LGOIMA Release – Pages Road Bridge Renewal Traffic Modelling

The report and summary are attached.

This report has been developed to assess the traffic impacts in an emergency evacuation situation. There are a number of assumptions that are detailed in the report.

This report does not address emergency evacuation requirements.

Summary of Traffic Modelling in an Emergency Evacuation Scenario - Pages Road Bridge Renewal Project

Date: 23 August 2023

Modelling Overview

As part of the Pages Road Bridge Renewal Project (Gateway to New Brighton) Scheme Design, CCC investigated multiple intersection options and road configurations to determine the most effective transport solution for the evacuation of the New Brighton area in an emergency. Traffic modelling of the various options was completed, sensitivity tested and subsequently peer reviewed by an independent consultant to confirm the findings. The emergency evacuation scenario adopted for the traffic modelling was based on a Hikurangi Trench earthquake and tsunami triggered near Kaikoura.

9 different road layouts and intersection options were tested by the traffic model. The road design layout and intersection types proposed in the current scheme design is the most efficient solution in an evacuation scenario reducing the overall evacuation time by approximately 40 minutes compared to the existing configuration.

Traffic Modelling vs. Evacuation Modelling

Traffic modelling was used to test various road layout options in order to select the most efficient option. Traffic modelling was done in Paramics Software

The traffic modelling considers one evacuation scenario in order to test the various road layout options, for example the modelling inputs have assumed the population of New Brighton leaves in vehicles (97% of people used vehicles in 2016 evacuation), with two people per vehicle and is based on a quick response time of 15 minutes. Assuming everyone evacuates by vehicles is a conservative evacuation model to inform the transport network change requirements' and therefore more people evacuating by walking and cycling should improve evacuation times for people evacuating by car .

There are a number of other emergency evacuation scenarios that could be used and this is outside of the projects remit and sits with Civil Defence unit. To model emergency evacuations outside of just vehicles, other modelling software would be more appropriate like agent-based models, where agents can make decisions on their evacuation. Each agent will choose different evacuation method, response time and evacuation route.

Road Layout Options

The road layout options that were modelled are listed in Figure 1 below.

ref	Existing network (Do nothing)	"Give way" controls	Free left turn from Seaview Rd	Traffic lights	Single lane design	Dual lane design	Single lane bridge	Double lane bridge	MCR signals	change priorities Seaview - Hardys	New Brighton Road approach added	Access from Owles Tce added
1	✓						✓					
2		✓			✓		✓		✓			
3				✓	✓		✓		✓			
4		✓				✓		✓	✓			
4a		✓	✓		✓			✓	✓			
7				✓		✓		✓	✓			
7a				✓		✓		✓	✓	✓		
8				✓		✓		✓	✓	✓	✓	
9				✓		✓		✓	✓	✓		✓

Figure 1 - Road Layout Options

Modelling Outputs

The modelling results for the various options are shown in Figure 2 and Figure 3 below which outlines the total evacuation rate vs. time. Figure 4 lists the exact times for each option modelled. Note: Once vehicles pass through the SH74 Anzac Drive intersection heading west are deemed 'evacuated.'

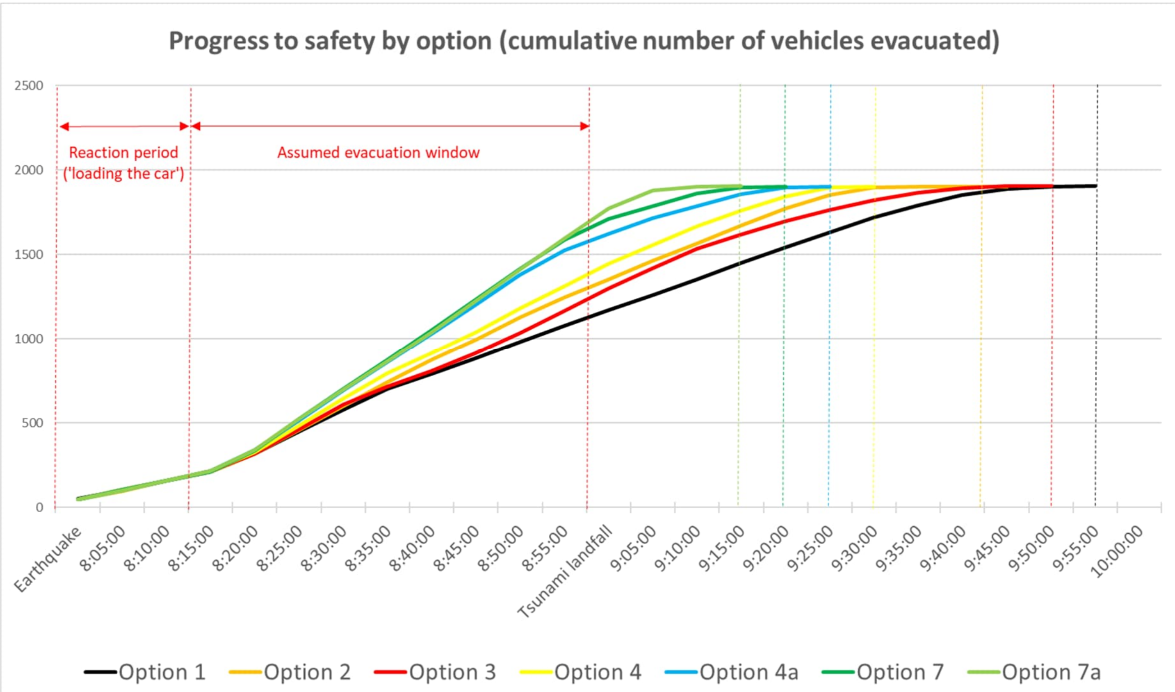

Figure 2 - Cumulative evacuation (vehicles through Anzac Drive intersection) of various road layout options

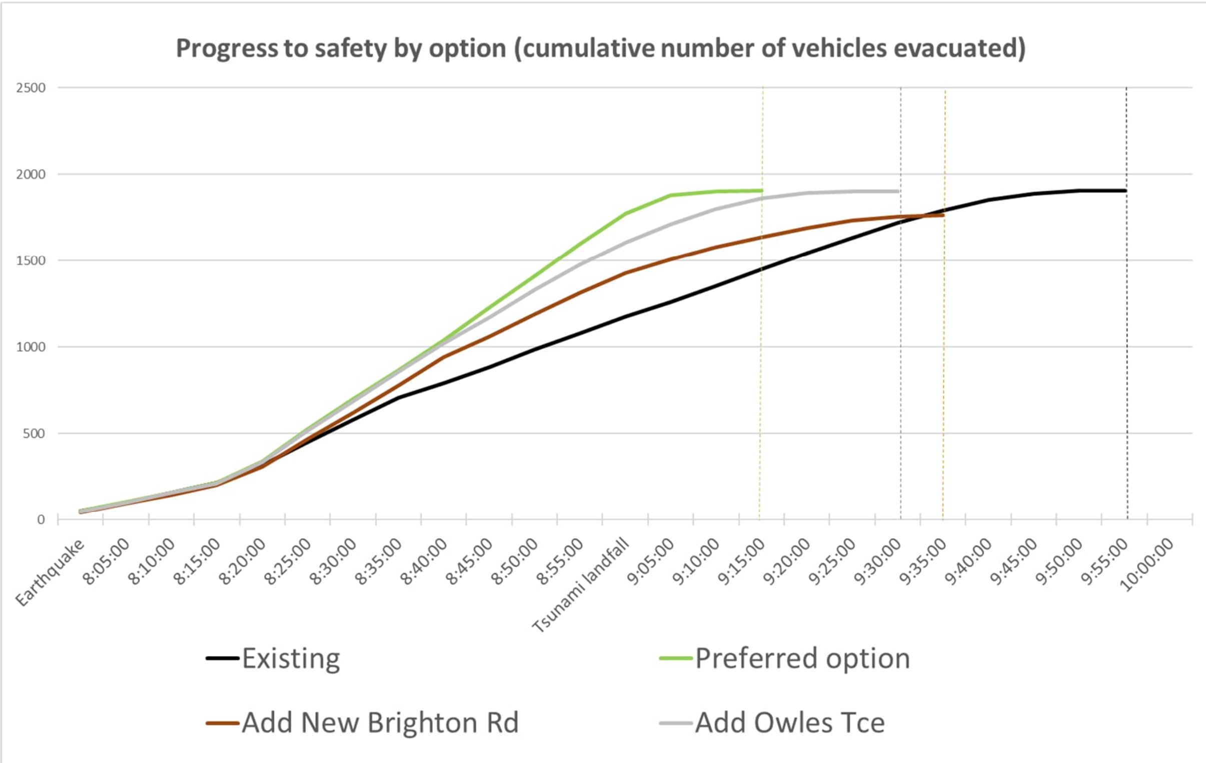

Figure 3 - Cumulative evacuation of adding Owles Terrace or New Brighton Road compared to recommended option (7a)

Scenario	run out time
1	9:57:03
2	9:35:47
3	9:48:37
4	9:24:30
4a	9:23:40
7	9:15:40
7a	9:12:25
8	9:36:01
9	9:18:44

Figure 4 – Evacuation Time outputs for each option

Modelling Outcomes

The existing network (Do nothing) is predicted to perform poorly, supporting an evacuation time of 1 hour 57 minutes.

The recommended option (7a) has the quickest evacuation time of 1 hour 12 minutes and includes the following;

- Signalised T intersection with two lane approaches and queue detection,
- Second westbound lane through the T-intersection, extending across the bridge to Anzac Drive traffic signals.
- Disconnecting New Brighton Rd and Owles Terrace from the intersection
- Reprioritising intersections along Hardy Street (to make Hardy Street and Seaview Road the direct route to the new T-intersection adjacent to the bridge)

Therefore, the recommended option (7A) is predicted to make emergency evacuation of the New Brighton Area over Pages Road Bridge 45 minutes faster (40 minutes reported in the public to be conservative considering sensitivity). The recommended option is the most efficient transport infrastructure solution for evacuating New Brighton in an emergency.

Other work needs to be done by Civil Defence to bring the evacuation time below 1 hour timeframe (i.e. public education on evacuation planning). Infrastructure alone, whilst being an indispensable component, will not ensure the outcome in the event of an emergency.

Pages Road Bridge Replacement

Traffic Modelling Report: Evacuation Scenarios

Christchurch City Council

CONTENTS

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EXECUTIVE SUMMARY

The Pages Road Bridge is a lifeline connecting the centre of New Brighton to the rest of the city, and it requires replacing to enhance resilience. There is an opportunity to investigate how well the current bridge and infrastructure could support a ‘rapid’ tsunami evacuation.

The tsunami threat for the New Brighton area is a 26% probability of a magnitude 8 or bigger earthquake on the Hikurangi subduction zone, within the coming 50 years. For context, the design life of the proposed bridge replacement is 100 years.

Tsunami hazard modelling shows that a magnitude 9 earthquake on the southern Hikurangi subduction zone (the largest earthquake considered possible from this source) could generate a damaging and potentially lethal tsunami for the Christchurch coastline that could arrive in 60-90 minutes. The New Zealand Probabilistic Tsunami Hazard Model indicates that tsunamis with wave heights of 5 metres or more (from all sources – close to New Zealand and from across the Pacific Ocean) can be expected along the Christchurch coast every 150-350 years.

Traffic modelling predicts that, under an emergency evacuation scenario for the existing Pages Road Bridge and surrounding transport network, even if the Community responded rapidly, the current estimated evacuation time is around 2 hours. Whereas tsunamis from regional sources such as the Hikurangi subduction zone can arrive in 1 hour.

The traffic modelling also highlights bottlenecks which will slow the evacuation and expose people to the hazard. The proposed design to include an extra outbound lane and removal of the five-arm roundabout, as part of the bridge replacement scheme, is predicted to reduce this exposure by over 1,000 people.

Though the overall probability of risk is low – most tsunamis are small and may not even inundate land, and many residents live in lower risk areas. The value of life “saved” - is extremely high, with a robust mid-point benefit-cost ratio of 15:1, which has been adjusted to take account of low occurrence probability

This report recommends that adding a second lane would generate value of life savings, even accounting for the low probability of a catastrophic tsunami event.

1. BACKGROUND

1.1. One of the main objectives of the Pages Road Bridge Renewal Project , is : "To construct a resilient replacement of the Pages Road bridge in New Brighton"

1.2. New Brighton is located in a Coastal Hazard zone, and faces the threat of tsunamis from multiple sources. Tsunami modelling commissioned by Christchurch City Council and Environment Canterbury, among other sources, indicates a threat to the Christchurch coastline from regional sources, and could arrive within 1 hour of an earthquake.

1.3. Transportation Planning and Modelling input has been sought by the Project and Delivery teams to consider how the Pages Road bridge replacement and Pages Road / Seaview Road intersection can be best designed to support a timely evacuation.

1.4. A platform for testing has been built in Paramics Discovery, using the highly effective vehicle following and dynamic assignment method, to inform the likely performance outcomes of each option to a required level of confidence. This model informs the likely risk of exposure to tsunami hazard, resulting from network reliance issues.

1.5. The conversion of exposure into monetised value of life generates overall monetised estimates, for purposes of informing investment assurance.

1.6. Literature from the University of Canterbury on the risks and likely outcomes of a tsunami represent the best available information for calibrating some key parameters of the models. This includes a survey of the affected community to ascertain evacuation behaviours following the Kaikōura Earthquake. Professor Thomas Wilson has also reviewed the proposed assumptions and sensitivity testing parameters for tsunami evacuation behaviours

1.7. Data and assistance from Helen Jack at Environment Canterbury Regional Council has allowed understanding into the context of risk exposure, based on recurrence and hazard by possible wave sizes (inundation, area considered 'hazardous'). Naturally, there are caveats behind these data, most of which is coming from uncertainties in earthquake and tsunami models.

1.8. Thanks is due to Tom Wilson, Helen Jack, Laura Tilley and Danielle Barnhill for their research, time and assistance in helping a transportation planner engage with tsunami dynamics.

1.9. Management and testing of uncertainty is a key aspect of this report, in order to provide a reliable and even handed assessment of options. Peer review and external expert review of the modelling and natural hazard assumptions provide added confidence.

1.10. Risk is treated in accordance with Waka Kotahi NZTA Risk Management Guide.

1.11. The outcome of this report is to identify a preferred design option, and consider the merits of investment for purposes of informing a business base.

2. METHODOLOGY

2.1. The project modelling methodology is indicated in Figure 1:

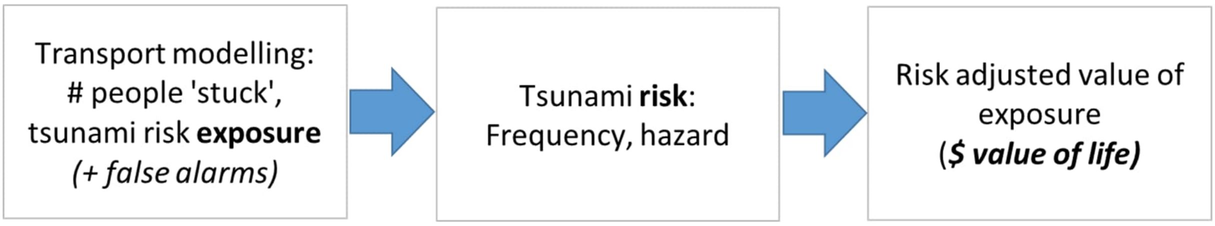

Figure 1: Project modelling methodology

2.2. Transport model calibration assumptions – including behaviour – are informed by best available research (Barnhill D et.al[1], Tilley L[2], and Barnhill D[3]) and kindly reviewed by Alice Evans, Laura Tilley and Professor Thomas Wilson, of Canterbury University [4]

2.3. Understanding of tsunami risk, including how to contextualise the transport modelling outcomes is informed by multiple sources, including Canterbury University, Environment Canterbury[5], Civil Defence, and NIWA and GNS Science tsunami modelling reports for many different tsunami sources (prepared for Christchurch City Council and Environment Canterbury)[6], and a GNS report on Tsunami hazard posed by the Kikurangi subduction zone interface (prepared for the Earthquake Commission (EQC))[7], all including some degree of tsunami modelling assumptions.

2.4. A critical determinant to a successful evacuation will be the community response time: how quickly households pack up and leave. This is determined by their 'risk perception'. There is no means to predict this. The only recent, local observation comes from the Kaikōura earthquake of 14 November 2016 (see page - 13 -). This cannot be used as a basis for testing

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[1] Barnhill D, Lee, L, Wilson, T, Hughes, M, Stewart, V, 2018, "Report on Survey of Eastern Christchurch and Banks Peninsula community's tsunami risk perception and evacuation dynamics following the 2016 Kaikōura tsunami: preliminary results".
[2] Tilley, L, 2018 "Tsunami Exposure Assessment – for New Brighton, South new Brighton and South shore, Christchurch, New Zealand." A Dissertation developed towards completion of Master of Disaster Risk and Resilience, Department of Geological Sciences, University of Canterbury
[3] Barnhill, D, 2020, Tsunami Evacuation Dynamics following the 2016 Kaikōura Earthquake in Christchurch and Banks Peninsula, New Zealand, to inform Tsunami Evacuation Modelling for Banks Peninsula, A Dissertation developed towards completion of Master of Disaster Risk and Resilience, Department of Geological Sciences, University of Canterbury
[4] Director of Disaster Risk and Resilience, University of Canterbury
[5] Helen Jack, Senior Scientist
[6] NIWA (National Institute of Water and Atmospheric Research), 2018, Land Drainage Recovery Programme: Tsunami study, prepared for Christchurch City Council
[7] GNS Science, 2019, Multiple tsunami modelling for Canterbury, prepared for Environment Canterbury

because the majority of evacuations occurred far too late, even after the first waves of the tsunami would have arrived.

2.5. Options which accommodate ‘late evacuation’ behaviour have not been tested. Aside from being far too late, the required expenditure to support a late, mass evacuation put simply could be uneconomic, considering the unlikelihood of a major tsunami occurring during the 100 year lifespan of the project.

2.6. Instead, a plausible assumption has been made – one which may need extensive communication and work with the community to guarantee – that 80% will commence evacuation between 15 and30 minutes after the earthquake. Effectively, that the Community is able to and does perceive risk to life after feeling a long or strong earthquake. This means that each option is being tested whilst the network is placed under immense pressure.

2.7. Further work is underway to help make this assumption a reality, by partnering with Civil Defence and engaging with the Community to inspire planning and awareness.

3. UNDERSTANDING THE TSUNAMI RISK

A. Source of natural hazard

3.1. Tsunamis are usually generated by earthquakes causing a sudden movement of the sea or lake floor, but they can also be caused by submarine landslides and volcanic eruptions. Tsunamis originate from local and regional sources (close to the New Zealand coast – within 3 hours' travel time of Christchurch) and distant sources (in and across the Pacific Ocean with 3-16+ hours' travel time to Christchurch), as shown in Figure 2, (from Jack, H, 2019)[8].

