP) response curve. The late response curve is used when there is a plenty of time available to evacuate the area. The late response curve was used in the simulation model of the Florida Keys, because two days were available for evacuation and the area has only one link to exit, which connected Florida peninsula to main land (Chen et al., 2006). While, the ASAP response curve is used for congested network. The ASAP was used for Galveston Island road network for evacuation modelling and all vehicles were loaded in the first five hours of simulation. In this study ASAP was used, assuming that in case of volcanic eruption the residents might want to evacuate at the earliest.

4. Results

4.1 Network clearance time

Only the results of the worst case scenario (Day Time Scenario) with the ASAP loading rate are presented in Figure 5. To count vehicles, detectors were placed at five viable exit routs: Harbour Bridge, Beach Road, Western Motorway, Southern Motorway and South-Western Motorway. The vehicle count data was recorded during simulation using these detectors and was used to determine calculate clearance time of each exit route. Evacuation was considered complete, when volume passing through the detector droped to zero. The following line chart shows the volume against time on five exit routs. The road network condition during the evacuation can be easily determined through this graph.

Figure 5: Network Clearance Time



Harbour Bridge and Beach Road facititated the majority of CBD evacuees.The Harbour Bridge accounted for the greatest traffic demand of evacuating vehicles. Heavy congestion was observed on upstream arterial and collector roads of Harbour Bridge. It was observed more than 12 hours would be required to completely clear the CBD area.

The Western Motorway route experienced a significantly high evacuee demand, with a peak value of 1178 vehicles in a 20-minute period near the start of evacuation. This route cleared up prior to simulation-end, having zero vehicles waiting to enter at the 9-hour mark.

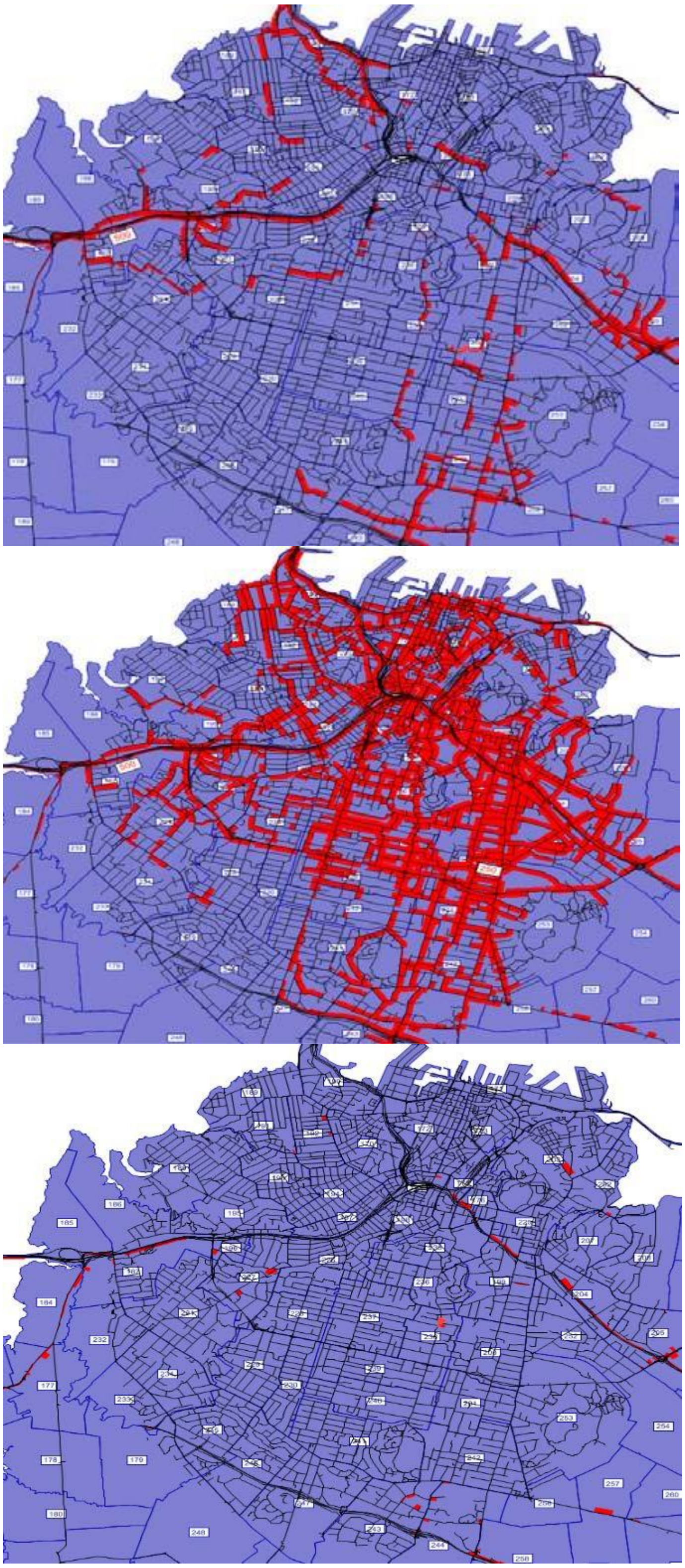
The Southern Motorway has a large number of vehicle on-ramps and this is potentially the reason for the fluctuating trend. As the vehicles from each suburb are loaded into the network based on the ASAP scenario, they evacuate in bunches. In comparison to the CBD traffic, there was relatively less demand and congestion was not as widespread. Both the Southern and South-Western Motorways cleared up before the simulation ended. It was noted that the South-Western exit route can take on a lot more demand, with clearance occurring much earlier around the 7-hour mark.

