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If a severe Tsunami warning was issued, how long would it take to evacuate the 13,000 people who live on Te Atatu Peninsula?

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Introduction:

Tsunamis are caused by sudden changes in the seafloor, usually as a result of earthquakes, volcanic eruptions or landslides under the sea. When these events occur, huge amounts of energy are released due to quick upward seabed movement. Initially, the tsunami carries a large amount of energy spread over a large volume of water. However, on approaching the coast, the energy is concentrated into a smaller volume.

In shallow water, the speed of the tsunami decreases and its amplitude increases:

The velocity of the wave in open ocean is equal to the wavelength divided by the wave period.

$$\mathrm{V} = \frac{\lambda}{P}$$

where V = velocity, λ = wavelength, P = period

However, we are more concerned with the velocity of the tsunami in shallow water, on approaching the coast. In this case, a different formula is applied to calculate the velocity of the shallow-water wave.

$$\mathrm{V} = \sqrt{gd}$$

Where V = velocity, g = acceleration of gravity, d = depth of water

NB: A wave is characterized as a shallow-water wave when the ratio of the water depth and wavelength is very small.

Assuming that the subtidal (the benthic ocean environment below low tide that is always covered by water) zone of the Waitemata harbour is approximately 5.5m (NIWA), the velocity of the tsunami wave would be as follows:

$$\mathrm{V} = \sqrt{gd} = \sqrt{9.81 \times 5.5} = 7.35\ \mathrm{ms}^{-1} = 26.4\ \mathrm{kmh}^{-1}$$

The height of a tsunami wave above still water line is equal to ½ the wave amplitude.
The height of the tsunami wave may range from a couple of metres to as high as 30m.

Therefore, the Te Atatu inhabitants should leave the area.

In this investigation, we will be calculating the minimum time taken to evacuate the 13,000 people at the Te Atatu peninsula and also the maximum time taken by considering two main methods of transport – by vehicle and by walking.

When walking, we will assume that the people initially travel by vehicle to the main road (Te Atatu Road) and then start to walk along down the Te Atatu Road. On the other hand, when transporting by vehicle, we are assuming that all residents travel by car, with all the cars completely filled (5 passengers on average) to minimise the number of cars that will need to be moved into the safe zone.

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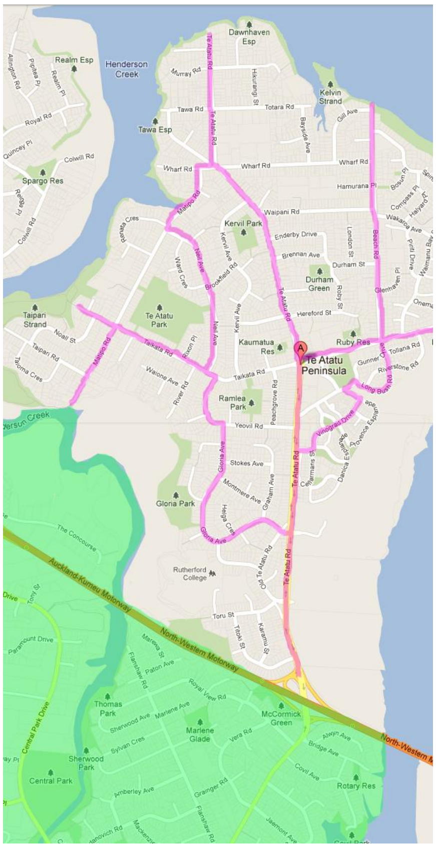
Assumptions made in this investigation:

To determine how long it would take to evacuate the 13,000 people at the Te Atatu Peninsula, we have assumed that…