3.2. The share of observed tsunamis by source is indicated in Figure 3

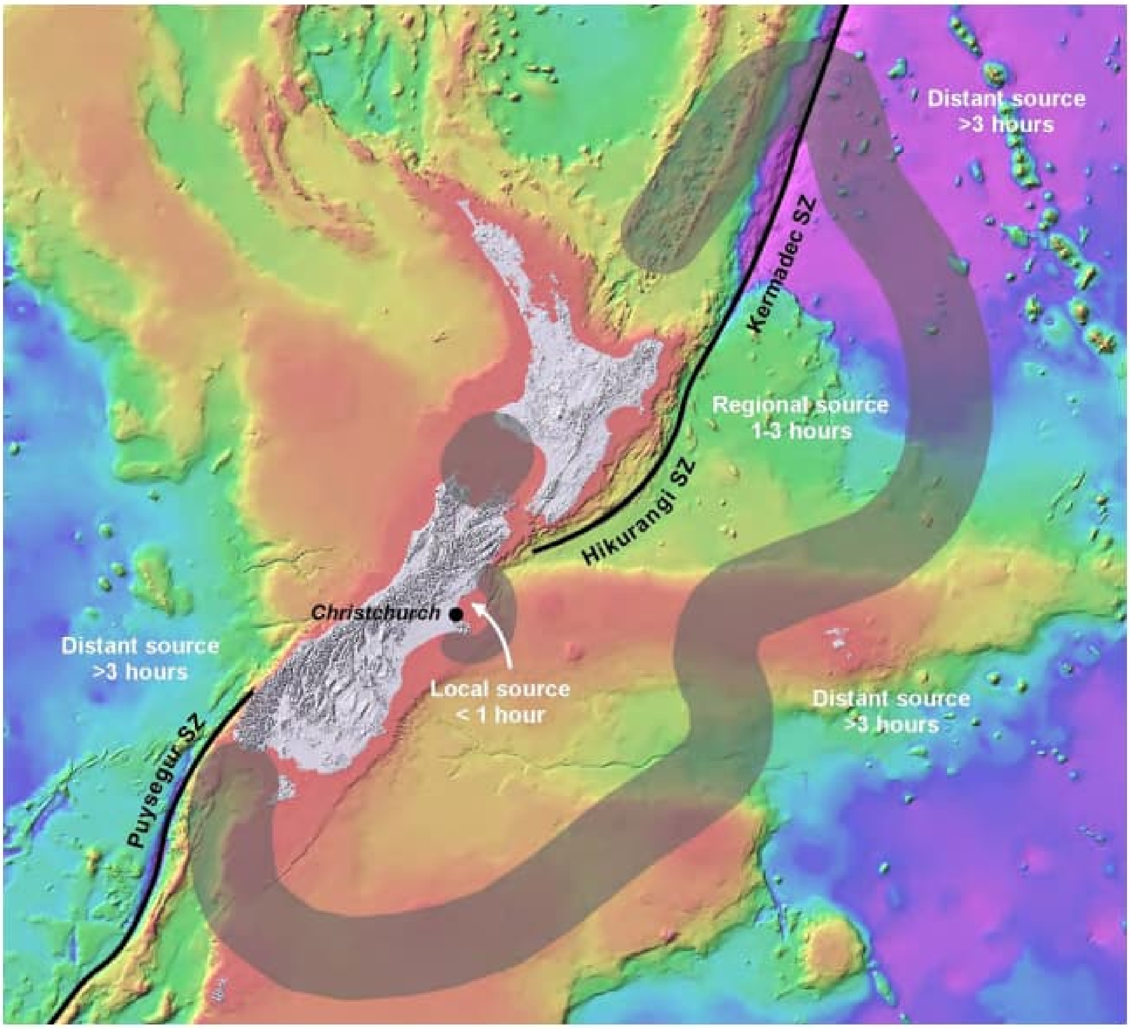

Figure 2: Location of Tsunami sources, Jack, H, 2019

[8] Source: Helen Jack, (2019) Environment Canterbury Technical Report Science Group: Review of tsunami evacuation zone for Christchurch City.
https://www.ecan.govt.nz/document/download/?uri=3734968

Year	Source	Earthquake Magnitude	Reference
1868	Peru	Mw = 9.1	(De Lange & Healy, 1986; Goff et al., 2012; Lane et al., 2012)
1877	Chile	Mw = 8.7	(De Lange & Healy, 1986)
1960	Chile	Mw = 9.5	(Borrero & Goring, 2015; Goff et al., 2012; Lane et al., 2012; Power, 2013)
2010	Chile	Mw = 8.8	(Lane et al., 2012)
2015	Chile	Mw = 8.3	(National Oceanic and Atmospheric Administration, 2015)
2016	North Canterbury	Mw = 7.8	(Lane et al. 2017)

Figure 3: Observed tsunami history, New Zealand[9]

3.3. Analysis of paleo tsunami (soil) deposits,[10] indicates the majority of earthquakes pre 19th century are from distant sources

i. Distant source

3.4. Historic records and tsunami modelling suggests that tsunamis affecting Canterbury most commonly originate from distant sources. With a 6 – 12 hour evacuation time, it is reasonably expected that the community will be able to evacuate and that an effective community evacuation plan would represent a more effective and valuable approach than infrastructure based. Risk might be found either in complacency, or attempting to re-enter in order to evacuate more possessions.

ii. Regional Source

3.5. Tsunami modelling suggests that tsunamis originating from regional sources, such as the Hikurangi or Kermadec subduction zones, occur less often than distant source tsunamis.

3.6. Regional sources are capable of generating large tsunamis that could arrive in 1 to 3 hours.

3.7. The Hikurangi subduction zone is capable of generating magnitude 9 earthquakes; with a 0.26 probability of a magnitude 8 or greater rupture in the coming 50 years, following increasing tectonic stress since the Kaikōura earthquake in 2016. The range of possible tsunamis generated from a magnitude 9 earthquake on the southern Hikurangi subduction zone include wave heights above sea level at the time (wave amplitude) at the Christchurch coast of between 3m and 8m, with a most likely wave height of 5 metres.

3.8. The Kermadec subduction zone trench could generate up to a magnitude 9.3 earthquake. Due to the relative remoteness from Canterbury, such earthquake may not be felt and perceived by Cantabrians as presenting a critical threat. However, due to the depth of the water, a tsunami could would travel quickly south and potentially arrive at Christchurch in two hours. There is presently a low degree of confidence that a wave of up to 12m could be generated. There is an estimated lower likelihood of a major tsunami from the Kermadec

[9] Source of tsunami history from Tilley, L, (2018, figure 2.1-1), adapted from Williams, J, 2016
[10] Power, 2013, shown in Barnhill, D (2020), Figure 2-4.

subduction zone trench relative to the Hikurangi subduction interface zone; however it remains a credible threat.

3.9. Regional Tsunami from the Hikurangi Trench is the Tsunami hazard used in the analysis as this poses the biggest risk to New Brighton residents evacuating. The evacuation time used in the analysis is 1 hour.

iii. Local source

3.10. Earthquake and tsunami modelling indicate that the local faults in Pegasus Bay and offshore north Canterbury are very unlikely to generate a damaging tsunami along the Christchurch coast, thus a local source tsunami is a much smaller threat than a regional or distant source tsunami for Christchurch. However, due to their proximity, if an earthquake did occur on one of these faults, effective evacuation would be unlikely.

3.11. The NIWA report (p100[11]) describes the different tsunami threats from four local earthquake sources, shown and explained in Figure 4 and Figure 5, respectively.

Figure 7-1: Faults used in local tsunami modelling. Single fault rupture scenarios of LeithfieldNC1137 and Pegasus1nw are modelled as well as combined fault of LeithfieldNC1137 and NortCant8 and Pegasus1nw and NorthCant4.

Figure 4: NIWA report to CCC p99: known source locations of local tsunami generation

[11] NIWA (National Institute of Water and Atmospheric Research), 2018, Land Drainage Recovery Programme: Tsunami study, prepared for Christchurch City Council

Table 7-1: Faults used in local tsunami scenarios. Maximum length, slip, magnitude and associated recurrence interval.

Fault Name	Length (km)	Slip (cm)	Mw	Recurrence interval (years)
Leithfield1137	45.1	236	7.4	12,500
Pegasus1nw	40.7	213	7.3	22,500
NorthCant4	25.3	132	7.0	35,000
NorthCant8	37.4	195	7.3	21,000

Figure 5: NIWA report to CCC p100: attributes and estimated occurrence of known submarine faults

3.12. Fortunately, a key prediction of NIWA[12] is that, individually, the faults would generate tsunamis more impacting on Banks Peninsula. This is partly due to the configuration of the faults, and that there is little known evidence to suggest that a larger tsunami could be generated. Wave heights would likely not exceed 1 metre above sea level at the time at the Christchurch coast.

3.13. There is an outlying possibility that a combined rupture of 'Leithfield1137' and 'NorthCant8' could generate 2-3m waves along the Christchurch coast. The compound frequency of the two faults would be 1/33,500 years.

3.14. There is little value in considering local threat tsunamis further, in terms of planning for infrastructure.

B. Tsunami risk – probability

3.15. Due to their proximity to the Canterbury coast and capability of generating large tsunamis, most consideration will be given to the threat posed by regional sources.

3.16. Although paleo tsunami data in Canterbury has not identified evidence of regional source tsunamis, analysis of shell layers in Lake Grassmere (located on the Cook Strait in Marlborough), deposited by tsunamis, contributes to a record suggesting four ruptures of the Hikurangi subduction zone in 2,000 years[13].

3.17. There is currently a 0.26 probability of the Hikurangi zone generating a >M8 earthquake within the coming 50 years. The recurrence range is estimated to be 335 – 655 years. A M9 event is considered the largest earthquake that could be generated on the subduction zone, and has a nominal recurrence interval of 2,500 years, with a large error margin[14].

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[12] NIWA (National Institute of Water and Atmospheric Research), 2018, Land Drainage Recovery Programme: Tsunami study, prepared for Christchurch City Council, p100
[13] https://pubs.geoscienceworld.org/ssa/tsr/article/1/2/75/605992/Paleotsunamis-on-the-Southern-Hikurangi-Subduction
[14] Jack, H, Environment Canterbury, Senior Scientist – Natural Hazards

C. Variables of a tsunami

3.18. The main economic benefit of improving Pages Road Bridge is expected to come from increasing ability to evacuate the community. The number of additional people who can be evacuated from a regional source tsunami (i.e. with a 1 hour warning time) between different road network scenarios makes up the majority of (monetised) benefits justifying infrastructure investment.

3.19. Two key variables are required: firstly, a robust network scenario evacuation performance, but secondly, a reasonable representation of the scale of human life lost in a given tsunami situation.

3.20. There are multiple methods used by experts in forecasting tsunami events. Predicting the frequency of major earthquakes is a major component, but not all major earthquakes will generate tsunamis, and multiple stochastic model runs are required to develop a range of possibilities.

3.21. The size of the earthquake is a key factor, but not the sole factor. For example, the amount of slip on different parts of the subduction zone interface during the rupture (differential slip), which cannot be known in advance[15].

3.22. The range of maximum wave heights expected to affect Christchurch from all sources range from 0.1m – 12m in height, depending on the location, magnitude and differential slip pattern of the source earthquake. A regional source magnitude 8 – 9 earthquake on the Hikurangi subduction zone is capable of generating anything between 2-8 m wave heights.

3.23. The path of the wave would also dictate the speed and therefore the amount of allowable evacuation time which could be considered. The southern extent of the Kermadec subduction zone, for example, is located 1,000 km from the Canterbury coast, yet could yield a tsunami arriving within 2 hours, as the deeper water along the Kermadec and Hikurangi trenches allows for faster wave speeds.[16]

3.24. The tsunami itself is usually measured or categorised in terms of the maximum wave heights; whereas a tsunami is a series of waves lasting several hours to days.

3.25. The position of the tide also impacts on the amount of land that may be inundated. However, tsunami events represent a series of waves delivered over a number of hours; henceforth it is likely that a single tsunami event could span a range of tidal positions.

3.26. Once on land, hydrodynamic modelling of velocity and inundation shows highly variable outcomes. The Christchurch east coast is characterised by a sand dune, predicted to mitigate to some degree the threat from the coast directly, in the majority of scenarios. The main threat of inundation would come from the Avon estuary, as shown in Figure 6. Figure 6

[15] ibid

[16] Jack, H, Environment Canterbury, Senior Scientist – Natural Hazards

clearly shows a blue line running on the east of the Southshore peninsula – indicating a lower probability of inundation during a Hikurangi subduction zone tsunami.

3.27. Figure 6 represents the likelihood of inundation from a tsunami generated by a magnitude 9 earthquake on the southern Hikurangi subduction zone, assuming the largest wave arrives at high tide. This is derived from 30 different slip scenarios, each producing a different size tsunami, ranging from 3-8 metres, with a mean of 5 metres.

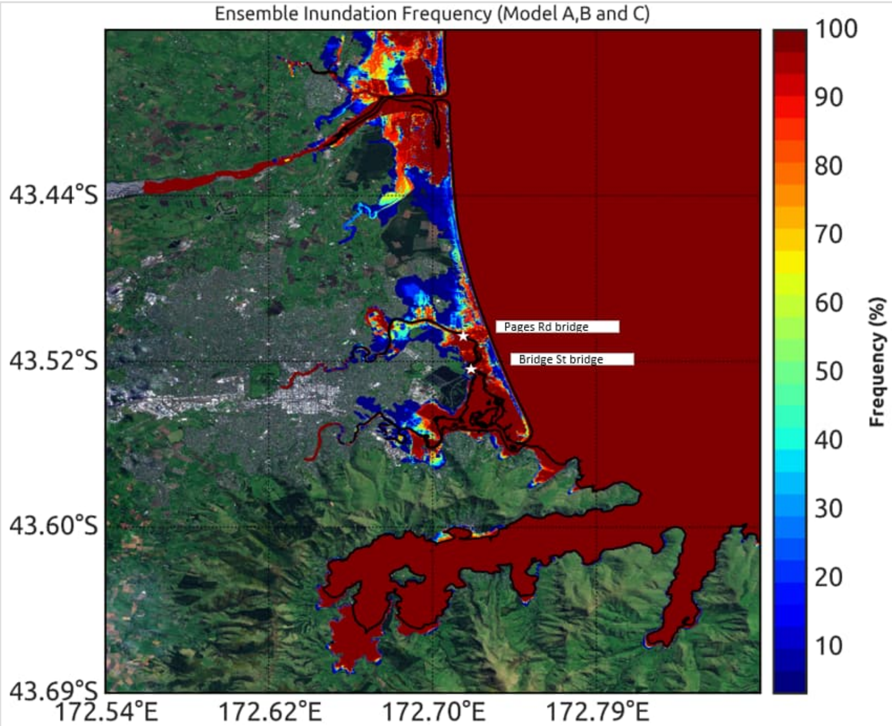

Figure 6: likelihood of inundation from a tsunami generated by a magnitude 9 earthquake on the southern Hikurangi subduction zone, assuming the largest wave arrives at high tide.[17]

3.28. Mesh block population analysis suggests that around 60% of the Pages Road bridge catchment would be located within areas almost certain to be inundated under the scenario.

3.29. Inundation can encompass a range of water depths. One measure of hazard used in river flood hazard analysis is the product of water depth (m) and velocity (m/s). Areas are considered 'high hazard' when the product is greater than or equal to 1m/s.[2] There are limitations to applying this to tsunami hazards, as sea water is often carrying a large amount of debris so is likely to be more hazardous at lower hazard values, but it could be applied with caution.

3.30. Further analysis from Environment Canterbury is indicative of a high degree of hazard: for areas estimated with a 90% or greater probability of inundation, about 90% could be considered to be 'high hazard' using this method.

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[17] Provided courtesy of Jack, H

3.31. There would also be the matter of debris, which are known to be extremely hazardous.

3.32. Finally, even if it were possible to predict with absolute certainty the depth, velocity, charge of debris and the *exact* extent of coverage, the human factor is another critical variable, and also difficult to predict.

3.33. The degree and speed by which the community responds and can evacuate is the leading detriment. This has been analysed in detail, and the number of people unable to leave the network 'in time' has been estimated to an acceptable degree of confidence. Helen Jack at Environment Canterbury suggests it would be an overestimation to assume that everyone left within New Brighton, South New Brighton and Southshore would be a casualty in a Hikurangi tsunami, given that not all of the area is inundated in the tsunami model. However it's also suggested that those who do end up within the 'high hazard' area seldom survive,[18] which does simplify the range of outcomes of exposure.

3.34. There is also the matter of uncertainties in the transport modelling, which are discussed in length and widely challenged / tested. The subsequent peer review of the modelling, including recommendations and advice have also been tested.

3.35. Therefore data relating to the above tsunami variables – ranging from earthquake frequency to inundation - will be used to scale the consequences of transport network performance shortfalls, in terms of the value of life exposed to varying degrees of hazardous inundation.

3.36. The philosophy of estimating monetised values must be based on realistic ranges, testing sensitivities to the greatest extent possible, purely to demonstrate assurance in significant infrastructure investment.

D. Review of Kaikōura evacuation

3.37. In order to understand human responses, and henceforth limit the bounds of behavioural uncertainties, observed evacuation data – relating to surveying communities after the Kaikōura 2016 earthquake – could offer insight.

3.38. Most traffic models can be validated against a ready supply of count and speed data. However, a model of an exceptional circumstance – such as a catastrophic tsunami from a regional source – has limited or zero data to inform variables such as response time, which dictate outcomes such as network density, route choice, delays, and the preservation of human life. Therefore, with higher stakes and less ability to validate, the treatment of uncertainty is *uniquely* important.

3.39. A rare insight into local evacuation behaviour is the Barnhill, D, et.al survey of coastal communities, following the Kaikōura earthquake, and subsequent tsunami response.

3.40. This research offers a rich array of information suitable for validating *some* assumptions.

[18] Marion Schonfeld, CDEM

3.41. But, because the evacuation was far too slow, and that ¼ are estimated to have not responded at all, the data is of limited to use in validating modelled network performance.

3.42. However, the model will be a useful tool in motivating a Community response plan. The Kaikōura earthquake ruptured multiple faults, and such events are more capable of producing larger tsunamis[19]. It might be considered fortunate a larger wave did not materialise, because at the point of landfall, more than half of the community were still present, (approximately 4,000 people) including 41% of residents still within their homes.

3.43. No amount of transport infrastructure provision would have made any difference. In the event of a 5m wave – instead of 0.5m - a death toll of hundreds to thousands would not be a fanciful supposition.

3.44. A critical parameter is response time, and the current public education message in New Zealand is 'Long and strong – get gone!'; if people feel an earthquake where the shaking is either long (more than one minute) or strong (making it hard to stand up) they should evacuate the appropriate tsunami evacuation zones immediately without waiting for an official warning. The current plan for responding to a life threatening tsunami from a local or regional source is that the Community respond to the long or strong earthquake and evacuate quickly, without being prompted by the tsunami sirens (Tilley, L, p17). The reason for this approach is that precious minutes would likely pass before a tsunami can be confirmed and the sirens manually activated. Even more time would elapse in establishing more complex management plans, such as traffic control systems – if indeed there were time to establish them, and personnel were willing to enter the evacuation zone, effectively risking their lives.

3.45. Therefore a key parameter for the modelling excludes the use of special management plans which require human activation.

[19] NIWA (National Institute of Water and Atmospheric Research), 2019, Land Drainage Recovery Programme: Tsunami study, prepared for Christchurch City Council, p100

3.46. A summary of variables relevant to the model:

3.46.1. Of those who did evacuate, 61% required 30 minutes or less to 'get ready'. The model assumes that 80% would leave after 30 minutes

3.46.2. It took between 2 and 120 minutes to evacuate – the model predicts between 2 and 117 minutes.

3.46.3. 80% evacuated by car, 2% walked and 1% cycled whereas the model assumes 100% would drive.

3.46.4. 36% were warned of the impending tsunami by the earthquake itself, 39% by the sirens. The model assumes that 100% would be warned by the earthquake

3.46.5. Those who evacuated quickly did not experience congestion. 39% of respondents observed congestion. In the model 80% of evacuees would experience some congestion, resulting from a more condensed reaction time.

3.46.6. The minimum time spent at evacuation point was 15 minutes, whereas in the model, no traffic returns

3.47. There are some useful observations around behaviour:

3.47.1. "people who left after the earthquake, having decided not to wait for a possible tsunami siren, did not experience congestion"

3.47.2. "People seemed calm and were giving way when they did not have to"

3.47.3. "Some vehicles avoided traffic by driving on the wrong side of the road"

3.47.4. "Some cars tried to exit their driveways, saw the traffic and went back inside"

3.47.5. "Only when the sirens came on did people start to move - this was when the roads became congested and the traffic was at a standstill"

3.48. There are clearly mixed accounts of the traffic environment, likely to be perceived at different points in space and time. Those who left early experienced no congestion, whereas the sounding of the siren appears to have triggered mass response and congestion. There would likely be a correlation between perceived congestion and aggression levels; whereby drivers' behaviour courteously when not exposed to congestion, and erratically, aggressively when there is congestion. (It should also be noted that 'congestion' is a relative term, depending on one's sensitivity to delay).

3.49. The modelling assumes that everyone perceives the danger and evacuates, and provides a basis for testing infrastructure options best suited to supporting this.

E. Assumed risk for study

3.50. The Waka Kotahi NZTA Risk Management Guide (Minimum Standard Z/44) applies to projects with a capital value of greater than $5m, and therefore requires consideration.

3.51. Risk shall be managed in accordance with principals contained within these guidelines, and is likely to be a requirement of attracting Waka Kotahi Funding Assistance.

3.52. The project can be considered in terms of the value of opportunity in mitigating a low likelihood event which poses an extreme threat, towards identifying the value of the opportunity to mitigate (see ibid Table 4.6: “NZTA threat and opportunity risk matrix”)

3.53. The modelling provides insight into the (present) value of the threat. Application of this must be adjusted for likelihood, and likelihood is estimated based on review of the hazards undertaken above.

3.54. Both the NIWA and GNS studies explicitly state that there are uncertainties within analysis, and in accordance with best practice approach to managing uncertainty, a range of outcomes shall be prepared, based on degree of frequency. More detailed discussions with Helen Jack (Senior Scientist at Environment Canterbury) provide a deeper understanding as to uncertainty, and to the context of tsunami model outputs for purposes of fulfilling an infrastructure investment assurance process.

3.55. The parameters used to estimate opportunity costs include (those discussed in more detail in section 3C “Variables of a tsunami”):

3.55.1. The robust transport model outcome
3.55.2. Estimated exposure of death derived from transport modelling, estimated across several tsunami scenarios.