On-ramps were identified as the primary zones of bottlenecking as two-lane ramps merge into a single lane. This creates a starting point for traffic build-up and slowly develops backwards from the ramp access.

4.2 Network performance results (day-time scenario)

Figure 6 shows the flow condition of the network during the first, sixth and tenth hour of evacuation respectively. Red colour indicates links with speed below 5 km/hr.

Figure 6: Link Speed on road segments during a) 1st hour b) 6th hour, and c) 10th hour



a)

b)

c)

5. Concluding Remarks

The performance of Auckland's road network is evaluated in case of volcanic eruption. A microsimulation model of Auckland road networks was modeled using AIMSUN software to conduct a scenario based on emergency evacuation. Day time scenario was found to be the worst case scenario and used to calculated the clearance time, which may be in the range of 10 to 15 hours. The network was highly congested during initial eight hours. Traffic congestion was observed on arterial and collector roads as well as areas near on-ramps, especially near the Auckland CBD. More than 12 hours would be required to completely clear the CBD area. The results also show that the South-Western motorway would be underutilized if no intervention is applied. The Harbour Bridge accounted for the greatest demand of evacuating vehicles from Auckland CBD.

Only private vehicles were used in this simulation model. Buses were less than 5 percent of total number of vehicles. In the future research, buses (public transport) will also be added in the simulation model.

No warm up traffic demand was used in this model. Therefore, better flow condition was observed during initial two hours of simulation. In future research, warm up traffic demand will be used, which may increase the clearance time. It is hypothisised that phased evacuations could have a substantial impact on reducing clearance time. Traffic loading rates have a heavy impact on on-ramp congestion and this type of congestion may be improved in future by using steady traffic loading rate..

Vehicle demand on the exit routes used in this simulation showed that there is a room for optimisation. The South-Western motorway was certainly under-utilized. Minimising the difference in clearance time between these routes will improve the overall network performance. Variable Message Signs (VMS) can be used to influence evacuees to take the optimal route to minimize the overall clearance time. Effects of traffic control strategies should be analysed to determine whether clearance time can be further reduced. The capacity of the road network can be doubled at bottleneck locations if contraflow is applied.

This simulation model presents the preliminary results without calibration. The model could provide reliable results after the callibration. The outcome of this research would help to understand road network of Auckland and provide base for further research in this area. Moreover, it will help to evaluate different traffic control strategies to improve road network performance during emergency mass evacuation. The research will help CDEM to better plan emergency mass evacuation

6. Acknowledgements

The authors would like to thank the Resilience to Nature's Challenges (RNC) National Science Challenge (NSC) and University of Auckland for their funding and resources

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