- The warning to evacuate has been given prior to the actual Tsunami, so the Tsunami has not happened yet and that there is enough time for people to be evacuated
- It will be possible to block off motorways (State Highway 16) and that administration of our evacuation plan can be taken care of
- The evacuation is efficient (i.e. there are no stops for fuel and no car accidents. Traffic will be in an orderly manner)
- All the drivers have the same following distances
- The roads highlighted in pink (on the map on the next page) can be turned into one-way roads, so that everyone is travelling in a North to South direction. And these roads highlight in pink are the main routes that will be taken by the people to evacuate into the safe zone
- The area highlighted in green (on the map on the next page) is considered ‘safe’ and once people are in this green region, they will be considered to be evacuated. Therefore, the time we have calculated in this investigation will be the time taken to get all 13,000 people of Te Atatu Peninsula into the green shaded area
- There’s only one way to evacuate (Te Atatu Road)
- Although the main routes for evacuation are made one-way which allows for two lanes for cars to go on, we have assumed that there will be no lane-switching of cars
- The warning for evacuation has been given on a week day, during school time so there will be students at school, and most people will be at work



Statistics of population of Te Atatu Peninsula:

Table showing proportion of age groups in Te Atatu Peninsula

Age group	Percentage of people in Te Atatu Peninsula	Number of people
0 – 4	8 %	1040
5 – 9	7 %	910
10 – 19	13 %	1690
20 – 39	28 %	3640
40 – 59	23 %	2990
60 and over	14 %	1820

Table showing proportion of residents per household in Te Atatu Peninsula

Residents per household	Percentage in Te Atatu Peninsula
1	19 %
2	32 %
3	19 %
4	14 %
5	7 %
6	4 %
7	1 %
8 and more	1 %

People who may need special assistance:

There are people that may require special assistance when evacuating.

- **People at the St Margaret's Hospital**

Maximum capacity of patients at this hospice is 50 people and the doctors/nurses/staff accompanying them will be approximated to be 20. Two buses will be sent to the St Margaret's Hospital as soon as the warning is given to the district, to collect these 70 people. For both cases of driving and walking as methods of transport that will be discussed in this investigation, we have decided that these 70 people will always be evacuated by two buses, and that these people will be evacuated first, before all the other people are.

Time taken to evacuate people at the hospital:

On a week day and during school time, the bus comes to Taikata Road every hour and goes to Britomart, which means the bus will lead people into a safe zone (the only way out of Te Atatu Peninsula is through the Te Atatu Road) But in an emergency such as this, the buses on the way to Te Atatu Peninsula or from Te Atatu Peninsula to Britomart will be immediately directed to and sent to Te Atatu Peninsula, or more specifically, to the St Margaret's Hospital. Time taken for a bus to travel from the bus stop at Taikata Road to the hospital is 4 minutes, and the time taken for a bus to travel from Britomart to the hospital is 19 minutes.

The maximum time taken for two buses to arrive at the hospital will be 19 minutes, but it is likely that the time taken will be much less because it is unlikely that the bus will be exactly at Britomart at the time the warning is given, which is the furthest point that bus will be at from the hospital. So we will approximate the time taken for the two buses to arrive at the St Margaret's hospital to be 15 minutes. We will assume that the patients at the hospital get ready to leave during the 15 minutes taken for the buses to arrive. And as soon as the buses arrive, the 70 people will board the bus and leave. It will take 7 minutes for the buses to enter the safe zone. In total, it will take 22 minutes for the people in the hospital to be evacuated. Once the 70 people in hospital are evacuated, the rest of the population in Te Atatu Peninsula (13000 – 70 = 12930) can be evacuated.