3.56. The outcome would then be factored by the design life of the bridge, estimated to be 100 years. For example, the consequences of an event returning once per 1,000 years would be assigned a 1/10 probability of occurring within the bridge design life, and henceforth 1/10th of the estimated monetised death toll would be applied.

3.57. There is no single method for estimating tsunami recurrence; this is estimated from paleo tsunami data (e.g. examination of evidence on land of tsunami activity), and also from modelling tsunamis from known earthquake sources. The estimation processes yield large ranges. The range of possible outcomes – and how these relate to monetised value of life preserved by a scheme – will be reported.

3.58. As reported, there is no real opportunity to validate the transportation evacuation model. Uncertainty is managed through:

3.58.1. close attention to modelling best practice
3.58.2. sensitivity testing critical variables
3.58.3. independent peer review

3.59. Therefore focus on scheme financial appraisal can only provide an overall high level investment assurance, rather than settling on an absolute figure.

4. TRANSPORT MODEL BUILD

A. Synopsis

4.1. The models are developed based on as much observation as is available, but also make some assumptions in the absence of reliable data.

4.2. Figure 7 indicates which parts of the model are observed, and which are assumed.

4.3. Some of the ‘assumed’ variables might normally be considered as ‘observed’, for example, behaviour. Most models are developed with ‘normal’ behaviour parameters, based on extensive observation and experience. For example, sensitivity to delay, aggression, the likelihood of driving on the wrong side of the road. However, in the event of a Tsunami evacuation, it is likely that behaviour would be different, especially if drivers had a high perception of danger.

Observed	Population	Based on 2021, resident
	Road geometry, design	Aerial photo / driven network
	Speed / times	Estimated from geometry / traffic calming
	Signal operations	Signal (SCATS) data
Assumed	Behaviour in evacuation scenario	Assumes normal values
	Safe area destination	Assumed to be Cowles Stadium
	Response / departure times	Assumes prompt reaction
	Mode choice	Assumes 100% car, 2 persons / car
Predicted	Route choice	Computed from geometry, speeds, behaviour
	Delays / network performance	Computed from all attributes

Figure 7: Observed, assumed, and predicted aspects of the model

4.4. There is a lack of empirical data presently to alter the behaviour parameters. At least by retaining ‘normal’ parameters, there is an understanding of how the model is behaving, and the outcomes can be properly explained and understood.

4.5. The model developed represents a consistent platform for testing the performance of the different scheme options.

4.6. Some of the uncertainties clearly need to be understood, and will be examined through ‘sensitivity testing’. That is, the performance of the recommended option will be tested against some of these, including different behaviour types, (varying degrees of ‘panic’) and population growth scenarios

4.7. Model development philosophy has been not to rely upon emergency action plans, which could be applied to the network. For example, changing the traffic signals to remain green to clear Pages Road.

B. Methodology

4.8. For the testing of the Pages Road Bridge and Seaview Road intersection, a detailed simulation has been run, using the software 'Paramics'. This bounds of this detailed simulation have been informed by the bigger (and less detailed model) "CAST".[20]

4.9. CAST informs broader route choice likelihood, including identifying the areas more likely to route via Pages Road or Bridge Road. The Paramics simulation provides a more detailed simulation of network performance, using demands derived from CAST.[21]

4.10. The extent of the Paramics network is determined on simulating the key routes (and available route choices) likely to affect arrive flow rates on the intersection approaches. This allows for dynamic assignment – route choice determined by operational conditions – and the optimum efficient outcome for each scenario tested.

4.11. Independent peer review has been sought to test and challenge assumptions, and provide assurance.

[20] Christchurch Assignment Simulation of Traffic (CAST), developed in Saturn v11.5
[21] As consistent with accepted modelling best practice

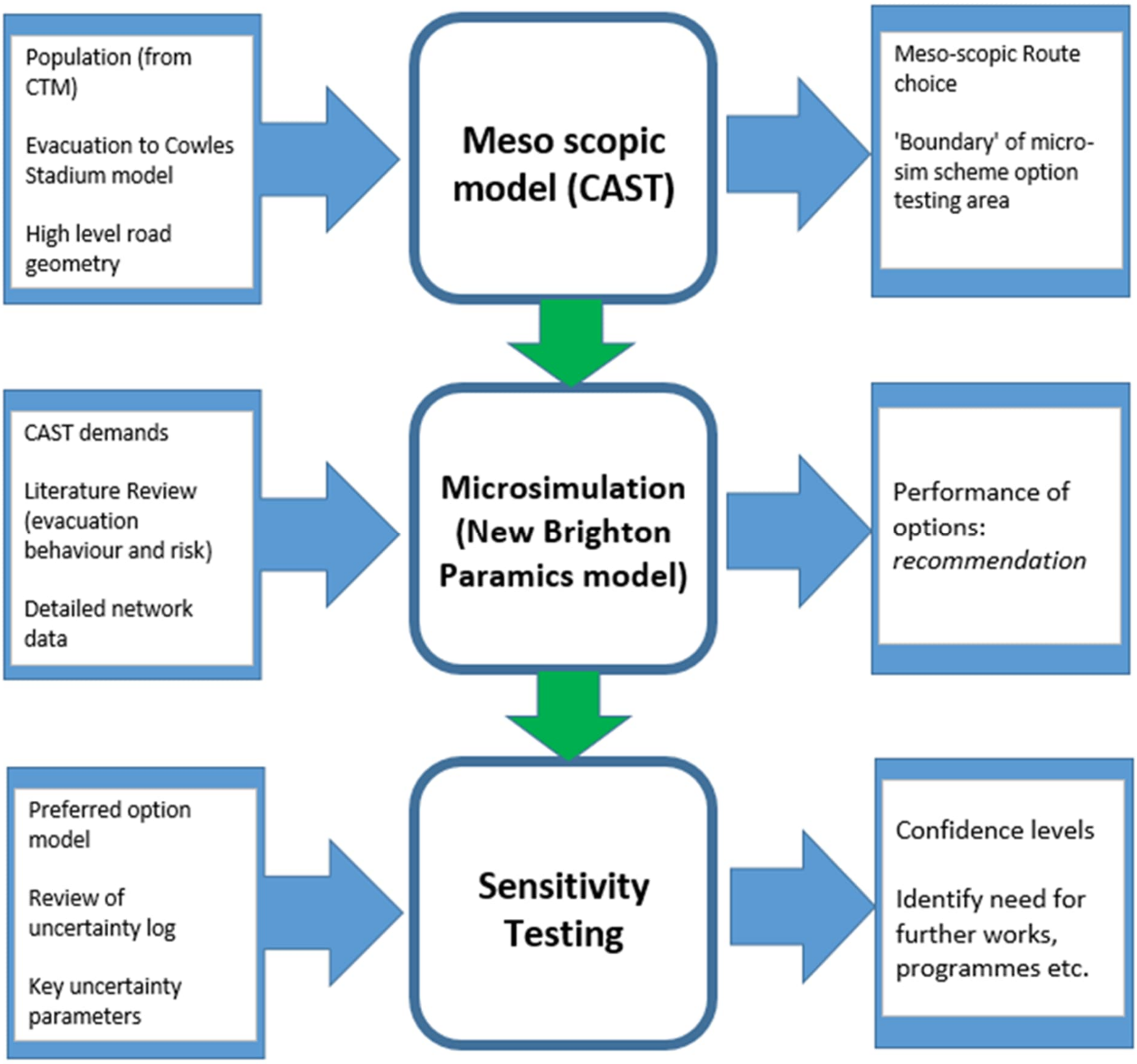


Figure 8: Transport modelling process

4.1. The simulation network is shown in Figure 9, and includes all of the routes of the Pages Road bridge catchment.

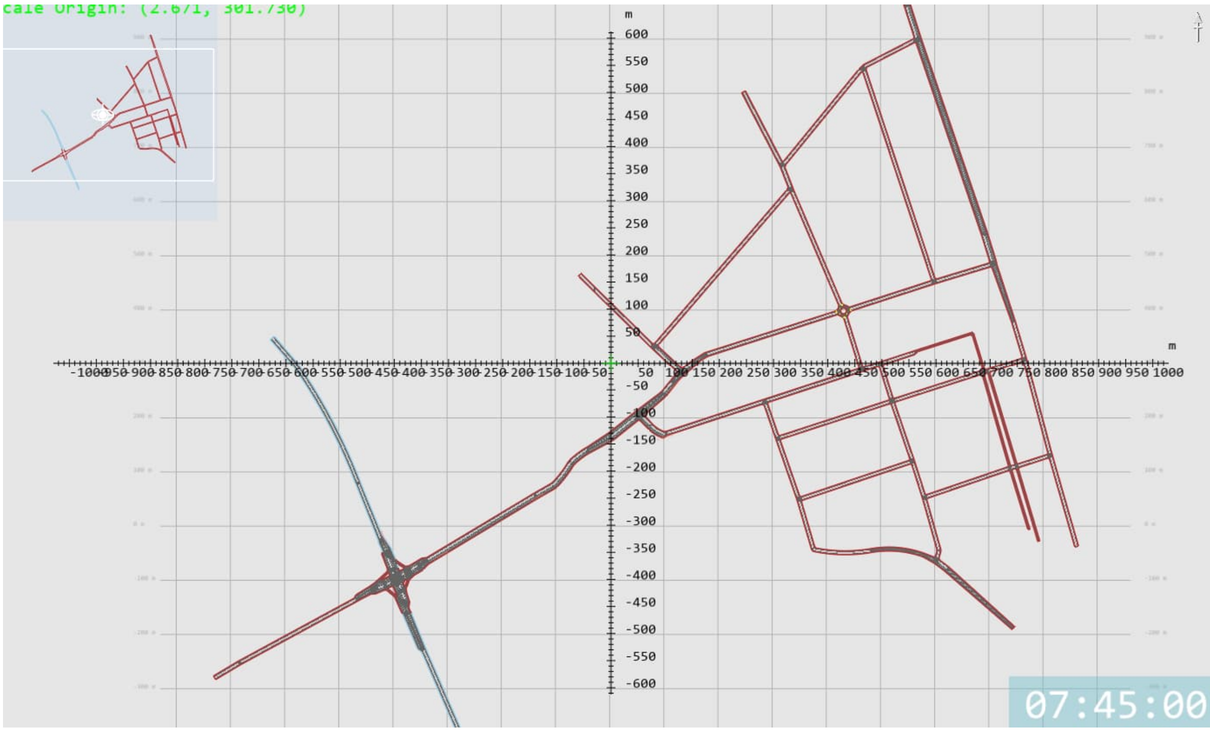


Figure 9: Modelled network for options testing

C. Testing philosophy

4.1. A key philosophy in testing is the avoidance of reliance on special traffic management measures, for example, changing the traffic light times, or using cones and similar Temporary Traffic Management (TTM) measures.

4.2. Whilst some TTM *might* be deployed, the project team have chosen to consider an environment where they are not. Agencies would likely be reluctant to deploy staff and resources, given the increased health and safety risk posed by the limited available evacuation time. Also the implementing of TTM on the ground would only be possible after a period of analysis, decision making and transporting resources.

4.3. *Instead,* there is an assumption that the Community will self-evacuate in the event that they experience a strong earthquake. The main public education message around tsunamis is '*long and strong – get gone!*'

4.4. A swift Community response is assumed, but would only be made possible through effective communication and education, and development of a Community led plan. Although targeted infrastructure improvements are valuable, they will not be effective without an effective and timely Community response. The modelling therefore assumes an effective community response, given that there is no realistic infrastructure based substitute to this.

D. Population distribution

4.5. The population catchment associated with evacuating via Pages Road is shown in Figure 10. It shows three zones:

4.5.1. Zone 1 – located around the south of Keys Road. North of this area is predicted (in CAST) to evacuate via Travis Road.

4.5.2. Zone 2 – including the Marine Parade – Lonsdale – Hawke Street 'block', including commercial area. North of this area is also predicted to evacuate via Travis Road.

4.5.3. Zone 3 – Located south of Beresford Street, and extending on Marine Parade south of Bridge Street. West of this area is predicted to evacuate via Bridge Street

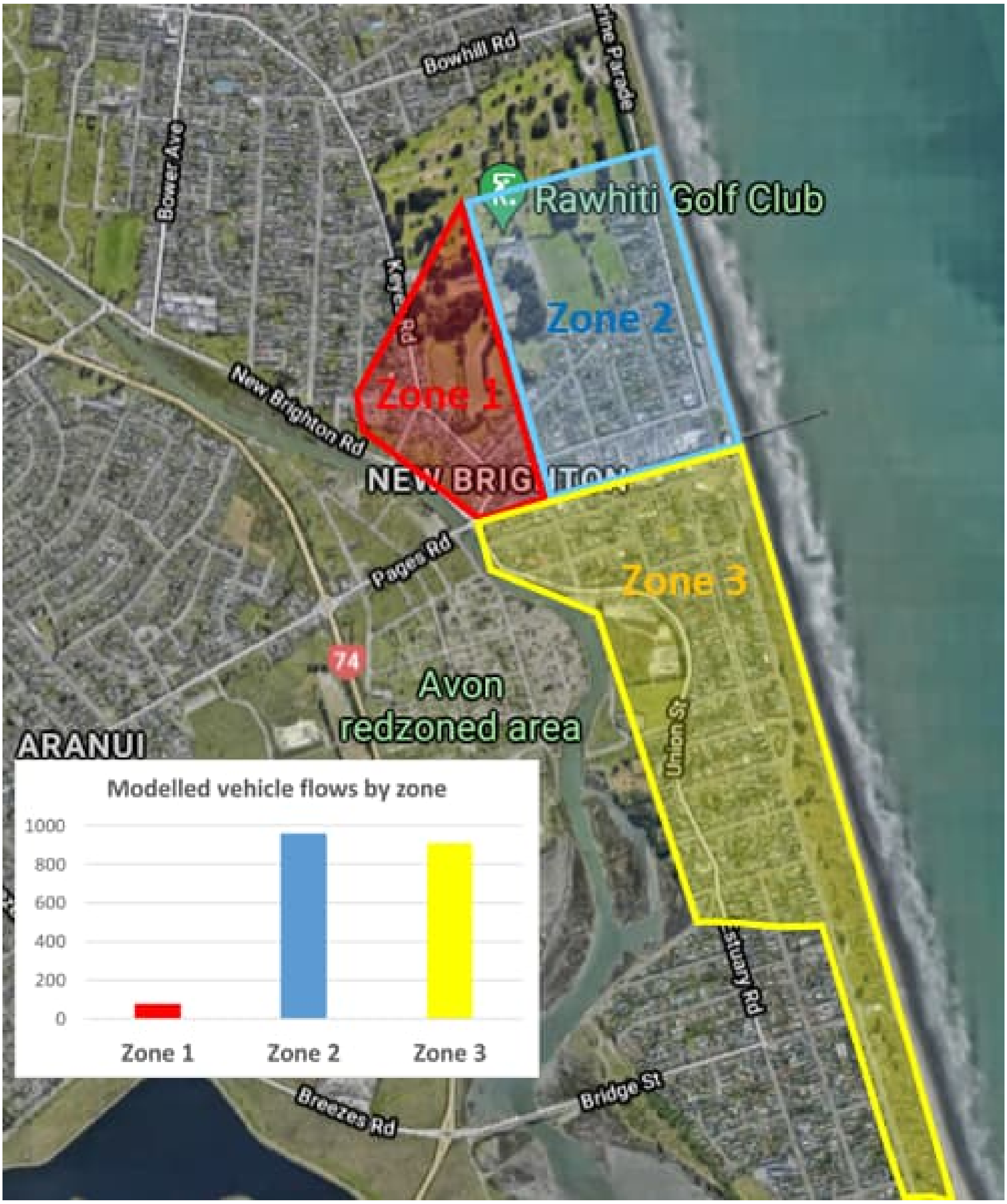


Figure 10: Estimated population catchments of the Pages Road route

4.6. A key outcome of the Saturn modelling is identifying that Zone 3 extends for south of Bridge Street. This is because Bridge Street is the only escape route serving the entire South New Brighton peninsula, and there isn't enough capacity on Bridge Street to support those demands. Consequently, approximately 16% of the Southshore / South New Brighton population is predicted to route north via Pages Road, to avoid congestion on Bridge Street.

4.7. Figure 10 also shows the origin of traffic attracted over Pages Road, and shows that Zone 2 – being closer, and including commercial areas – produces the most traffic on Pages Road

4.8. It will also be shown (see Figure 14) that the greatest exposure to risk (associated with the Pages Road option testing) involves people travelling from zone 3, given that routes from zone 3 are required to give way to traffic from other zones. The analysis of the hazard[22] also shows that several of the bottlenecks affecting zone 3 traffic exist with high risk inundation and water-hazard areas as well.

E. General network coding assumptions

4.9. The route choice parameters (controlled through many settings, including perturbation) have been retained at 'normal' levels, (a variable which is scrutinised in sensitivity analysis).

4.10. Gap acceptance simulation has also been retained at normal levels, with no extra ordinary 'risk taking' coded.

4.11. Zones locations are intended to represent a near to 'centre of gravity' location of the geographical area represented, and also allowing for likely route choice availability.

4.12. Signal operations are derived from SCATS, and, not relying on special signal plans (as discussed below), scripts intended to simulate SCAST variability, i.e. responding to unexpected high demands on Pages Road, are predicted to do so within the upper observed bounds (from the SCATS history file). Therefore it is intended that a normal SCATS response is simulated, rather than a special plan.

4.13. For the base model, the roundabout geometry has been replicated as closely as possible, noting that it is an unusual design layout.

[22] Using the GIS inundation modelling shared by Environment Canterbury (Jack, H), see Figure 6

5. DESIGN OPTIONS

5.1. The tested options are shown graphically in Appendix 1: Scheme Drawings, and listed in

5.2. Scenarios 8 and 9, (adding New Brighton Road, and access from Owles Terrace) are subsequently added. They haven't been recommended to date, given that the project team are intending to minimise conflict points at the intersection, to achieve maximum efficiency.

ref	Existing network (Do nothing)	"Give way" controls	Free left turn from Seaview Rd	Traffic lights	Single lane design	Dual lane design	Single lane bridge	Double lane bridge	MCR signals	change priorities Seaview - Hardys	New Brighton Road approach added	Access from Owles Tce added
1	✓						✓					
2		✓			✓		✓		✓			
3				✓	✓		✓		✓			
4		✓				✓		✓	✓			
4a		✓	✓		✓			✓	✓			
7				✓		✓		✓	✓			
7a				✓		✓		✓	✓	✓		
8				✓		✓		✓	✓	✓	✓	
9				✓		✓		✓	✓	✓		✓

Figure 11 Design options

6. OUTCOMES: MODELLED PERFORMANCE BY OPTION

6.1. The outcomes of the options listed in are shown in Figure 13.

6.2. Figure 13 shows the traffic count on Pages Road, through the Anzac Road intersection, at five minute intervals. Vehicle heading west from Anzac Drive are deemed ‘safe’.

6.3. The existing network (Do nothing) is predicted to perform poorly, supporting an evacuation time of 1 hour 57 minutes (after the assumed earthquake time); whereas a Hikurangi subduction zone tsunami could make land fall after 1 hour.

6.4. The evacuation success rate for each modelled scenario is shown in Figure 12, as numbers of people evacuated or not evacuated as the tsunami makes landfall.

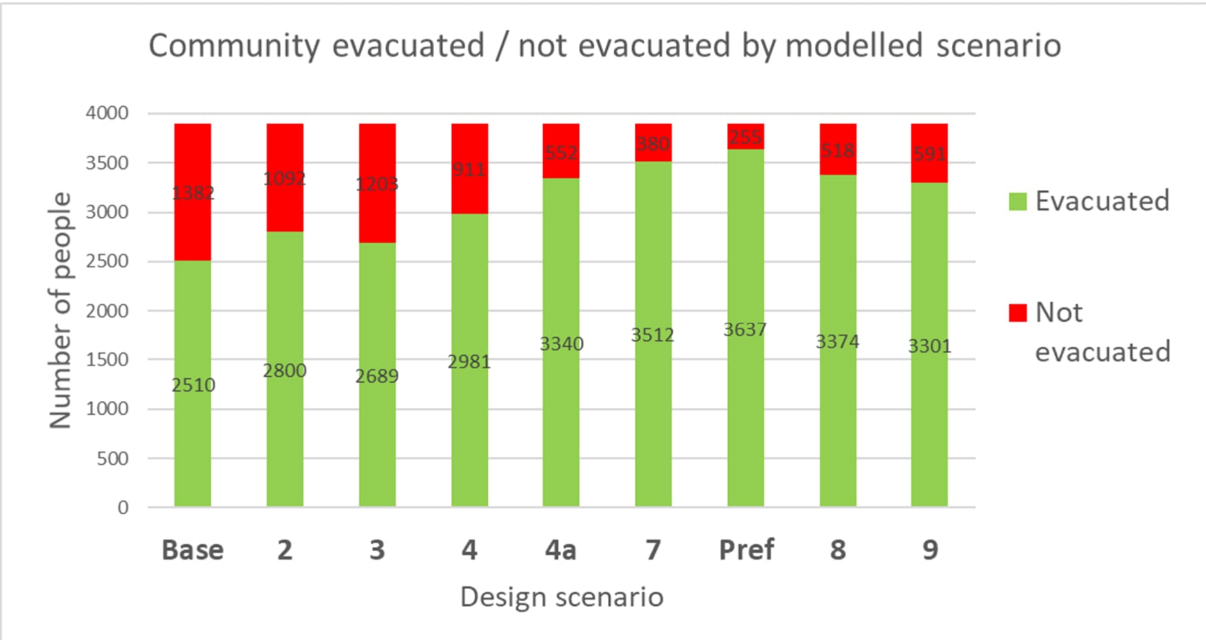


Figure 12: Rate of evacuation by scenario

6.5. The total evacuation rate and time per scenario is shown in Figure 13

6.6. The recommended option is for a signal controlled intersection with two-lane approaches and a two lane bridge, (with local minor intersection changes of priority). This network would support an evacuation time of 1 hour 12 minutes.