Consideration of various methods of transport and the congestion involved:

Method 1

An existing 'steady flow rate' model states that the minimum evacuation time can be calculated according to the following formula.

$$T^* = \frac{N}{lq^*} + \frac{D}{v^*}$$

Where:

T* = Minimum Evacuation Time
N = Number of Vehicles
l = Number of lanes
D = Total distance travelled
q*= Maximal traffic flow
v* = Optimal velocity

v* is calculated using the following formula:

$$v^* = \sqrt{\frac{1}{\gamma}[L + Dl/N]}$$

q* is calculated using the formula:

q* = k*v* where k* is determined as follows:

$$k^* = \frac{\beta y^{1/2}[L + Dl/N]^{-1/2} - 2\gamma \frac{[L + \frac{1}{2}Dl/N]}{[L + Dl/N]}}{[\beta^2 - 4\gamma L] - \gamma \frac{[Dl/N]^2}{[L + Dl/N]}}$$

Where:

β = Reaction Time
y = The reciprocal of twice the maximum average deceleration of a following vehicle
L = Average length of a vehicle
(Malone, Miller, Neill)

Applying the Minimum Evacuation Time Model to the situation at Te Atatu Peninsula:

The model above was applied to the evacuation situation at Te Atatu to determine a range for the Minimum Time to evacuate all the inhabitants.

Values calculated:

N = Number of vehicles = 2586

This was calculated assuming that the 12930 people remaining after evacuation of the hospice all travel out of Te Atatu by car, with each car holding 5 people.

l = Number of lanes = 2

There will essentially be 2 lanes on Te Atatu Rd heading towards North-Western Motorway as both lanes will be made one-way.

D = Total distance travelled = 4000m = 13 123.3596 ft

According to Google Maps, Te Atatu Rd measures 4.0 km in distance.

Values approximated:

L = Average length of a vehicle = 10 ft

β = Reaction Time = 1s

Theoretical values:

y = The reciprocal of twice the maximum average deceleration of a following vehicle = 0.0115 $\sec^2$/ft   Rothery, (Car Following Models)

Thus, calculations using the formulas on the previous page showed that:

v* = Optimal velocity = 41.85850221 ft/s
k* = Optimal traffic density = 0.0138873371 cars/ft
q*= Maximal traffic flow = 0.5813031307 cars/s
T* = 2537.829991s ≈42.3 minutes

Limitations of Applying the Steady State Model:

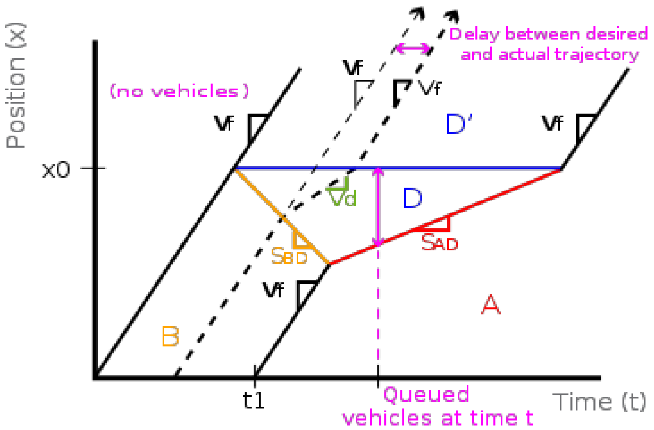
While this model is quite accurate in modelling the traffic behaviour on long, unvaried roads, it may not accurately model the behaviour for the peninsular highway for several reasons:

1. There is only one main road of the of the Peninsula (the Te Atatu Rd), which means all smaller roads will eventually merge
2. Eventually this will have a bottleneck effect as the rate of incoming traffic will exceed the rate of traffic that is able to leave the Te Atatu Rd.

Bottleneck = Region where the rate of incoming traffic exceeds the rate of outgoing traffic so that a queue of cars / people is formed and restricts the flow of traffic. In this case the bottleneck is at the bottom of Te Atatu Rd where all vehicles must eventually go through to leave the peninsular.

How does the incoming traffic affect the steady flow rate?

In the previous calculation, we assumed that traffic will not diverge, as there is only one road out of the peninsula, Te Atatu Rd. However, in reality, there are many possible avenues to get onto the main road (Gunner Drive, Vinograd `Drive, Yeovil road, Gloria Ave, Old Te Atatu Road and Titoki Street, etc.). Thus the merging of traffic from these roads will have an effect on the steady state model.



The bottleneck capacity = maximum outgoing flow rate through the bottleneck region. We can **assume** that this is a constant, according to a research paper by Profession Daganzo (Laval & Daganzo, 2011 http://www.ce.berkeley.edu/~daganzo/mlhm%20TRB05.pdf)

Case study: the steady state flow rate is greater than the bottleneck capacity. In this circumstance, the queue size will increase until the traffic jam extends back to its starting point: the beginning of Te Atatu Rd. At this point, the flow of traffic is steady again and its maximum rate is the same as the bottleneck capacity.

Earlier we calculated the time taken to evacuate all 12, 930 people was 65.4 minutes. However, this is not what we want. We want to minimize the time taken to evacuate everyone so we want to avoid the bottleneck scenario or at least minimize it to increase the bottleneck capacity.

Possible solutions include:

1. Positioning police cars at each junction / merging lane onto the main road to ensure that all cars are full to the maximum so no unnecessary cars are taking up space
2. "Staggering" – setting up a system so that the starting traveling time of cars from different areas of the peninsula are staggered ie. Decreasing the number of cars on the road as new cars may only enter the road once the cars before have gone to safety

Deeper analysis of each possible solution to reduce flow rate:

To address point 1, we can assume that car owners have been instructed to pack their cars to the extreme. Assuming that there are on average 5 people in a car, excluding the 70 hospice residents taken away by the bus, there are in total 12, 930 people in need of transport. Thus 12930/5 = 2586 vehicles on the road, assuming that the government has issued a statement that requires all people to go via car.

$$v^* = \sqrt{\frac{1}{\gamma}[L + Dl/N]} \text{ as N increases v* increases}$$

$$\text{and } T^* = \frac{N}{lq^*} + \frac{D}{v^*}$$

So, overall as N (number of vehicles on the road) decreases, the overall time taken decreases.

If we address point two, lets see what happens if the time of departure is staggered. Firstly, to keep it simple (we want the process to be as simple as possible to avoid chaos), we can split up the peninsular into four regions as shown below:

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Staggering process: Allow the population located in region four to exit first, entering Te Atatu Rd via Gunner Drive and Vinograd Drive.

Allow population located in region three to exit next, entering Te Atatu Rd via Yeovil road, Gloria Ave, Old Te Atatu Road and Titoki Street.

Region two will be evacuated next, with vehicles travelling down mainly down Te Atatu Road and Beach road merging with Te Atatu Road at the town central.

Our hypothesis: Staggering is a good idea because it will reduce the severity of the bottleneck effect that will occur at the bottom of Te Atatu Rd as shown below:

Using the steady flow rate model to find the time taken for Region one:

N = Number of Vehicles = 647 (assume 2586/4)

l = Number of lanes = 2

D = Total distance travelled = 13123.3596 ft

L = Average length of the vehicle = 10 ft

q*= Maximal traffic flow

β = Reaction Time = 1s

y = The reciprocal of twice the maximum average deceleration of a following vehicle = 0.0115 sec^2/ft

v* = Optimal velocity

v* is calculated using the following formula:

$$v^* = \sqrt{\frac{1}{\gamma}[L + Dl/N]}$$

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$$v^* = \sqrt{\frac{1}{0.0115}[10+13123x2/647]}$$

$$=66.31$$

q* is calculated using the formula:

q* = k*v*

$$k^* = \frac{\beta y^{1/2}[L+Dl/N]^{-1/2} - 2\gamma\frac{[L+\frac{1}{2}Dl/N]}{[L+Dl/N]}}{[\beta^2-4\gamma L]-\gamma\frac{[Dl/N]^2}{[L+Dl/N]}} =$$

$$\frac{0.0115^{1/2}[10+13123x2/647]^{-1/2} - 2x0.0115\frac{[10+\frac{1}{2}13123x2/647]}{[10+13123x2/647]}}{[0.0115^2 - 4x0.0115x10] - 0.0115\frac{[13123x2/647]^2}{[10+13123x2/647]}} = 0.44842$$

q* = k*v* = 29.735

so T for region 1 =

$$T^* = \frac{N}{lq^*}+\frac{D}{v^*} = 20.66 \text{ minutes}$$

Time taken for region two will be similar as the value of D and N are the same in this case. Therefore, total time for region 1 and 2 =20.66x2 = 41.32 minutes