6.7. It is acknowledged that the recommended option does not achieve a full evacuation within the one hour; however further work will be recommended subsequent to the Pages Road bridge replacement (see section 12, (p- 64 -)).

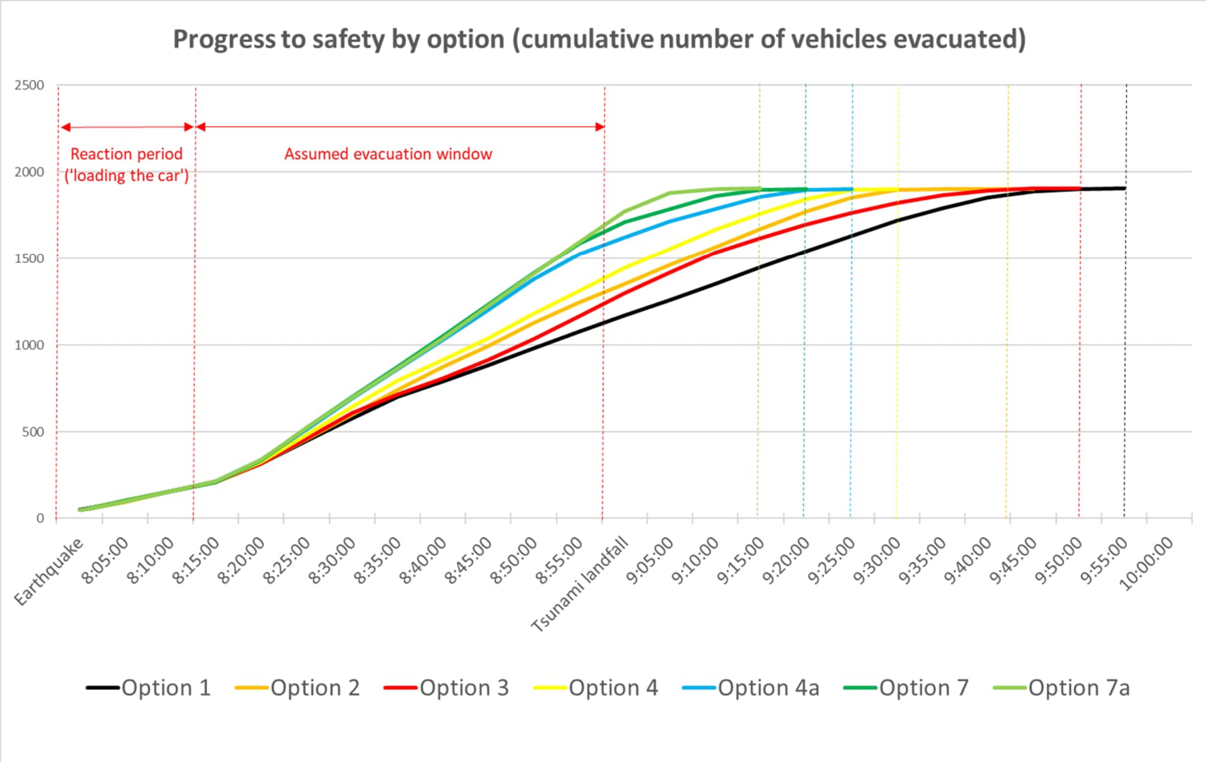


Figure 13: Cumulative escape (vehicles through across Anzac Drive)

6.8. Figure 14 shows some detailed outcomes for each option. It shows the location of 'unreleased vehicles,' (that is, demands that cannot enter the network due to extreme congestion). In real world terms, these would be people unable to exit their driveways. Figure 14 relates to the zones indicated in Figure 10, (p- 22 -)

Scenario	run out time	Un-released vehs at 0900				People in network at 09:00	Additional evacuees by option
		zone 1	zone 2	zone 3	total		
1	9:57:03	0	136	213	349	1382	-
2	9:35:47	0	0	224	224	1092	290
3	9:48:37	0	16	264	280	1203	179
4	9:24:30	0	0	189	189	911	470
4a	9:23:40	0	0	95	95	552	829
7	9:15:40	0	0	0	0	380	1002
7a	9:12:25	0	0	0	0	255	1127
8	9:36:01	0	0	0	0	947	435
9	9:18:44	0	0	0	0	591	791

Figure 14: Performance by option

6.9. Number of people present in the network is used to represent exposure to the tsunami hazard, when network performance is converted in to Value of Life actually lost, relative to each option. (See Section 10, p- 47 -).

6.10. Zone 3 – including South New Brighton and northern area of Southshore – is consistently the majority of people ‘trapped’ in the network at 09:00:00 across all scenarios.

6.11. The reason is to do with intersection control types and priorities, and not based on population distribution of those attracted over the Pages Road Bridge. (Figure 10 shows that the Pages Road Bridge attracts more traffic from Zone 2).

6.12. In the base model (Scenario 1), at the roundabout, traffic from Zone 1 effectively has priority over Zones 2 and 3, due to the ‘give way to the right’ priority regime. Under this scenario, once Zone 1 is discharged, Zone 3 traffic gives way to Zone 2 traffic.

6.13. In the scheme models, Seaview Road (serving Zone 3) gives way to Pages Road – Hawke Street (serving Zone 2).

6.14. All models allow for route choice: a lot of traffic from Zone 3 will filter north (including on Marine Parade) in order to access the ‘main’ road.

6.15. The recommended option (7A) is predicted to reduce hazard exposure by 1127 people, with none trapped in their homes. However, the 255 people left within the network mostly originate from Zone 3, indicative of more work required (beyond the scope of this scheme options appraisal) towards realising a 100% safe evacuation of the New Brighton Community.

6.16. Recommendations towards achieving this are made in section 12 “Recommended further action”.

7. ADDITIONAL OPTIONS – ADDING NEW BRIGHTON ROAD AND OWLES TCE

7.1. Two variations to the design have been tested, based on the recommended option, including:

7.1.1. Adding a fourth arm to the intersection: New Brighton Road (Scenario 8)

7.1.2. Adding access to Seaview Road from Owles Terrace (Scenario 9)

7.2. The New Brighton Road option has been modelled to run on demand only, limiting the impacts the additional approach has on the intersection efficiency. The scheme has been initially coded in CAST (consistent with methodology), which predicts how much traffic bound for Travis Road might reroute, given improved access to Pages Road bridge from the north. It is not much – about 65 vehicles per hour.

7.3. The Owles Terrace option includes an exit from Owles onto Seaview only. However, in accommodating the additional road, the overall approach geometry from Seaview Road has been reduced.

7.4. The traffic flow rate through Anzac Drive is shown for each option in Figure 15. For context the 'base model' and recommended scheme design options are also shown.

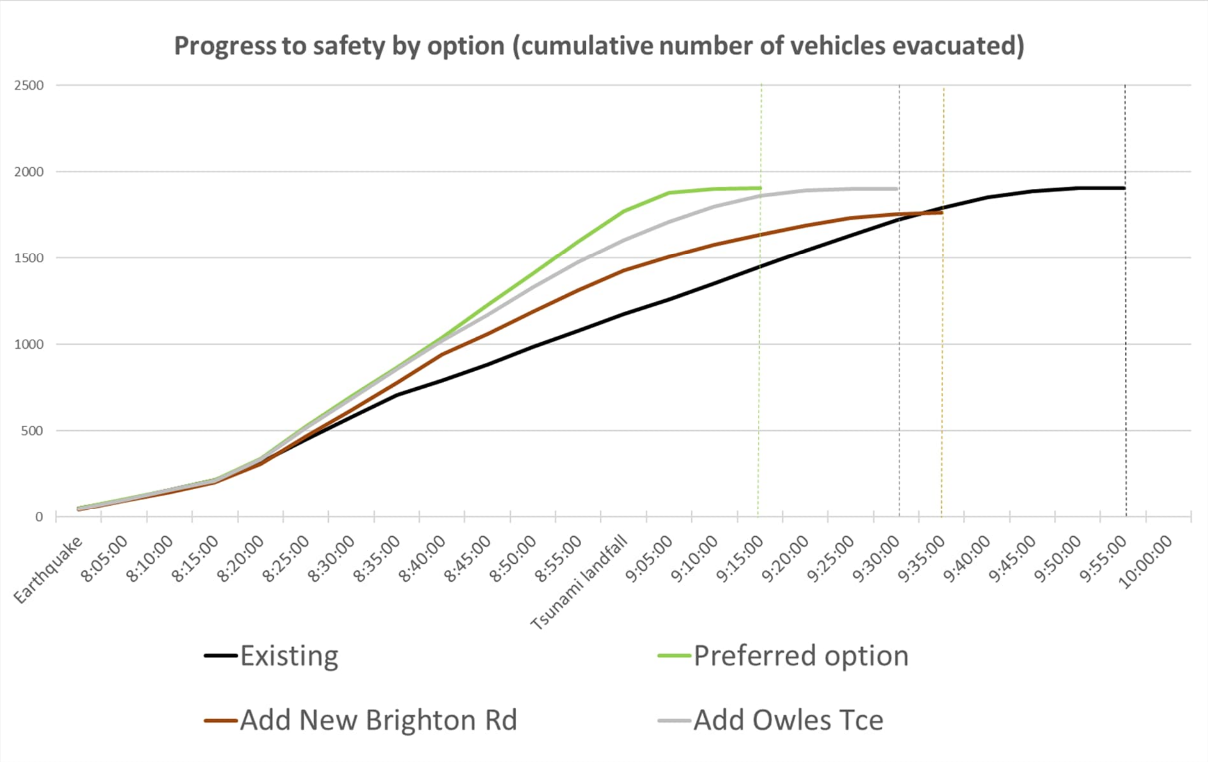


Figure 15: Relative performance of recommended option with additional scenarios

7.5. Figure 15 shows that adding New Brighton Road results in a twenty-four minute slower time than the recommended scheme, and adding access from Owles Terrace increases evacuation time by around 10 minutes.

7.6. The human life context is shown in Figure 14. Although an improvement compared to 'Do-nothing', the recommended option is predicted to evacuate 346 and 168 more than Option 8 and Option 9, respectively.

7.7. For the New Brighton Road scenario, the worse performance is due to:

7.7.1. An increase in traffic passing through the intersection, following increasing access from the north

7.7.2. Decrease in operation efficiency: a three arm intersection has 9 conflict points to manage, a four arm has 20 conflict points. This means more signals phases to manage these conflicts: more delay for the Pages Road movements. The effect of adding one additional ‘phase’ incurs an additional 3.5 minutes per hour of amber – red time, compared to Option 7. For context, the evacuation flow rate measured from scenario 7 amounts to 213 people / 2.5 minutes

7.7.3. Further, the design cannot safely accommodate the two left turn lanes from Seaview Road to Pages Road, resulting in significantly less capacity affecting half of the Pages Road bridge catchment population (affecting ‘zone 3’, (see Figure 10, p- 22 -)).

7.7.4. Given that the model is a ‘dynamic assignment model’, (allowing for route choice to compensate for available capacity), a reduction in capacity at either of the Hawkes Street or Seaview Road corridor approaches to the Pages Road bridge will represent an overall reduction in capacity available to evacuate the entire community.

7.7.5. When considering the catchment distribution of population, (see Figure 10, p- 22 -), connecting New Brighton road via a four arm intersection benefits only ‘zone 1’ - less than 5% of the catchment – at the expense of zones 2 and 3.

7.8. For the Owles Terrace scenario, the worse performance is due to:

7.8.1. A necessary shortening of the second left turn lane from Seaview Road to safely accommodate the design option; effectively a reduction in lane capacity

7.8.2. Addition of another priority intersection control; a further point of friction.

8. MANAGING UNCERTAINTY IN EVACUATION MODELLING

A. Synopsis

8.1. A key step towards determining confidence levels in model outcomes is to identify causal variables and to sensitivity the model with these. This provides opportunity to challenge the validity of the conclusion, and the extent of the benefits calculated.

8.2. Following (draft) research of the Engineering New Zealand Model User Group,[23] an Uncertainty Log has been maintained through the project, and sensitivity testing undertaken.

8.3. The log is summarised in Figure 16, with kind review undertaken by Professor Thomas Wilson of Canterbury University.

[23] Research led by Clark, I, (2017) (Flow Transportation Specialists), including a summary of the world leading research by Flyvbjerg, B, (2009), Cambridge University, on Causal variables, bias and how they impact upon Transport scheme appraisal outcomes; and working towards how this might be considered in a NZ context

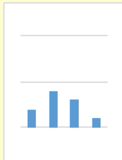
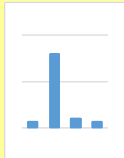
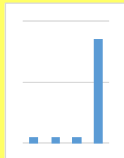
Step		Variable / characteristic		Assumptions: (red = where we could seek specialist expertise)		
				Best case	Medium	Worst case
Trip Generation		Population		Resident	Resident	Resident + visitor
		Growth	Development rate (supressed vs "fashionable" suburb)	Min or no growth	Trend growth	Maximum land yield
		Catchment	Synthetic distribution of population	Constant	Constant	Constant
Distribution	space	Safe area destinations		multiple locations	single location	single location
		Safe area accessibility		accessible	accessible	accessible
		HH density / pop dist.		Constant	Constant	Constant
	time	Lag time between EQ, tsunami	Evacuation target time	1h 20	1 hour	1 hour
		Timing of evacuation response		10 minutes after	15 mins after	30 mins after
		Response (departure) time	The lag time and response rate (i.e. storm discharge of traffic, or even-spread network loading)			
				incremental loading	storm, early	storm, late
Mode share		Demographic	Proportion able to drive	Constant	Constant	Constant
		Vehicle ownership		Constant	Constant	Constant
		Vehicle occupancy		2.5	2	1.5
		Mode share	more cyclists implies smoother evacuation	90% drive	100% drive	100% drive
		Number of vehicles evacuated / HH	Asset preservation	1	1	1.5
		Weather, random events	If raining, no one cycles	normal	normal	rain
Assignment		Aggression / panic	Courtesy' vs 'every man for himself'	Normal behaviour	Normal behaviour	Erratic behaviour
		Sensitivity to delay (likelihood of re-routing)	Controlled through four separate parameters	Normal	Normal	extra sensitive
		Network familiarity		Normal	Normal	some visitors
		Geometry	Network design details (avail. Site distance, design speed etc.)	Constant	Constant	Constant
		Road hierarchy, speed, cost		Constant	Constant	Constant
		Network management	Normal or "emergency" traffic signal operation plan?	Emergency plan ops	Normal, with ITS	Normal, no ITS
		Operating conditions	Assumes fully maintained network (no liquifaction, etc.).	Normal	Normal	Closed links

Figure 16: Parameters and sensitivities

A. Trip Generation

University of Canterbury comments

8.4. *"UC team identified that it would be important to clearly justify what exposed population data and assumptions are used.*

8.5. *"UC team identified that it would be important to clearly justify what exposed population data and assumptions are used.*

8.6. *We felt that it was important to acknowledge that population exposure would be dynamic and that there could be very high exposures, beyond what is modelled here, if there are high transient/visitor population (e.g. there is an event on in the community).*

8.7. *We stress this would be relevant for all input parameters listed…* [as population, catchment, safe area destinations, safe area accessibility, household density / population density]…

8.8. *Previous evacuation models has shown considerable sensitivity to population exposure when considering spatio-temporal variation. We agree with the best case scenario including only residents but would recommend considering the inclusion of visiting populations into the medium scenario.*

8.9. We would also recommend for both the medium and worst-case scenario to consider spatio-temporal parameters. Parameters to consider include: time of day (diurnal patterns), day (weekday vs. weekend), season (winter vs. summer), locations (residents at work vs. at property) impaired and peak-medium-low tourist season. Tilley, L (2019) conducted an analysis on spatio-temporal variation for New Brighton".

Response

8.10. A key theme is time of day, and the presence of visitors. In order to capture the worst case, the scenario tsunami generating event occurs at 08:00, when the population of the area will be high (i.e. people who haven't left for work / school), coinciding with the wider network peak operation.

8.11. In terms of guest accommodation, I have undertaken a search for hotels (google) and Air bnb, shown in Figure 17.

8.12. It is my working assumption that Figure 17 represents a total overview (or close enough to a total overview) of existing accommodation options for visitors (not staying with relatives etc.).

8.13. I've drawn a conclusion that the overnight visitor population is not presently high.

8.14. However, overall population considerations will be a major area for sensitivity testing, given the 100 year design life assumed for the infrastructure.

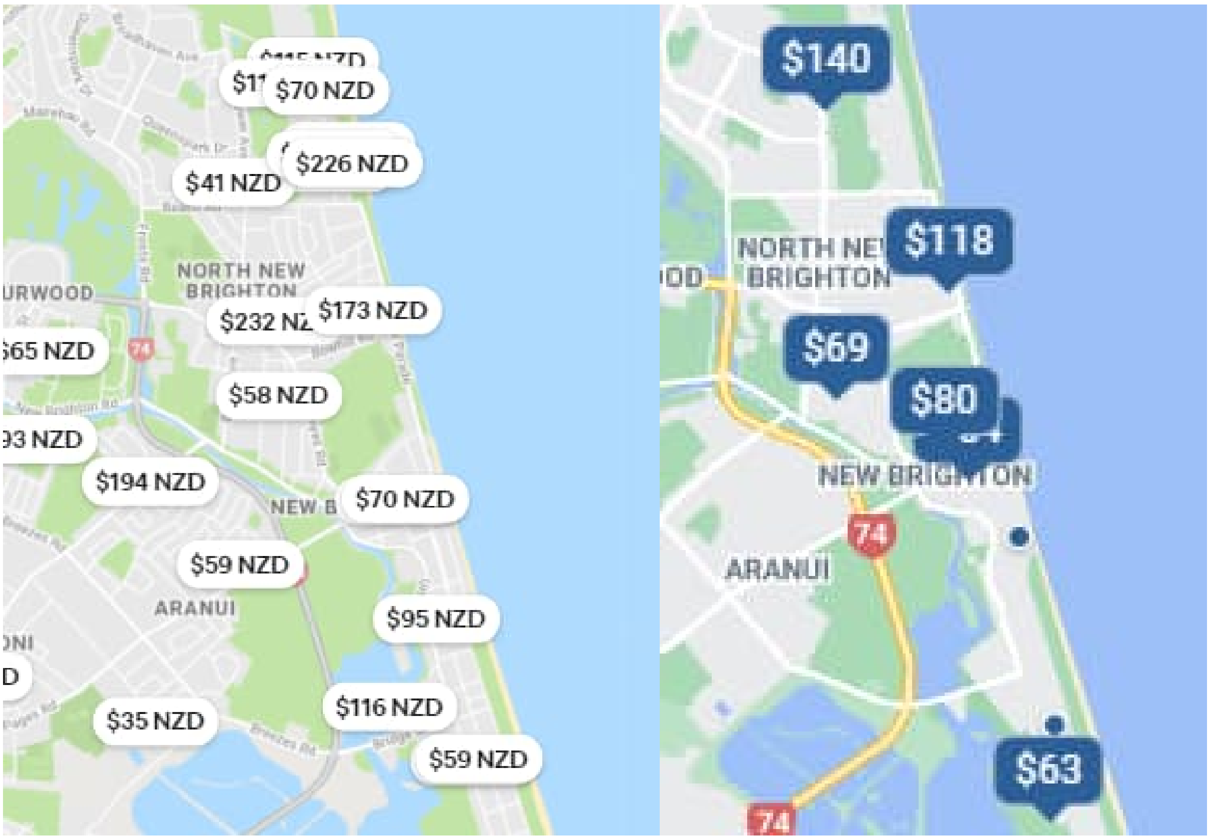


Figure 17: Search results from Airbnb (left) and google for 'hotels' (right)

B. Trip Distribution

University of Canterbury comments

8.15. UC comments on 'distribution of population / trips in space has already been covered under 'trip generation'.

8.16. In terms of distribution of trips in time:

8.17. *"We believe it's probably appropriate to use a 1 hour lag time between EQ (trigger) and tsunami arrival -- on the basis of assuming the most likely credible scenario of a large, close tsunami trigger would be a (southern) Hikurangi subduction earthquake.*

8.18. *However there does need to be consideration that if there's an earthquake from any source, the messaging is 'Long or strong, get gone' which may lead to considerable congestion early in any evacuation sequence and potential panic/confusion/anxiety amongst the population.*

8.19. *We also note that while it is probably reasonable to assume there is no known fault structure in Pegasus Bay capable of producing a tsunami, based on current science advice, this should be considered a key uncertainty and a critical assumption.*

8.20. *Recent events in NZ have demonstrated that very complex earthquakes with multiple faults rupturing are possible and could/should be considered as a tsunami scenario for this community more generally (e.g. Kaikōura EQ in 2016). We do anticipate you will consider this beyond scope - but we felt it important to flag".*

Response

8.21. The basic assumption in scenario testing is an early response – with 80% of the population discharging into the network in Quarter 2, (15 – 30 minutes after the earthquake event). The 'early congestion' which Wilson suggests is apparent in the model performance.