Using the steady flow rate model to find the time taken for Region three and four:

N = Number of Vehicles = 647

$$v^* = \sqrt{\frac{1}{\gamma}[L+Dl/N]} = 49.65$$

$$k^* = \frac{\beta y^{1/2}[L+Dl/N]^{-1/2} - 2\gamma\frac{[L+\frac{1}{2}Dl/N]}{[L+Dl/N]}}{[\beta^2-4\gamma L]-\gamma\frac{[Dl/N]^2}{[L+Dl/N]}} = -0.0077311$$

q* = k*v* = -0.383849

so T for region 3 =

$$T^* = \frac{N}{lq^*} + \frac{D}{v^*} = 10.54 \text{ minutes}$$

Therefore time taken for regions three and four = 2x 10.54 = 21.08 minutes

Therefore total time = 21.08+41.32+ 22 (time taken to evacuate hospice residents first) = 84.4 minutes in total.

Since 84.4 minutes with staggering > 64.3 minutes without staggering our hypothesis is incorrect.

In the evacuation reports for other cities, staggering reduced the time taken for the overall evacuation time. However, in the case of the Te Atatu peninsula it actually INCREASES the time taken. This may be because splitting the peninsula into four regions is not an effective way to reduce the time, or because due to the size of the peninsula, it is actually more effective to evacuate at once and not stagger.

Method 2

First, as in the previous method, the inhabitants of the hospice will be evacuated by bus. Then, (we assume that all) inhabitants will drive to the Te Atatu town centre and park their cars at the car parks, driveways and parks in the area. Finally, they will all walk along Te Atatu Road, which is made a one-way street following the evacuation of the hospice inhabitants to the safety zone boundary at the North-Western Motorway. The one-way street is to maximise the capacity of pedestrian flow out of the Te Atatu Peninsula as entering of people into the danger zone is heavily discouraged and not permitted in this evacuation procedure.

<u>Time taken for all inhabitants to drive to Te Atatu town centre:</u>

We will calculate only the farthest distance as it is assumed that this is the longest time taken. The arrivals of inhabitants will be staggered so we assume that there is negligible traffic congestion hindering movement and slowing traffic. The distance from the tip of the Peninsula i.e. the end of Te Atatu Road to the town centre is 1900m (*Google Maps*). The speed is taken to be 50kmh^{-1}=125/9ms^{-1}=13.88888…ms^{-1}.

$$Time = \frac{Distance}{Speed} = \frac{1900}{125/9} = 2.3\ minutes(2.s.f.)$$

However, due to delays such as intersections and traffic lights, we have estimated an extra 2 minutes travelling time so the time taken to arrive at the town centre is approximately 4.5 minutes.

<u>Time taken for all inhabitants to walk from the town centre to the safe zone:</u>

We estimate the average stride, to be a length of 0.7m. (This was obtained by measurement of four 17 year old females' strides and calculating the mean as shown below. The mean height of the four females is 1.63m.)

Height of Female (m ± 0.01m)	Length of Stride (m ± 0.01m)
1.59	0.64
1.60	0.68
1.63	0.69
1.70	0.79

$$\therefore \mu_h = \frac{159 + 160 + 163 + 170}{4} = 1.63m$$

$$\therefore \mu_s = \frac{0.64 + 0.68 + 0.69 + 0.79}{4} = 0.7m$$

This of course has limitations as each person's stride length is different and under stressed conditions is subject to change however it seems to be a reasonable approximation for the purposes of this investigation. Also, although 0.7m may seem a short stride length, it is more reasonable to approximate a shorter stride length in this investigation due to the properties of congested movement. The flow of pedestrians approximates the lowest values of stride length and speed.