8.22. The concept of 'panic' and irregular driver behaviour has not been assumed, but will be tested as a sensitivity test parameter.

C. Mode share

UC comments

8.23. *We would recommend looking at Stats NZ 'place summaries' for stats on demographic composition and transport means i.e. number of vehicles owned*

8.24. We would recommend looking at Stats NZ 'place summaries' for stats on demographic composition and transport means i.e. number of vehicles owned

8.25. *We spent considerable time discussing this and looked into a number of recent NZ studies on tsunami evacuations. We don't have a lot of information on these specific values from past datasets and typically just made assumptions for these values using census information or have indicated number of vehicles per household rather than vehicle occupancy. Our take is that these values are pretty good albeit the worst case scenario value may be a little high. We would suggest altering the worst case scenario value to 1.5. We would also suggest referring to census data for this information. It's worth considering that there could be a high transient population present too.*

8.26. *There could be other obstacles along with weather such as debris, road accidents, damage to utilities etc. which should be considered in both 'normal' and 'rain' as they are seen frequently. Obstacles to note during the 2016 Kaikōura event that contributed to congestion included road damage (subsidence), bridge failure and a fallen lamp post across road. Although there were no notable congestion barriers following the 2016 Kaikōura EQ in New Brighton-Southshore, there was mention from survey respondents of heavy traffic congestion along Bridge St, Pages Rd, and Estuary Rd.*

Response

8.27. The basis of mode share and car generation is based on the NZ Household Travel Survey, and the number of car trips applied to the CAST modelling stage (with network assignment outcomes being inherited by the microsimulation modelling) are a product of car ownership by household, and number of available drivers per household. The vehicle occupancy is a product of population divided by number of cars evacuated.

8.28. The basis of mode share and car generation is based on the NZ Household Travel Survey, and the number of car trips applied to the CAST modelling stage (with network assignment outcomes being inherited by the microsimulation modelling) are a product of car ownership by household, and number of available drivers per household. The vehicle occupancy is a product of population divided by number of cars evacuated.

8.29. Section 0D (Review of Kaikōura evacuation) indicates that the vast majority evacuated by car, with 3% of respondents have walked or cycled. The weather was fine during the evacuation, with an overnight low temperature of 12°C and light south – westerly breezes,[24] which would represent fine cycling weather. However, occurring at night, it was dark.

8.30. In the scenario hour being tested – 08:00 – 09:00, this hour always occurs during hours of daylight.[25] However, additional parameters of mode selection might include an adrenalin based decision making, responding to a genuine fear of impending danger to self, whānau, pets and assets. There is data on how this relates to mode share. It is therefore assumed that the whole population would evacuate in a car, simply because of the ability to transport whānau, pets and valuables, and supplies; and that it is possible that weather would not be conducive to comfortable active travel.

8.31. There still remains an uncertainty as to what proportion of the fleet would be evacuated, and whether the response to danger would translate into evacuation of more assets – noting that cars typically *are* a major asset, and readily available to evacuate. The modelling assumes that 2/3 of the fleet is evacuated, meaning that 1/3 of the fleet is left behind. The degree of model sensitivity to this parameter clearly must be tested, in the absence of an empirical data source.

8.32. In terms of managing network failures – through crashes or debris, I agree that these issues would clearly impact on network performance.

8.33. For crashes, (which Marion Schoenfeld of Civil defence also advises) – we might consider the existing network hazards from crash data observation, and the extent to which the specific crash type and outcome could impact on the evacuation.

8.34. In terms of debris or partial network failure – this would be a so called 'black swan event' and almost impossible to predict. In the context of infrastructure option testing, it might be considered that the proposed scheme would be designed to perform better under excessive stress than previous, and that the consideration of wider network reliance might be beyond scope of scheme option testing.

[24] https://www.timeanddate.com/weather/new-zealand/christchurch/historic?month=11&year=2016
[25] Hours of daylight commence at 08:03 on winter solstice (https://www.timeanddate.com/sun/new-zealand/christchurch)

8.35. There may be broader scope identified for wider network testing, and broader resilience issue might be considered therein.

D. Network Assignment

UC comments

8.36. *It would be beneficial to run the simulation (particularly worst case) under both erratic and normal behavioural conditions to test the model's sensitivity to the parameter. Some of the previous survey data (although considering that sampling bias could have had an effect) shows that evacuation behaviour was relatively normal.*

Response

8.37. I agree that this is clearly an important parameter, and as previously acknowledged (Figure 7) is based entirely on assumption. The surveyed response to the Kaikōura event is interesting, but possibly due to a low perception of personal risk.

8.38. The CDEM survey on Kaikōura responses found that, of the 73% who evacuated, 61% left within 30 minutes and largely encountered minimum congestion on the roads. There were reports that driver behaviour was even courteous.

8.39. Some report that congestion occurred after the sirens were sounded. Some of the accounts speak of erratic behaviours, with vehicles travelling on the wrong side of the road. Although it is difficult to paint a clear picture with certainty, my interpretation of the research was that the sounding of the sirens did trigger certain behavioural responses, including the rapid mass movement of a large number of residents, (noting that some had already evacuated and returned at this point) including some possible panic.

8.40. If the sirens were a driver of behaviour (unlikely to be activated in time), this suggests that the sounding of the sirens heightened community perception of risk. From this we could conclude that irregular driving behaviour – such as driving the wrong way down the street – should be considered as a likely behavioural response and will be tested.

E. Time of day

8.41. A standard parameter for network analysis is usually considering more than one time period. In this case, only one time period has been analysed.

8.42. In this case, one time period is represented, coinciding with an earthquake occurring just before the AM peak – a time when the population of the area is ‘high’, as most people would still be at home.

8.43. Analysis of link counts on Pages Road show to what extent time of day could bias the population present within the Pages Road catchment, at time of evacuation. Figure 18 shows the estimated deviation of the population vehicle fleet by time of day

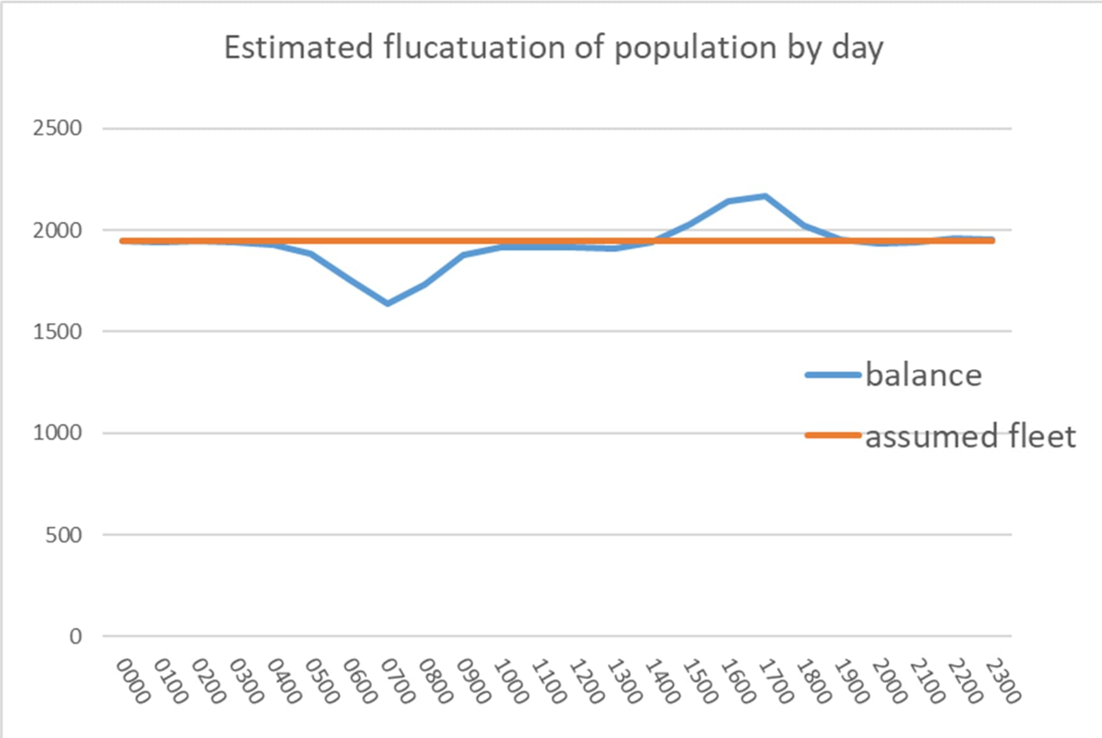


Figure 18: Estimated fluctuation in population present, by time of day (derived from Pages Road link count)

8.44. The time period modelled can be shown to be 'typical', with the average 24 hour variance from the modelled fleet being 0.992.

8.45. There would be limited value in extensively modelling other time periods.

9. EVACUATION MODEL: SENSITIVITY TESTING

A. Synopsis

9.1. The identified variables from section 8 (*Managing uncertainty in evacuation modelling*, p- 30 -) have been considered in terms of scope with the project, given degrees of certainty and also the possibility of responding to some parameters with non-infrastructure (potentially better value for money) options.

9.2. Figure 19 suggests parameters which lie within the scope of the design option testing brief, but also alludes to others which might be better tested in partnership with Civil Defence, under a new brief.

<table>
<tr><th colspan="2" rowspan="2">Attribute / scale</th><th rowspan="2">Scheme / sensitivity testing</th><th colspan="2">Recommended additional evacuation programme</th><th rowspan="2">Notes</th></tr>
<tr><th>On road changes</th><th>Civil Defence / community preparedness</th></tr>
<tr><td rowspan="3">Population growth</td><td>Low</td><td>✓</td><td>✓</td><td>✓</td><td>"Background rate" against growth projections</td></tr>
<tr><td>Medium</td><td>×</td><td>✓</td><td>✓</td><td rowspan="2">Not antipcated in near term. Future programme could be justified on supporting significant growth</td></tr>
<tr><td>High</td><td>×</td><td>✓</td><td>✓</td></tr>
<tr><td rowspan="3">Perception of risk - driving behaviour</td><td>Calm</td><td rowspan="3">✓</td><td rowspan="3">✓</td><td rowspan="3">✓</td><td rowspan="3">Consider a mix of reactions in the sensitivity test. But potetnially highlight need for further work. Also can be resolved by increasing 'preparedness'.</td></tr>
<tr><td>Mid</td></tr>
<tr><td>Panic</td></tr>
<tr><td rowspan="3">Response time</td><td>early</td><td>✓</td><td>✓</td><td rowspan="3">✓</td><td rowspan="3">Designing for late departures likely to be prohibiteively expensive. Better VFM likely through better Planning / Community prepardeness</td></tr>
<tr><td>Mid</td><td>✓</td><td>✓</td></tr>
<tr><td>late</td><td>×</td><td>×</td></tr>
<tr><td rowspan="3">Mode choice / veh. Occupancy</td><td>Low traffic</td><td>×</td><td>×</td><td rowspan="3">✓</td><td rowspan="3">Shouldn't assume 'low traffic', e.g. could be raining. Howeve, planning could 'sell' benefits of evaucation by bicycle to beat the traffic</td></tr>
<tr><td>Med traffic</td><td>✓</td><td>✓</td></tr>
<tr><td>High traffic</td><td>✓</td><td>✓</td></tr>
</table>

Figure 19: Causal variables which could be tested, subject to scope

9.3. The matters within scope of the scheme options testing are then subject to testing, in accordance with the schedule listed in Figure 20.

9.4. It is important to note at this stage that the parameters are tested individually. Interaction of parameters could be recommended, if there were more than one significant parameter. However, it is found that only Sensitivity test 1 proves to be significant.

Test	Theme	Parameters
Sensitivity test 1	Demands	mode share, growth: 36% more cars
Sensitivity test 2	Behaviour	overtaking, higher sensitivity to delay
Sensitivity test 3	Profile	Later response time, incramental loading

Figure 20: Parameters within scope of Option design testing

9.5. Figure 21 shows the outcome of the sensitivity testing, using the same metric as applied for outcomes in section 6.2. For context, the outcome of three sensitivity test is plotted alongside the base model and the preferred option outcomes, (which are unchanged).

9.6. The result clearly shows that demands are sensitive, whereas 'panic' and the slower response time assumed are not. It is critical to bear in mind the parameters assumed for 'later response time', especially given that the later time here would outperform the response time witnessed during the Kaikōura earthquake and subsequent Tsunami threat. More details of the sensitivity test parameters are set out below.

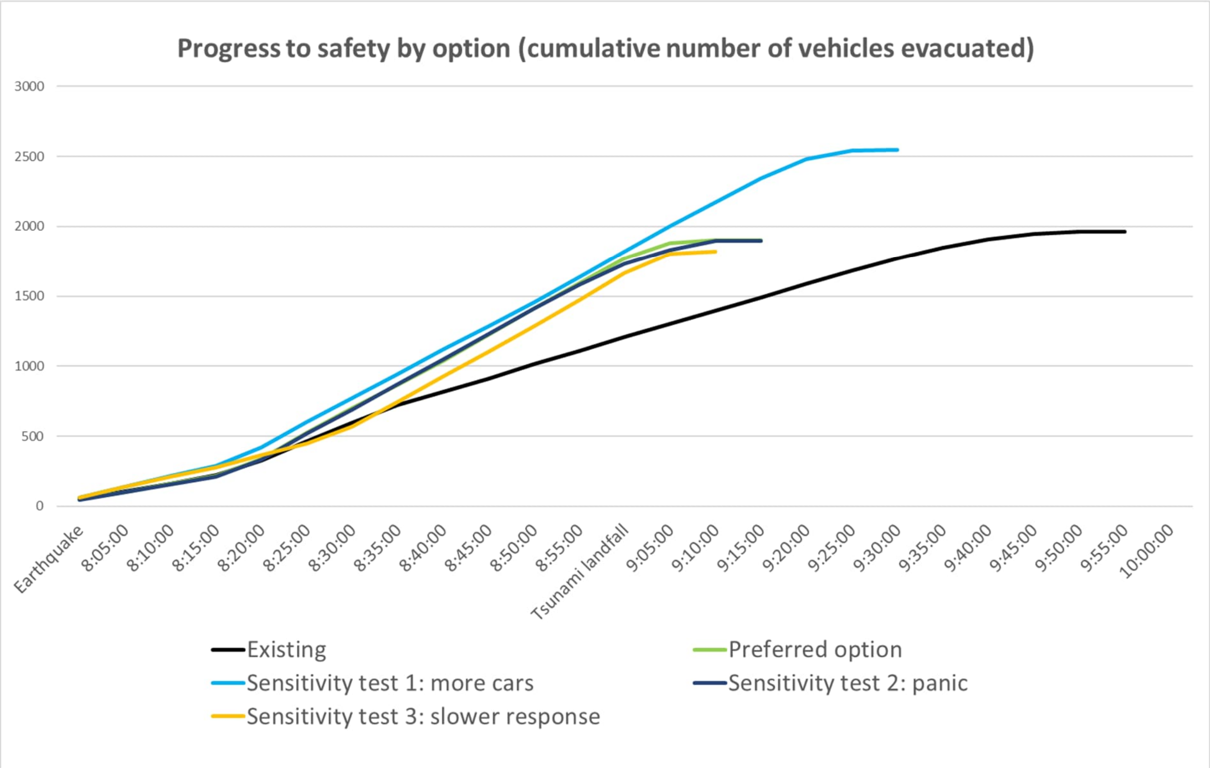


Figure 21: Outcomes of sensitivity testing, shown along- side existing and (non-sensitivity tested) preferred option outcomes

9.7. Figure 22 shows the performance, again, in the same format as for section 6.2. It indicates the location within the network where 'unreleased' vehicles are located. Once again, the majority of losses would be located in zone 3 (mapped in Figure 10)

9.8. Please note the reason for the Sensitivity test 1 high 'people in network' value is due to this test being demand based, with 36% more traffic assumed in the network under this scenario.

9.9. Figure 26 shows more detailed outcomes for the three tests, benchmarked against the preferred option outcomes

Scenario	run out time	Un-released vehs at 0900				People in network at 09:00
		zone 1	zone 2	zone 3	total	
Senstivity test 1	9:27:53	0	169	258	427	1827
Senstivity test 2	9:11:59	0	0	0	0	336
Senstivity test 3	9:13:14	0	0	73	73	467
Preferred option	9:12:25	0	0	0	0	255

Figure 22: Performance by Sensitivity test

9.10. The parameters assumed in the testing are explained below.

iv. *Parameters within scope of Option testing*

TEST 1

9.11. Test 1 considers the implications of car usage having been underestimated.

9.12. In undertaking the CAST modelling, Mirbaha estimated the number of cars available to each household, (from 2018 census), and generated a scenario based on 2/3 of the available fleet being evacuated at a rate of 2 persons per vehicle.

9.13. The sensitivity test parameter has been developed, evacuating 83% of the fleet, at a rate of 1.5 persons per vehicle.

9.14. It is possible that in the event of an evacuation, the Community may respond to the threat by evacuating their most readily available and valuable assets, including their cars. 56% of households own more than one car, which generates a significant uncertainty.

9.15. The testing shows that the evacuation time would be 15 minutes slower than the standardised test assumption for the preferred option, but still out-perform the base model (existing road layout) by around 25 minutes, and bearing in mind the base model flows are unadjusted:

9.16. 36% more traffic outperforms the base model because of the improved intersection geometry).

TEST 2

9.17. Test 2 considers the impacts of changing behaviour, to allow overtaking and driving on the wrong side of the road, coinciding with increased sensitivity to delays.

9.18. Figure 23 is an extract from the model, showing vehicles forming a queue on the wrong side of the road, approaching the Hawke Street / Shaw Avenue roundabout. However, the dual queues cannot continue through the roundabout, and are required to merge again.

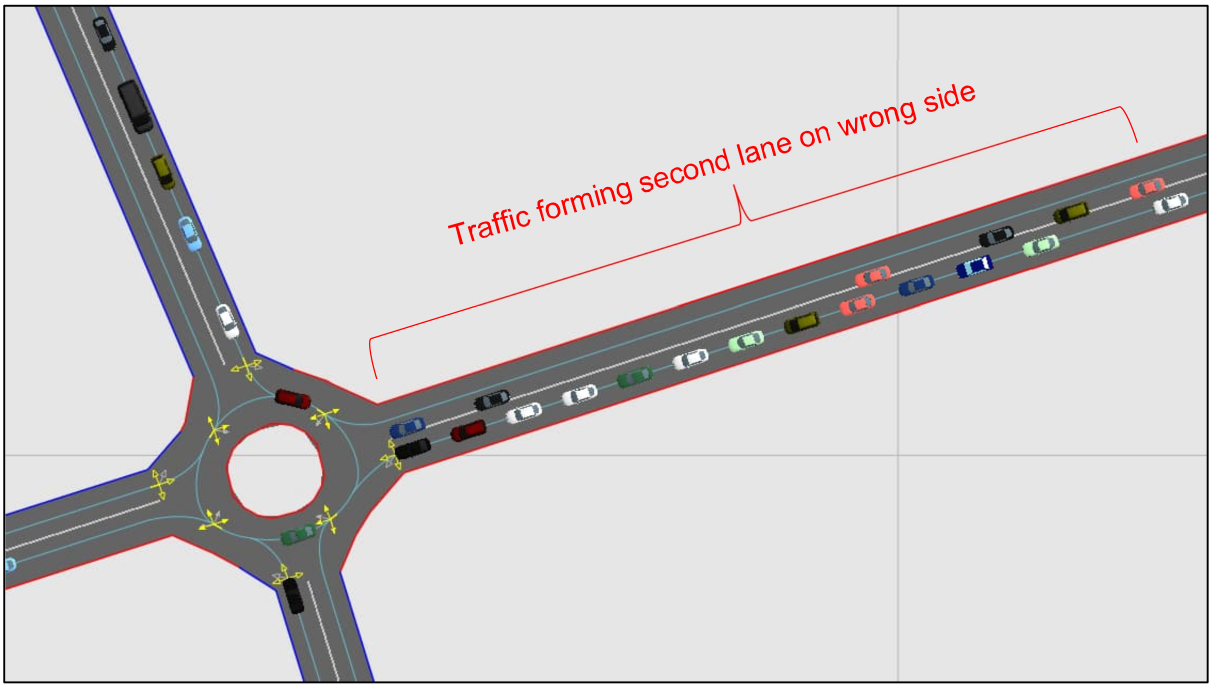


Figure 23: Extract from sensitivity test model, showing modified driver behaviour

9.19. Several other instances of overtaking and formation of dual queues occurs within the model, including on the Seaview Road. However, the additional queues do not speed up the evacuation.