Hence, the area occupied by each individual pedestrian or the area of each 'cell' is estimated as the length x the width, or $(0.7 \times 3) \times 1 = 2.1m^2$. The length is 0.7x3 because of the space between people to avoid collisions, and we have estimated the width of each cell to be 1m. We have made the assumption that each square cell fits together perfectly and it is constant for each pedestrian, at each point in time.

The width of Te Atatu Road is measured (see Appendix 1) as 17.8m. (Note: we have made the assumption that the width is constant for the entire length of the road however this is obviously unlikely and is a limitation to our model. We have assumed it as such because the effects of any discrepancies in width, i.e. wider or narrower road, are assumed to either cancel out or be negligible in this discussion.)

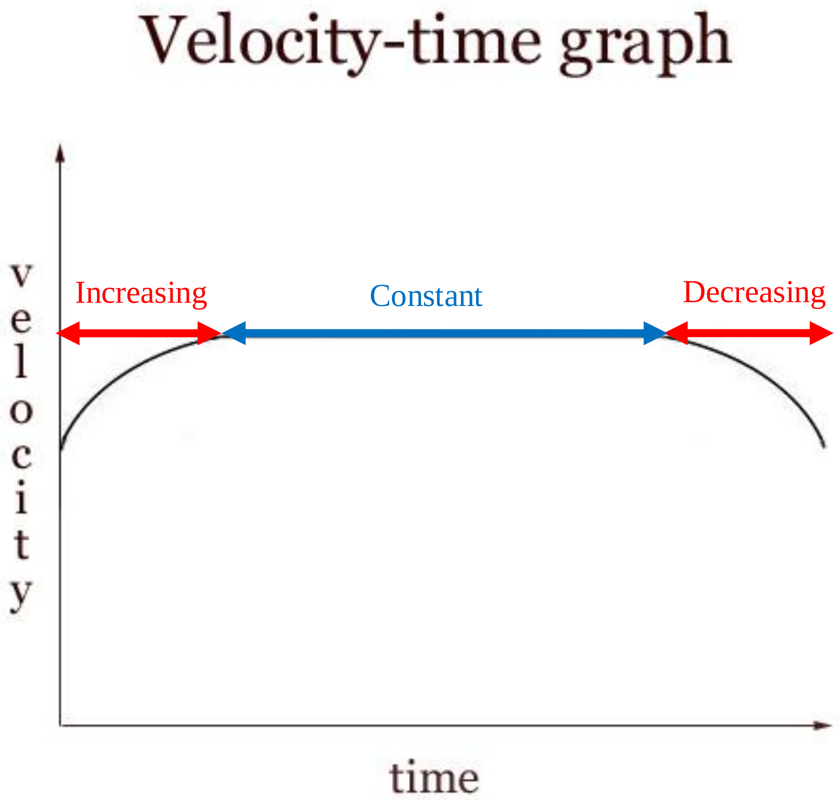
The length of Te Atatu Road (from the Te Atatu town centre roundabout to the safety zone boundary at the North-Western Motorway) is 1800m (*Google Maps*). So the area of Te Atatu Road is :

$$17.8 \times 1800 = 32040m^2$$

The maximum number of cells i.e. pedestrians on Te Atatu Road at one moment in time is estimated at $\frac{32040}{0.49} = 15257$. Hence the entire population is able to fit on Te Atatu Road without spilling over onto adjacent streets or being forced to stop and wait for space on the road.