9.20. At Pages / Seaview intersection, the design capacity – the amount of traffic that can get through – is defined by the traffic signal operations. Figure 23 shows that the roundabout capacity ultimately determines the speed at which the adjoining networks discharge.

9.21. There is little difference found in the outcome of Test 2, simply because, although additional queues may form, it has nowhere to go. Evacuation is defined by a few key pinch points in the network, and in either test they are already performing at saturation capacity levels.

TEST 3

9.22. A critical parameter will be the response time of the community to a threat, in terms of 'milling around' time, and also the rate at which the entire community packs its cars and enters the network. In the model, this is controlled by the demand profile.

9.23. Figure 24 shows the demand profile used in the options testing (red), and then a sensitivity test profile in blue. The options testing profile assumes a rapid response – that 80% of the population departs within 15 – 30 minutes of the earthquake.

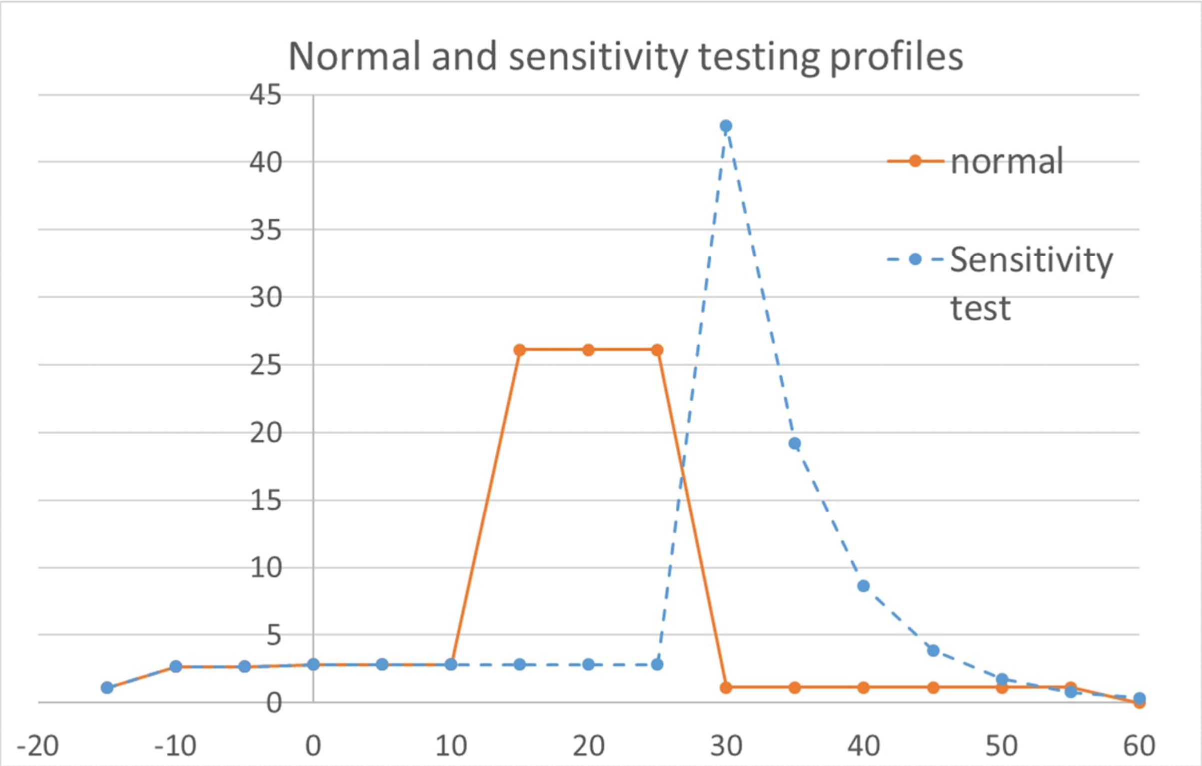


Figure 24: Vehicle release profiles used for general option testing, and for the sensitivity test

9.24. The sensitivity parameter assumes a slower reaction, and the peak occurs at 08:30 – 15 minutes later. A negative exponential distribution of the peak discharge is also estimated, rather than a 'flat top' peak.

9.25. It is likely that, given a later departure, more of the community will already have left the network – heading to work and school, and so the overall sum of the peak period is slightly less than that assumed for the option testing (red) profile.

9.26. Of interest, the sensitivity test run out time is very similar. Figure 25 clearly shows a delayed peak discharge of traffic next to the standard test (green line), but a five minute period of intense flow rate (equivalent to 2280 vehicles per hour) around 9am. Despite the enormous spike shown in Figure 24 the run out time is similar.

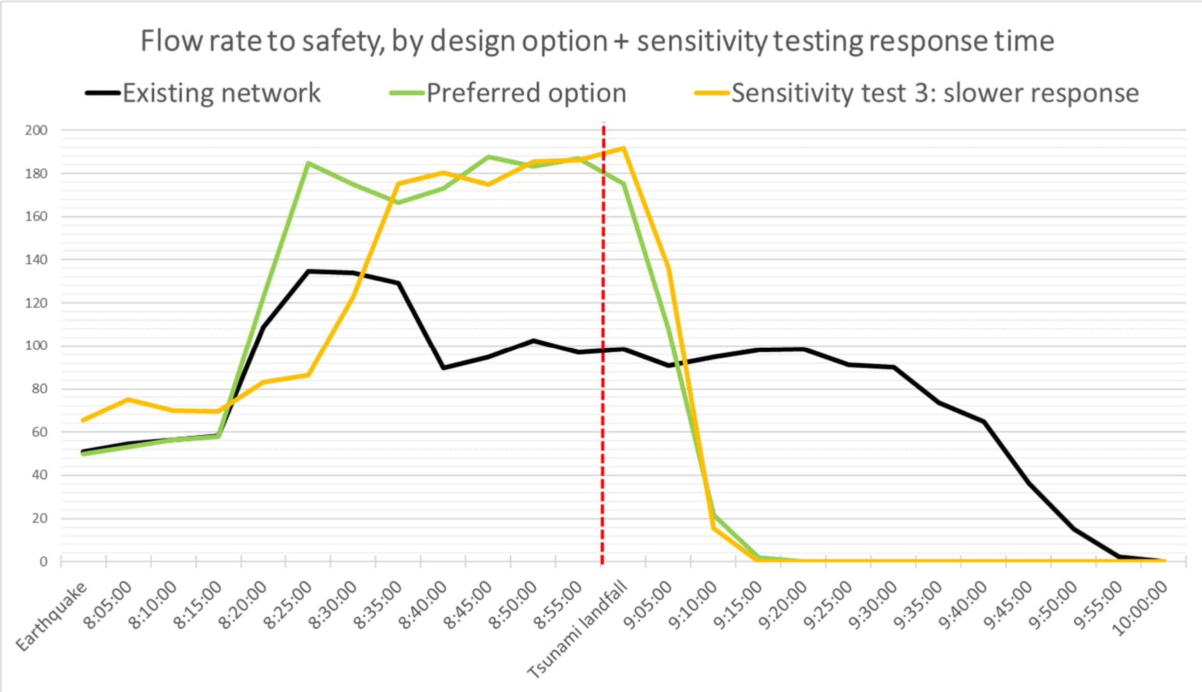


Figure 25: Sensitivity test 3: delayed response, compared to base model and standard preferred option testing

9.27. This is because the network later, but more gradually in the sensitivity test.

9.28. The option could be tested to breaking point, by applying the (orange line) profile shape, with its flat top, but applying it to the second or third quarter hours. This would increase the run out time by one or two quarter hours, which would be catastrophic in a real Tsunami event.

9.29. However, this would be beyond the reasonable scope of infrastructure testing, as a degree of Community preparedness must be assumed to some extent in order to plan for affordable infrastructure of realistic scale.

v. Parameters beyond scope of Option testing

SIGNIFICANT POPULATION GROWTH

9.30. The Canterbury earthquakes resulted in red-zoning of 190 properties in the New Brighton / Southshore areas, and a further weakening of the local economy through wider rezoning in the east and potentially a negative multiplier effect, (readily observable through shop closures and un-let commercial properties).

9.31. Consequently, New Brighton became unfashionable; with minimal interest in housing development. In the present time, it is difficult to imagine a massive population growth scenario for New Brighton.

9.32. The long term future of New Brighton is uncertain. The *Coastal Hazards Assessment (2021)*[26] is underway, which includes a high level analysis of risk. This will lead to a *Coastal Hazards Adaption Planning Programme*, which could include a range of scenarios from coastal retreat to sea-walls and other resilience based infrastructure.

9.33. However, the current District Plan parading identifies New Brighton as a Key Activity centre, with surround medium density residential zoning. (See Figure 26, below). The proposed New Brighton Master Plan[27] seeks to revitalise the commercial centre, with developments already underway – for example, the Hot Pools development which opened in 2019.

9.34. Therefore, although the longer term future remains uncertain, a mass retreat from New Brighton would be a stark contrast to the present District Plan paradigm for the area, especially if resilience infrastructure is feasible, pressures to house a rapidly increasing population, and changes in fashion favouring access to the coast, come to bear.

9.35. High level analysis of the potential for increased residential density suggests there could be an additional (estimated) 472 dwellings, within the RSDT and RMD zones. This means an additional 472 vehicles might be considered in a future evacuation scenario, (based on the option testing assumption that 2/3 cars are evacuated at a rate of 2 persons per vehicle).

9.36. However, given the uncertainty, and for the scope of other projects to support and enable this growth, this higher population growth scenario is outside the scope of the intersection and bridge design option testing brief.

[26] https://ccc.govt.nz/environment/coast/coastalhazards/how-we-assess-coastal-hazards
[27] https://ccc.govt.nz/the-council/plans-strategies-policies-and-bylaws/plans/suburban-centres-master-plans/new-brighton-centre-master-plan

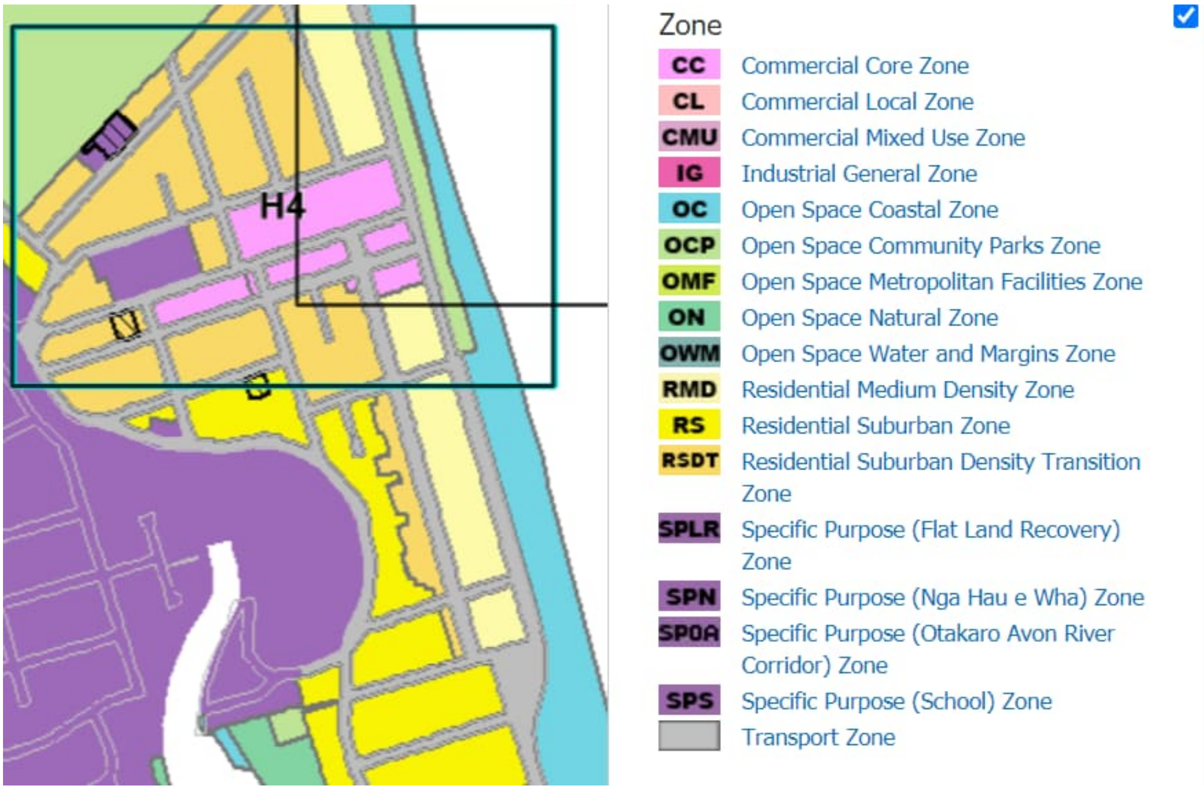


Figure 26: Extract from District Plan, showing zones which allow for higher residential development densities.

LATE REACTION TIMES

9.37. The outcome of modelling and sensitivity testing suggests that a prompt response can be accommodated by the scheme within 1 hour and 15 minutes from point zero.

9.38. Infrastructure provision needs to follow value for money principals. The value for money associated with educating the community to ‘preparedness’ is clearly greater than designing for ‘un-preparedness.’ Such a design scenario would include multiple vehicle lanes and very high capacity intersections, built on land claimed from other uses (probably housing), and for 99.9% of the time representing an over-capacity provision of road capacity, *ad absurdum*.

B. Outcomes of sensitivity testing

9.39. Demand – increased traffic – is the main sensitivity parameter, and not behaviour or response times (within the ‘reasonable bounds’ described above).

9.40. This is because the key to unlocking performance is addressing the pinch points – the points of least capacity, as is true for any network.

9.41. The impact of ramping up the demands to sensitivity testing in the full analysis (i.e. ramping up the base values as well) will serve to increase the level of benefits calculated (next section).

9.42. It is likely that the vehicle demands modelled and reported in section 6.2 are mid-range: some residents could and probably would cycle; whereas some would also attempt to evacuate all their assets.

9.43. It is my opinion therefore that the parameters used in the model are robust and defendable, and that Decision makers can accept the treatment of uncertainty with a high degree of confidence.

10. ESTIMATED BENEFITS

A. Synopsis

10.1. The majority of benefits are derived from Value of Life (VoL) benefits. These are estimated by converting the transport model outcomes, (i.e. for the recommended scheme option, monetising the value of *extra* people evacuated from the network by merit of the scheme) into VOL savings by exposing these to an estimated tsunami outcome, occurring during the 100 year life of the scheme (bridge design life duration).

10.2. The exposure to risk has been defined by the transport modelling, whereas the risk itself is estimated from a range of possible outcomes, including return period, wave heights and corresponding population affected by hazardous water.

10.3. The outcomes are summarised in Figure 27, a BCR range of 5 – 25 is reported, and a midpoint of 15 is recommended to provide investment assurance.

Benefit		Parameter		
Type	Metric	low	mid	high
Human life savings	VoL	$ 83,738,965	$ 250,605,615	$ 417,472,266
False alarms	VoT, VoC	$ 38,365.49	$ 57,548.23	$ 76,730.98
	Crash saving	$ 30,775.19	$ 46,162.78	$ 61,550.37
	TOTAL	$ 83,808,105	$ 250,709,326	$ 417,610,547
	Indicative BCR ($17m spend)	5	15	25

Figure 27: Origin and value of transport benefits relating to investment.

10.4. The VoL values are high; yet equates to 4.7% of the 1,177 additional persons potentially 'saved' by the scheme.

10.5. Effectively, there is a very low probability of death in the event of a tsunami. In the event of a M9.3 earthquake and a 9m maximum wave height, none left within the network, exposed, would be expected to survive;- a monetised outcome of -$6.5b[28]. Yet, when factored by the probability of this particular scenario actually happening, the actual applicable adjusted VOL cost is a little more $88m (1.6% of the 'exposed' cost, 0.7% of the weighted VOL total).

10.6. The analysis shows that the tsunami impact is a low probability, extreme severity event; the development of values shown above can be used for investment assurance.

[28] Assuming Treasury estimated value of life of $4.7m

10.7. Whilst Figure 27 reports on the benefits relative to the entirety of the scheme, (i.e. comparing scheme, base network benefits, dividing the adjusted benefits by the total scheme cost ($17m)), the same exercise has been undertaken to investigate the difference between a single outbound lane and double outbound lane. In other words, the value associated with spending an additional $2m to add another traffic lane to assist tsunami evacuation.

10.8. The outcome is shown in Figure 28: in the medium and high scenarios, the vast majority of the total scheme benefits can be seen to derive from providing the second vehicle outbound lane, compared to Option 3 which includes a single outbound lane.

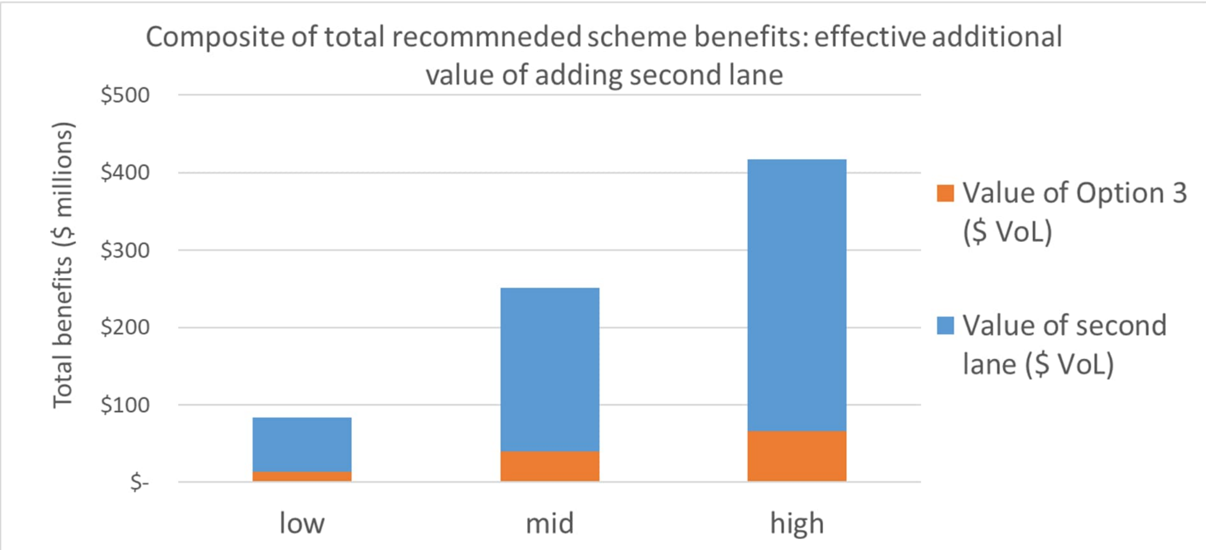


Figure 28: Composition of benefits across scheme, (relative value of adding second vehicle lane)

10.9. The components of Figure 27 are set out below, including methodologies and assumptions. Section 3 of this report (p- 7 -) includes useful information about tsunamis that has been instrumental in deriving monetised benefits.

B. Monetised Risk – loss of life

10.10. The process interfaces with modelled outcomes – which identify the number of people *exposed* to tsunami risk, as 'trapped' within the network.

10.11. Figure 29 shows the exposure for appraising the full recommended option, in terms of deriving value from the full amount spent, and also the opportunity value associated with constructing additional lane capacity.

10.12. The difference between providing a single lane and double lane scheme (options 3 and 8, respectively), incur a $2m additional spend (approximate estimate). The increased spend results in a much more efficient evacuation, with 948 fewer people in the network compared with option 3, (and 1,127 fewer than 'do nothing').

Appraised:	People 'stuck' in network, by scenario			Value (exposure to tsunami risk)		
	Base model	Option 3 (signals, single lane	Option 8 (signals, dual lane)	Analysis	# ppl less exposed	$ (value ppl less exposed
Value of $17m	1382	1203	255	Option 3 minus base	179	$ 5,412,888,000
Value of extra $2m (opportunity)	1382	1203	255	Option 8 minus option 3)	948	$ 1,148,130,000

Figure 29: Appraisal and extent of exposure to scenario risk: core scheme and value of additional $2m spend

10.13. The values shown in the right hand column are the 'starting point' in estimating the network performance in terms of loss of life. These are people still present in the network at the end of the simulation runs. The monetised quantum of un-evacuated people represent the exposure to critical personal risk.