For the purposes of this investigation, we use the most simplistic model and conditions. We assume that every person other than the inhabitants of St Margaret's Hospital walk the entire journey from the Te Atatu Peninsula town centre (the roundabout near 595 Te Atatu Road) to State Highway 16. there is a continuous flow of pedestrians and individuals arriving at Te Atatu so that there is no 'bottleneck' effect, forcing a complete stop at any point on the road. This is due to the travelling times from various points in the Te Atatu Peninsula and the improbability of every person arriving at the town centre at the same time.

We also assume a constant speed of walking of $4.5kmh^{-1}$=$1.25ms^{-1}$ (*Walking*), even though it is unlikely as the flow of pedestrian traffic is not always constant. Yet this assumption should still give a reasonable approximation in our calculations as the effects of congestion and slowed walking should be balanced out by the accelerated velocities or greater speeds of pedestrians at the beginning and end of the duration of evacuation as shown by the curved slope at the beginning and end of the graph as shown below.



If we treat the flow of pedestrians as a wave, the number of individuals in a 'wave front' is determined by $\frac{width\ of\ road}{width\ of\ cell} = \frac{17.8}{1} = 17$ (as a whole number). Thus we can approximate the movement of the group of pedestrians as the time taken for x number of pulses or wavelengths to travel the distance from town centre to the safety zone. For x number of wavelengths, $x = \frac{12930}{17} = 761$ (as a whole number). The 'wavelength' can be approximated by the length of a cell, i.e. 2.1m. The length of 761 wavelengths is $761 \times 2.1 = 1598.1m$.

The time taken for everyone to be evacuated to the safe zone is the time taken for the first wave front to travel the distance to the safety zone (1800m) + the time taken for a wave front to travel the distance of 761 wavelengths (1598.1m).

$Time = \frac{Distance}{Speed}$. Thus the time taken = $\frac{1800}{1.25} + \frac{1598.1}{1.25} = 2718.48s \approx 45.3\ minutes\ (3.s.f.)$

Total time taken to evacuate the 13,000 people:

Time taken to evacuate hospice inhabitants + time taken to reach town centre + time taken to walk to the safe zone

$= 22 + 4.5 + 45.3 = 71.8\ minutes$

Conclusion:

For the safety of the Te Atatu peninsular population, we have developed and tested several models of evacuation traffic flow. The aim of this investigation was to work out how long it would take to evacuate the 13,000 people at the Te Atatu Peninsula. From this investigation we calculated that the minimum evacuation time would be 64.3 minutes using a steady flow rate model to model the rate of traffic. We also investigated other variables to determine whether this time could be reduced. When investigating how the leaving time would be affected if the evacuation was staggered, we found that the time would actually increase, contrary to our hypothesis that staggering would decrease the evacuation time. Our data suggests that staggering the leaving time will not overall decrease the evacuation time, despite our hypothesis. Thus the evacuation should NOT be staggered. Also, we investigated how a different evacuation plan would affect the evacuation time and found that by this second evacuation procedure, the evacuation time would increase to 71.8 minutes.

The main limitation of this investigation is that the minimised time of evacuation was obtained using a steady flow model, which contains several limitations such as the random fluctuations in traffic. We also made several assumptions, which would undoubtedly affect the evacuation time. Within the limits of our investigation, we have arrived at the conclusion that evacuation of the Te Atatu Peninsula could take between 64.3 minutes and 71.8 minutes.

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Appendix 1

Google Maps. Retrieved October 1, 2011 from

http://maps.google.co.nz/maps?hl=en&rlz=1C1CHMR_en-GBNZ432NZ433&gs_upl=1757l1757l0l1968l1l1l0l0l0l0l0l0ll0l0&safe=active&q=te+atatu+peninsula&um=1&ie=UTF-8&hq=&hnear=0x6d0d409cc0e8169b:0x500ef6143a30ad0,Te+Atatu+Peninsula&gl=nz&ei=u2SGTojUG-2ziQfbtfHBDw&sa=X&oi=geocode_result&ct=image&resnum=1&ved=0CCcQ8gEwAA