10.14. In the majority of instances, it is unlikely that there would be a significant death toll. In the 2016 Kaikōura earthquake, the consequential tsunami was 0.5m high and did not present a risk.

10.15. Section 3 includes some details as to the real world tsunami risks, and are applied where possible to the process of defining the costs of personal risk exposure (posed by transport network inadequacy) for a range of possible tsunami outcomes.

10.16. Given that there are different methods and approaches on estimating tsunami frequency and recurrence, (an outcome from section 3), different approaches are adopted for understanding the range of loss of life:

10.16.1. Method 1: Extrapolating hazard data from a 5m tsunami scenario, in detail, to the estimated 5m wave return frequency and then factoring by the 'share' of tsunamis from regional sources.

10.16.2. Method 2: Extrapolating hazard data from a range of tsunami wave height probabilities, based on expected and low return intervals.

vi. Method 1

10.17. Method 1 effectively engages with New Zealand Probabilistic Tsunami Model (2013) data, which 'returns periods for different size tsunamis for 20km segments of the New Zealand coastline' (Jack, H, 2021). Information used includes the return interval for 5m waves in Canterbury (from all sources, 150 – 350 years). Method 1 then factors by the 15% 'share' of tsunamis originating from regional sources. The basis of the data is explained in Section 3

10.18. The outcomes shown in Figure 30; based on a 150 – 350 year return, a 0.536 hazard (based on inundation and rapid water movements), a 15% probability of a regional source (i.e. actual application of the $ exposure value from the 1 hour tsunami evacuation model), the adjusted Value of Life (VOL) range is $122m - $284m.

10.19. This means that the benefit of spending $17m on the Pages Road bridge and intersection recommended option (Option 7a, see Figure 14, p- 26 -) is estimated to be between ~$100m - ~$300m (relative to 'do nothing).

10.20. The corresponding BCR range is between 7 - 17

Simulated recurrence	($ exposure, VOL)	Hazard exposure	Range of return: 5m wave height	P within design life	wave height	P regional source	VOL adjusted for risk
High	$ 5,294,916,600	0.536	150	0.67	5	0.15	$ 283,542,784
Medium		0.536	250	0.40	5	0.15	$ 170,125,670
Low		0.536	350	0.29	5	0.15	$ 121,518,336

Figure 30: Method 1 Risk adjusted Value of Life (VOL) outcome

10.21. The hazard exposure is based on the inundation coverage derived from GIS modelling for Environment Canterbury: using mesh block data, approximately 60% of the population are located within an area with p = >0.95 inundation, of which area 85% would experience hazardous water movement, for a sustained period. This yields a hazard exposure weighting of 0.54.

10.22. What this means in plain English, is that, although the transport predicts that the network will perform better with the scheme, the rate of exposure of risk to those who can't 'get out' in time is relatively low. This is based firstly on the infrequency of a significant tsunami, and the derived hazard (when applied to the area of the Pages Road bridge catchment).

10.23. Of the $5.3bn value of life (the value of 1,127 people theoretically not evacuated without the scheme), only between 2-5% of this value could be used.

10.24. Careful consideration has been given to the inclusion of the Kermadec subduction zone tsunami scenario as well as the Hikurangi subduction zone. Whereas tsunami arrival time from the southern Hikurangi can be as little as one hour, arrive times of tsunamis from the Kermadec area are expected to be at least two hours after. The transport modelling suggests that two hours would be enough, if community reaction is sharp.

10.25. However, being located over 1,000km from the Canterbury coast, it is possible that a major earthquake in the Kermadec area would not be noticed, or perceived as a threat[29], and hence the Community evacuation would be reliant on warning mechanisms such as emergency mobile alerts and sirens, which would require time to be actuated.

[29] Jack, H, Environment Canterbury, Senior scientist

10.26. There is no sound basis to verify the likely Canterbury experience of a magnitude 9.3 earthquake in the Kermadec area, simply because there hasn't been one. A magnitude 8.3 earthquake in the Kermadec area occurred in March 2021, and Geonet[30] 'felt reports' indicated a weak – moderate experience in Canterbury. Though Helen Jack points out that a magnitude 9.3 earthquake would be ten times larger, (thus rendering the March 2021 earthquake information as largely irrelevant), the null hypothesis that a significant earthquake could occur within a regional source, and not be perceived as 'long or strong' cannot be disproven

10.27. This is important: the issuing of a tsunami warning / activation of sirens can take time. For this reason, the public message presently is: 'long and strong, get gone!' Yet there is a possibility that an earthquake from the Kermadec area would not be experienced as 'strong'. On this basis, the tsunami threat from the Kermadec islands should be treated the same as from Hikurangi, in terms of critically limited evacuation time.

vii. Method 2

10.28. Method 2 effectively engages with earthquake projections for the southern Hikurangi subduction zone source and tsunami modelling data from Environment Canterbury, specifically relating to the probability of maximum wave heights (range = 3 – 8m, across 30 model runs), and corresponding hazard posed by each.

10.29. The hazard is estimated to be the same as per Method 1, (i.e. compound frequency of inundation and hazardous water movement, derived from Environment Canterbury GIS modelling), approximately scaled based on maximum wave size.

10.30. Method 2 engages with data for Hikurangi and Kermadec interface zone, and runs estimates two ranges based on available 'expected' recurrence and 'low' recurrence rates. The detailed tsunami data is only available for the Hikurangi zone, whilst less data is available for the Kermadec, with a considerably lower return period, albeit for a M9 – 9.3 which is likely to generate a 5m wave. There is a low degree of confidence that the Kermadec trench could generate a 7-12m wave. Owing to the low degree of confidence, it is not recommended as ready for inclusion.

10.31. For reasons set out under Method 1, effects of tsunamis from the Kermadec area also require consideration.

10.32. The outcomes are shown in Figure 31, representing a range of ~$90m - ~$750m for Hikurangi and a $60m outcome for a 5m wave from Kermadec.

[30] https://www.geonet.org.nz/earthquake/2021p169764

Source	Simulated ranges	($ exposure, VOL)	Hazard exposure	Expected EQ return (y), >M8	P within design life	Max wave height	P wave size (tsunami model generation)	VOL adjusted for risk
	worst case		1.000			>8m	0.03	$ 88,248,610
			0.789			7	0.07	$ 139,168,058
Hikurangi			0.646	200	0.5	6	0.17	$ 284,932,700
	Likely		0.536			5	0.53	$ 756,114,090
		$ 5,294,916,600	0.288			4	0.77	$ 584,558,793
	small		0.000			3	0.00	$ -
Kermadec	*extreme*		1.000	2500	0.04	7-12m	0.03	$ 7,059,889
	Likley		0.5355	2500	0.04	5	0.53	$ 60,489,127

Figure 31: Method 2 Risk adjusted Value of Life (VOL) outcome, expected return

10.33. The plain English definition is the same as per Method 1 (paragraph 10.22); in this case there is between a 1% - 10% application of the initial risk data. This means that whilst people ‘stuck’ in the network are more than likely to survive (>90%, all scenarios), the adjusted value is still going to be significant, simply because of the very large value of the risk exposure.

10.34. Because Figure 31 considers a 2,500 year range, (within which there is a theoretical mid-point return of 10 tsunami events at 5m from all scenarios, including potentially 2 from a regional source), the Hikurangi and Kermadec adjusted outcomes are summed.

10.35. Figure 31 includes a huge range from the Hikurangi area, yet in reality only one of these events will materialise. Therefore, a single figure has been extracted – set out in Figure 32 – which is the product of weighted risk, and represents all of the possible outcomes.

Actual risk	Weighted risk	Actual value	weighted value
0.0167	0.0476	$ 88,248,610	$ 4,202,765.06
0.0263	0.0751	$ 139,168,058	$ 10,451,978.30
0.0538	0.1538	$ 284,932,700	$ 43,813,096.81
0.1428	0.4080	$ 756,114,090	$ 308,527,605.44
0.1104	0.3155	$ 584,558,793	$ 184,406,302.70
0.3500	1.0000		$ 551,401,748.32

Figure 32: Processing data from Figure 31 into a total of weighted outcomes

10.36. The overall analysed outcomes, for both expected frequency (see Figure 31) and an additional lower frequency event (1/2500 year) are shown in Figure 33, including the weighted totals

10.37. Of note, the low return scenario, (within which time, again, evidence suggests an average 10 tsunami events at 5m from any source could occur) yields a BCR of 3, the (theoretical) equivalent of 10 lives saved by implementing the recommended scheme option. The high estimate represents the (theoretical) saving of 85 lives.

VOL benefit, per:		Weighted total VOL ($)
Expected recurrence		$ 551,401,748
Low recurrence		$ 45,959,593
BCR on full scheme ($17m)	high	32
	mid	18
	low	3

Figure 33: Analysed adjusted VOL applicable, and indicative BCR range

viii. Conclusions to monetised Value of Life

10.38. Figure 34 shows the Value of Life outcome, by method. The mid-points for the two methods are within the $200m - $300m mark.

Method:	VOL outcomes by method		
	Low	Med	high
Method 1	$ 121,518,336	$ 202,530,560	$ 283,542,784
Method 2	$ 45,959,593	$ 298,680,671	$ 551,401,748
Dif.	-164%	32%	49%

Figure 34: Value of Life range outcomes by method

10.39. All of the data used in the above analyses are entirely theoretical; there is no observation to benchmark against. However, the purpose of using the two approaches – one derived from paleo tsunami, and the other from earthquake frequency and tsunami modelling – is consistent with the approach based on providing confident funding assurance.

10.40. The application of hazard exposure is based on normal population distribution, whereas it might be applied to the distribution of the population at the point tsunami hits.

10.41. Around 40% of the Pages Road catchment live within close proximity of the sand dunes, which is shown to provide a high degree of protection. (See Figure 6, p- 12 -), and this is a drag factor in the value of risk. However, in order to evacuate this population must move through hazardous space in order to reach the bridge. From analysis of the transport model, the majority of people 'stuck' in the network are stuck in high risk locations.

10.42. If the analysis is adjusted to account for the shift of population in ‘real time’, the hazard exposure factor increases by 50% (*ceteris parebus* – meaning that the reported adjusted value of life applied increases by 50% as well).

10.43. The analysis is therefore conservative: the mid-point range could be as high as $350,000,000 (an equivalent BCR of >20).

C. Monetised benefits – false alarms

TIME AND OPERATING COST SAVINGS

10.44. The network performance has been ‘skimmed’ from the paramics models and run through an economic interface[31] and performance monetised in terms of:

10.44.1. Value of time

10.44.2. Value of time, exposed to congestion (higher perceived cost of time)

10.44.3. Vehicle Operating Costs

10.44.4. Vehicle Operating Costs exposed to congestion (‘idling’)

10.45. The based model generates a total cost to society of $27,000 (2020 values) based on the above, compared to $15,000 for the scheme, depicted in Figure 35.

10.46. These figures do not assume any crash savings, (which is explained more below).

[31] Developed using the Waka Kotahi NZTA Monetised Benefits and Costs Manual

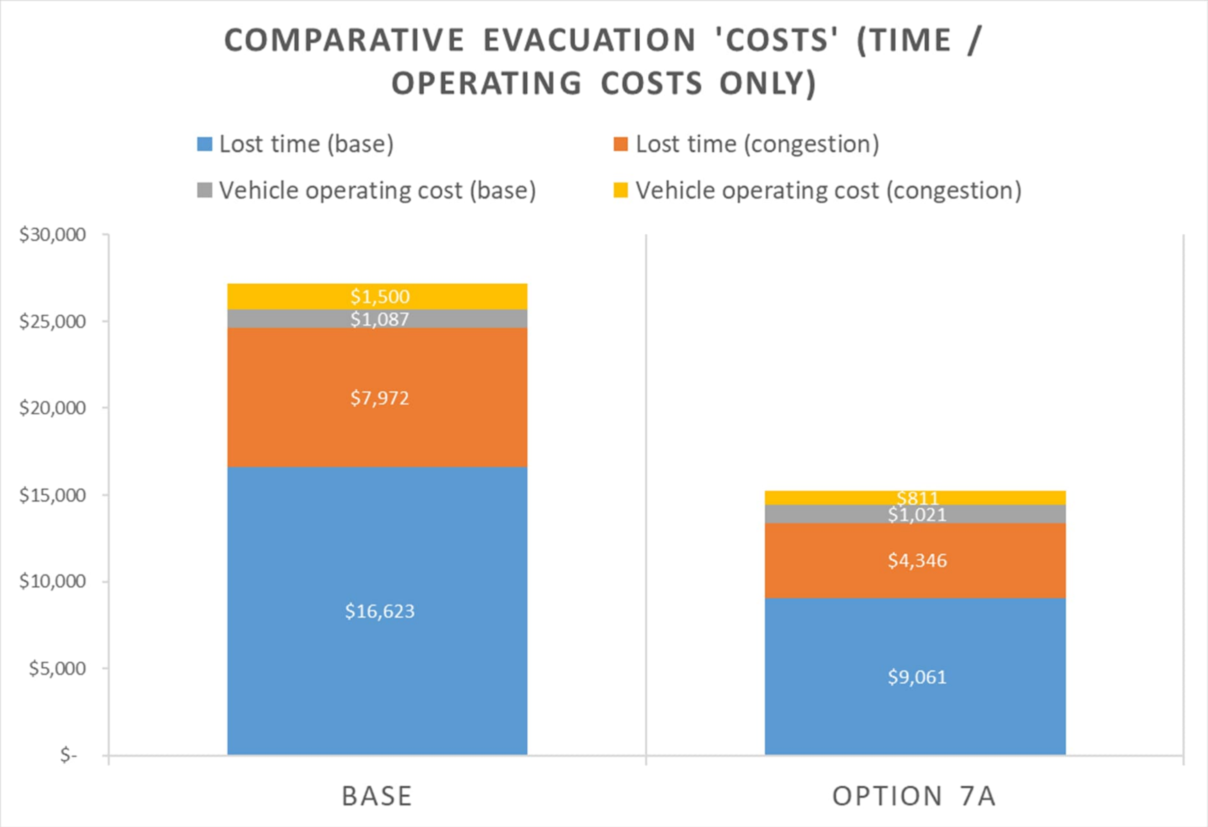


Figure 35: Value of 'false alarms' by network option

10.47. The value of the saving: $12,000 is almost totally insignificant in the context of a 'normal' economic evaluation. Figure 36 shows that the 60 year value, (subject to discounting at 4%)[32] over 60 years is worth approximately $40 - $80,000, depending on the frequency of 'false alarms' assumed. This is almost too small to consider.

Assumption	Inflation adjusted benefit		Annualised discounted total (at 4%)
	Over 60 years	Per year	
1 / 10 years	$ 195,672.17	$ 3,261.00	$ 76,730.98
1 / 20 years	$ 97,836.08	$ 1,630.60	$ 38,365.49

Figure 36: Annualised value of savings from 'false alarms'

[32] In accordance with Waka Kotahi NZTA Monetised Benefits and Costs Manual

CRASH SAVINGS

10.48. Civil defence advises that crashes are an expected part of an evacuation. On the context of Option testing at the Pages / Hawkes / Seaview intersection, the relative improvement of the scheme against the roundabout could be considered.

10.49. A basis for estimating evacuation based savings is to consider the underlying design risks (presumably manifest in crash history), and predicting from this which of these hazards might surface during an evacuation.

10.50. Examination of the roundabout crash history[33] shows 10 crashes across 10 years, of which 7 are 'non-injury' based. The frequency and severity are shown in Figure 37, and the collision diagram is shown as Figure 38

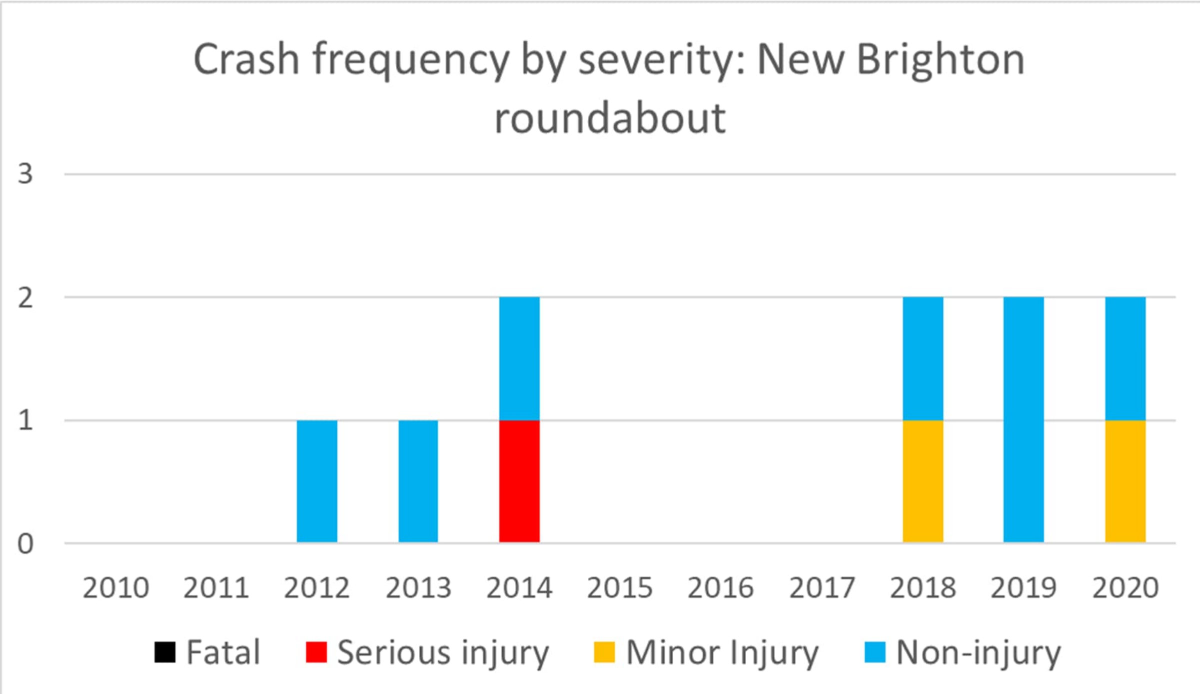


Figure 37: Crash history at existing roundabout

[33] Using the Waka Kotahi NZTA Crash Analysis System

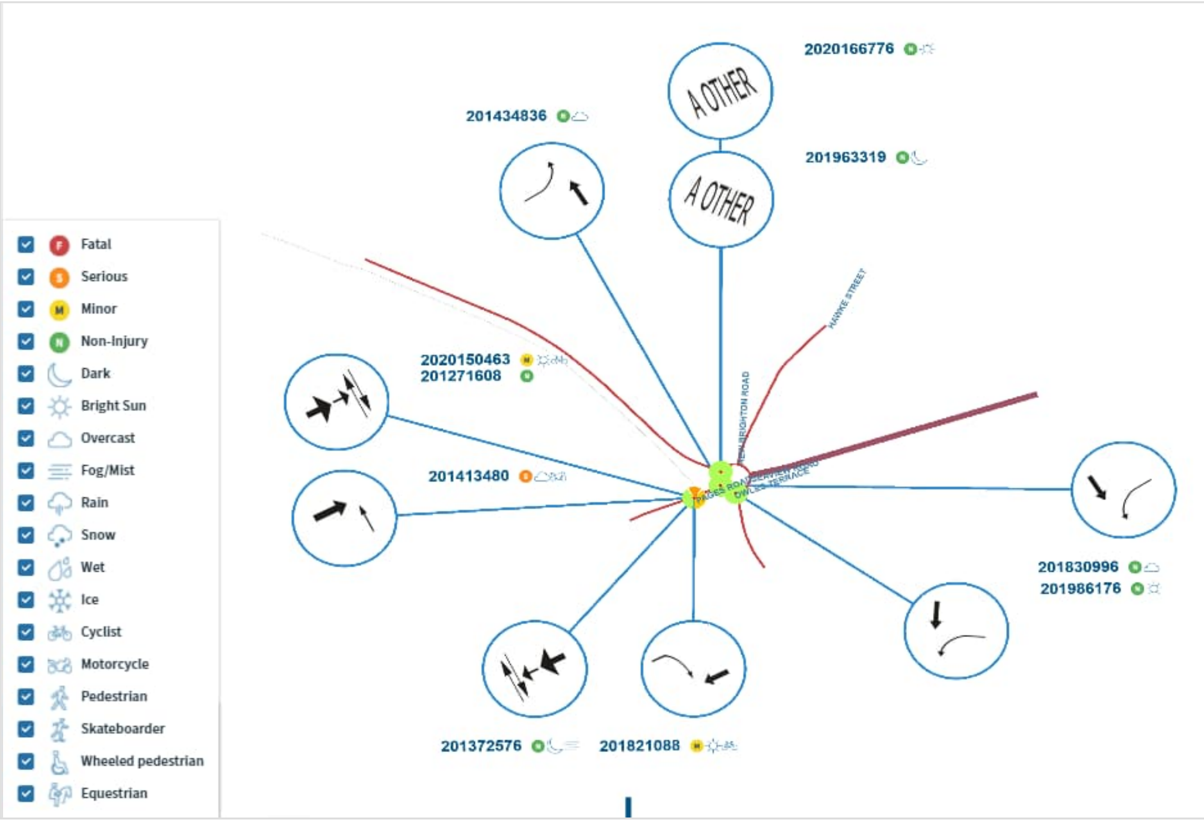


Figure 38: collision diagram, New Brighton roundabout – 10 year crash history

10.51. There were two minor injury and one serious injury crash recorded within the period, representing a 30% injury rate; which is reasonably low.

10.52. The likely reason for a low injury rate is the slow vehicle speeds. Typically, drivers on or approaching the roundabout will be travelling slowly, and therefore the severity of the crash outcome will be limited.

10.53. The exception is for crashes involving two wheeled vehicles, where the human body is more exposed to the forces of collision. Two of the injury crashes involved cyclists and the third involved a motorcycle.

10.54. From this, it is possible to estimate how a crash scenario would play out during an evacuation. It would be difficult to imagine a crash scene which cannot be 'cleared' quickly, if it involves low speeds, and/or two wheeled vehicles. So the delay factor could be limited.

10.55. The merits of the preferred scheme option include:

10.55.1. A significant reduction in the number of vehicle conflict points

10.55.2. Management of conflict points with signals

10.55.3. Management of cycle crossings with signals

10.56. Signalised intersections do not 'resolve' all crashes, and traffic signal controls are not considered to be considered as a crash reduction measure, without careful consideration.

10.57. There are certain crash types under certain circumstances know to increase following the introduction of signals to an intersection. This can include an increase in:

10.57.1. 'Right turn / against'

10.57.2. Certain types of pedestrian crossing crashes.

10.58. However, in an evacuation scenario, neither of these two crash types would be anticipated.

10.59. There would be very little 'right turn' demand from the west, as this involves travelling into New Brighton. Also, it is unlikely that many people would evacuate on foot (noting that 2% of respondents in the Canterbury University post- Kaikōura survey (2018)).

10.60. Therefore, in my opinion, (and without further data), the safety benefit of the scheme during an evacuation could be assumed to be the saving of a minor injury crash to a cyclist.

10.61. It will also be recommended to include a safety analysis as part of a revised scope, given that there are much higher risk crash locations reported in the Crash Analysis System (CAS). These might be treated as part of developing an area wide infrastructure evacuation plan.

D. Qualitative assessment / other important considerations.

ACCESS TO LIFELINES

10.62. In the event of a major incident, of which tsunami might be one of a number of threats, access to/from Civil Defence assets would likely be critical to the implementation of a response plan.

10.63. Some critical civil defence assets (e.g. Fire Station) are located on the New Brighton side of the Pages Road bridge, as shown in Figure 39.

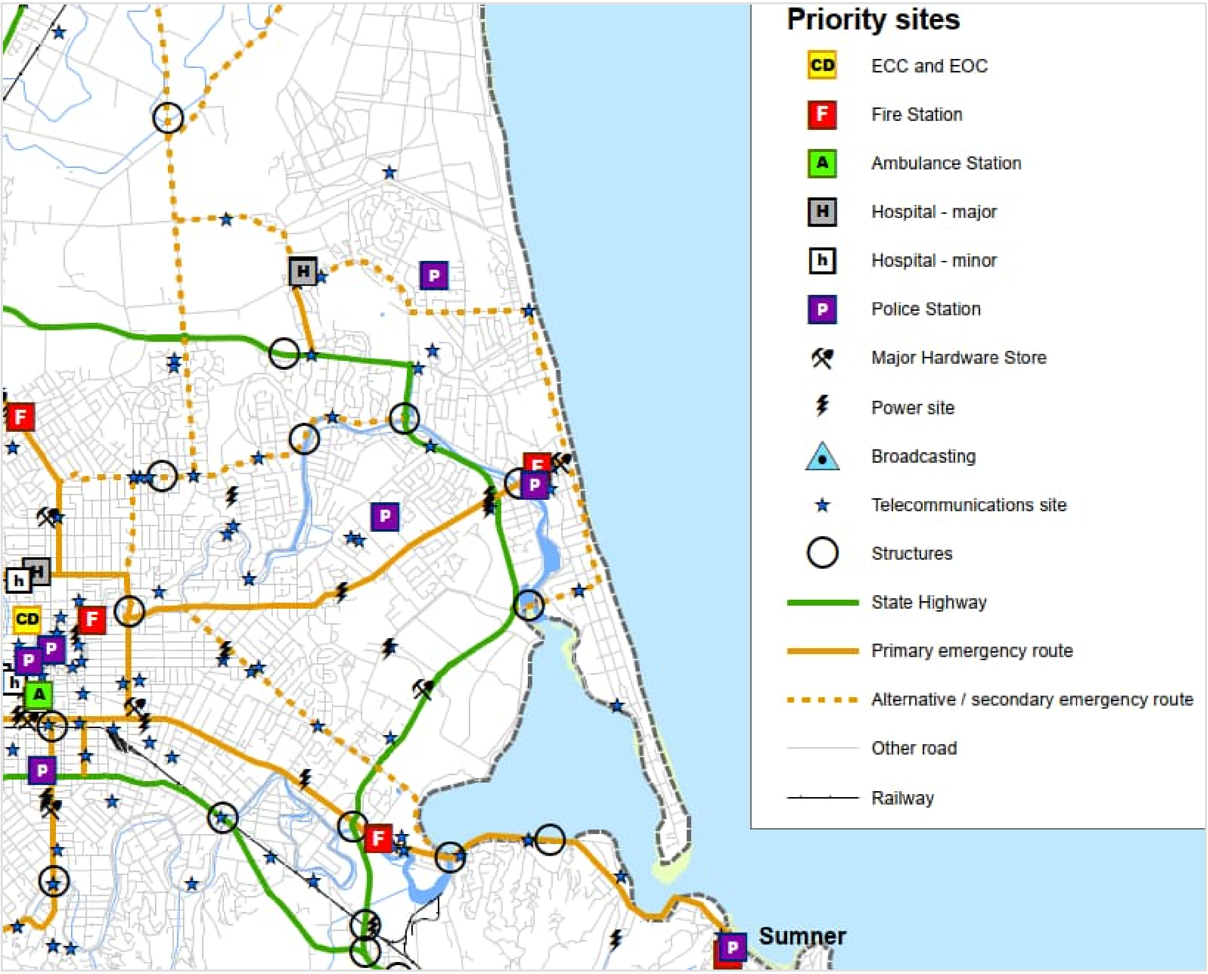


Figure 39: Civil Defence 'life lines': location of key assets

10.64. Maintaining access to these assets might be considered a strategic outcome of the scheme. This can be considered either in terms of the bridge being usable (i.e. not suffering structural failure), or the ability for emergency services to navigate congested traffic conditions.

LONGER TERM POPULATION TRENDS

10.65. Longer term growth has been considered beyond scope of the project to consider, in terms of defining causal variables for sensitivity testing (see section 9 A (v) (Parameters beyond scope of Option testing)). This is because there would be several other factors to consider, and uncertainties in longer term forecasting, (assuming that near term significant development is not anticipated).

10.66. However, it is not fanciful to consider significant growth in the longer term, fuelled by forecast significant in-migration to Christchurch city, low land values, and changing fashions.

10.67. There is uncertainty around longer term population changes in the New Brighton area. The *Coastal Hazards Assessment (2021)*[34] is underway, which includes a high level analysis of risk. This will lead to a *Coastal Hazards Adaption Planning Programme*, which could include a range of scenarios from coastal retreat to sea-walls and other resilience based infrastructure.

10.68. The District Plan identifies New Brighton as a Key Activity Centre (KAC), and associated provision for 'medium density' housing within the immediate catchment. The proposed New Brighton Master plan is a major intervention to promoting economic activity and revitalisation. If fully developed, there would be a significant increase in population, underpinning the need for improved tsunami evacuation planning.

10.69. Therefore, although the longer term future remains uncertain, a retreat from New Brighton would be a stark contrast to the present District Plan paradigm for the area, especially if resilience infrastructure is feasible. An alternative future might be one of growth and expansion, given the overall regional pressures for housing a rapidly increasing population, coupled with a desire to live close to the coast, noting the international experience that proximity to coast adds to perceived quality of life and property values.

10.70. Given the possibilities of two contrasting long term population trends, longer term changes have not been considered; effectively, assessment treats modelled tsunami risk as constant, based on uncertain population derivatives.

E. Opportunity costs of an enlarged scheme

10.71. The conclusion finds that Option 7 – a high capacity signals intersection with dual lane bridge – would be effective in mitigating most of the estimated risk presented by a tsunami. The report also finds that the additional benefits from adding a second lane far exceed the benefit of a single lane option, (i.e. Option 3).

10.72. Figure 40 shows the total benefits of the $17m double lane bridge and intersection scheme, in terms of composite values: the value of the first $15m, being a mid-point of $40m, and the value of adding a second lane, with a mid-point of $211m.

10.73. In plain English, spending a further $2m for a larger scheme, (being a +13% capital outlay) would results in a five-fold increase in value of life benefits.

Option / capital value analysed		Value of Life benefit		
		High	Med	Low
Option 3: (signals, single lane option)	$15m	$ 66,277,332	$ 39,785,809	$ 13,294,285
Option 7: (signals, double lane option)	$2m	$ 351,194,934	$ 210,819,807	$ 70,444,680
Total	$17m	$ 417,472,266	$ 250,605,615	$ 83,738,965

[34] https://ccc.govt.nz/environment/coast/coastalhazards/how-we-assess-coastal-hazards

Figure 40: Value of opportunity, additional $2m outlay

F. Waka Kotahi NZTA - Risk Management framework

10.74. For NZTA funding assistance, the value of the risk and opportunity would probably be considered against the Waka Kotahi Risk Management guide. In summary, the *clear expression of risk* (framed in terms of s3.2.1) can be stated as:

10.74.1. Threat / Opportunity: that the Pages Road bridge cannot support a mass evacuation scenario. Opportunity is in designing a scheduled bridge replacement to accommodate a successful tsunami evacuation, and avoid potentially catastrophic loss of life.

10.74.2. Cause: The cause of the threat is a major tsunami and limited evacuation time, through a network not capable of processing evacuation traffic in a timely manner. The cause of the opportunity is ability to address a long term threat, as efficiently as possible, taking advantage of the cost efficiencies already offered by a project in process.

10.74.3. Consequence: By taking advantage of the opportunity to future proof, including the extending of capital outlay from $15m to $17m, the adjusted value of the scheme increases by $250m, worth equivalent of 53 lives.

10.74.4. (If the maximum tsunami threat actually occurs, the value of lives saved by adding a second lane would be 948).

11. CONCLUSIONS AND RECOMMENDATIONS

11.1. Several design options for the Pages Road / Seaview Street / Hawke Street and Pages Road Bridge have been modelled, and the merits of each considered in terms of resulting community exposure to a tsunami hazard.

11.2. For purposes of informing economic assessment, the extent of the tsunami hazard itself – likely to be from a regional source with a 1 hour arrive time - has also been considered. Estimated outcomes consider the value of exposure, weighed by risk of multiple possible tsunami outcomes.

11.3. The recommendation is to fund Option 7a, simply because the value of opportunity; please see Figure 40 (above)). Option 7a includes dual westbound lanes, signalised Pages Road / Seaview Road / Hawke Street, ITS at the signals for evacuation optimisation and Hardy Street change of intersection priority.

11.4. Extensive transport modelling sensitivity testing has been undertaken, along with external peer review. There is sufficient confidence in the simulated network performance.

11.5. The greater determinant to analysis is the scale and recurrence of the tsunami itself. In the vast majority of cases, the tsunami would not threaten, or be small, and in most circumstances considered, the majority of those 'stuck' in the network would not be exposed to a life threatening tsunami hazard.

11.6. However, even accounting for low probabilities, the resulting value of life range is enormous. This conclusion is arrived at using a risk adjusted metric, the same approach applicable to any project type with low occurrence, but extreme severity.

11.7. The application of the monetised values would be subject to typical caveats in the field of economic analysis. (For example, starting point of the value of life is the HM Treasury valuation of human life, and associated caveats). However, a key outcome is identifying a solid funding assurance outcome. The scale of intervention is clearly appropriate in light of the scale of the risk.

11.8. Sensitivity analysis is undertaken to test the analysis to breaking point: determining just how scarce some of the probabilities would need to be, before the *low* end of the estimates ceases to justify expenditure.

11.9. Figure 41 shows the point at which the *low* estimate would drop to be equal to investment, (i.e. $17m), against three variables.

Variable	outcome	Interval		
		Low	Mid	High
Hazard (inundation, movement)	0.39	$ 17,203,735	$ 116,125,208	$ 215,046,682
Recurrence	2.7	$ 17,022,072	$ 78,225,797	$ 139,429,523
Wave height occruence	0.37	$ 17,005,049	$ 110,511,848	$ 204,018,647

Figure 41: Sensitivity testing tsunami

11.10. Analysis of the three variables revealed that:

11.10.1. Testing the natural hazard factor (i.e. the amount of population affected by inundation and water hazard), the *low* estimate broke even when this hazard was factored by 0.39. (The low estimate *also* assumes a recurrence of 2,500 years). It is also notable that the estimates are conservative to begin with, as hazard is assumed for population origin, and not where the population is located when the tsunami makes landfall. The path to safety from the lower risk areas is through space where probability of inundation > 0.90, and where water movement would likely be hazardous. Modelling shows congregation of the population inside these high risk areas when the tsunami is expected to arrive.

11.10.2. Testing the recurrence factor (retaining hazard to 'normal values'), the *low* estimate broke even when recurrence was factored by 2.7. That represents a *low* interval of 6,750 years. Bearing in mind that the 'high' value of 200 years is evidence based, and could be used, the mid-point (equivalent of 1,350 years) is clearly conservative.

11.10.3. Testing the wave height probability, the *low* estimate broke even when the modelled wave height probabilities were factored by 0.37.

11.11. Therefore, both the transport modelling and tsunami incident based analysis are rigorously tested and demonstrating investment assurance.

11.12. The methodology assumes a constant value of life, at $4.7m, whereas in reality this would increase over time. Furthermore, there is no accounting for net present value, given that the same threat would be considered present in year 99 as in year 1.

11.13. The report only considers benefits of network resilience in the event of a regional source earthquake. Other factors supporting the conclusion include:

11.13.1. That long distance earthquakes provide a longer evacuation time, but behaviour / use of this time is largely unknown and therefore it wouldn't be detrimental to provide infrastructure to support evacuations from any source. Again, recurrence of ~5 metre wave height tsunamis from any source is estimated at once per 150 – 350 years for the Christchurch coast.

11.13.2. That only known sources can be considered. Tsunamis can be caused by more than just earthquakes, or unknown earthquake sources.

12. RECOMMENDED FURTHER ACTION

A. Synopsis

12.1. The project scope for Option testing infrastructure at the Pages Road bridge and Sea View Road intersection has been completed, with risk and uncertainty managed to the best possible degree.

12.2. The hypothesis was that the key to a successful evacuation is increasing capacity on the bridge and current roundabout layout. Doing so is predicted to decrease the evacuation time by around half.

12.3. However, modelling has exposed that evacuation is hampered by other capacity constraints within the network. Furthermore, all testing has been undertaken on assumption that evacuation response behaviour is swift and rational.

12.4. Whilst the shape of the network lends itself to providing flow paths to safety, the management of the network does not allow for this. Routes include a mix of priority and yield arrangements at intersections, and a confused hierarchy, preventing a continuous path of movement.

12.5. Positive aspects of this design configuration includes effective speed management. However, the hydrodynamic consequence of this configuration is friction. The changing of priorities at a single intersection (Beresford – Hardy) was found to improve run out time by *five minutes*.

12.6. The recommendation is that further work be undertaken in collaboration with CCC Civil Defence, to both assist Community dialogue and also inform a best value infrastructure management, geared mostly towards facilitating flow paths through least cost initiatives.

B. Recommended scope of additional investigation

WORK WITH CIVIL DEFENCE, AND CONTRIBUTE THE EFFECTIVE MODELLING TO DEMONSTRATES THE ISSUES AND BENEFITS OF DIFFERENT OUTCOMES

12.7. Paramics is a powerful tool, where Planners without a specialist in modelling can witness the queue dynamics and issues being raised, using the visualisation suite.

12.8. It includes ability to simulate all modes of transport – including bicycles, and an array of behaviours.

12.9. We could estimate optimal transport outcomes, work with Civil Defence to incorporate these into planning, and translate these issues into effective Community dialogue.

IDENTIFY PINCH POINTS AND COST EFFECTIVE CHANGES TO NETWORK MANAGEMENT

12.10. Some of the existing flow path obstructions currently benefit the Community by facilitating slower speeds and safer, more liveable streets. Therefore, careful attention would be paid towards the creation of flow paths, whilst retaining these positive attributes.

12.11. This is also an opportunity to provide a near-term response.

INVESTIGATE AND RECOMMEND INFRASTRUCTURE PROVISION

12.12. A longer term response could be to replace other critical intersections which impede a successful evacuation. The investigation would also engage more with the sensitivity parameters considered beyond the scope of the Pages Road replacement project brief.

12.13. This work could be tied in with the pre-existing priorities for the area. Other due considerations might also include designing for pedestrian / cycle levels of service and securing opportunities for longer term growth.

INVESTIGATE AND RECOMMEND INFRASTRUCTURE PROVISION

12.14. Improving community preparedness likely represents better value for money than infrastructure, but we have shown that infrastructure cannot accommodate a safe evacuation, even with a swift response time. Therefore, finding the right mix can mitigate the risk at the lowest capital outlay.

13. APPENDIX 1: SCHEME DRAWINGS

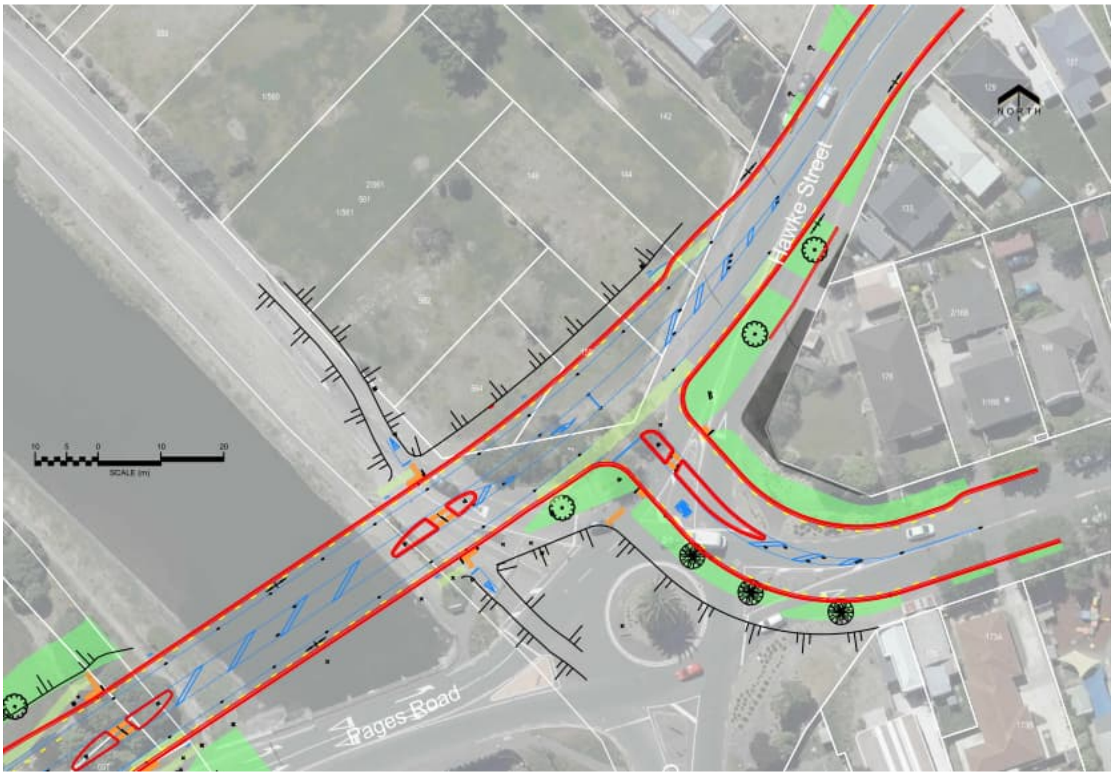


Figure 42: Option 2: Give way, single lane geometries

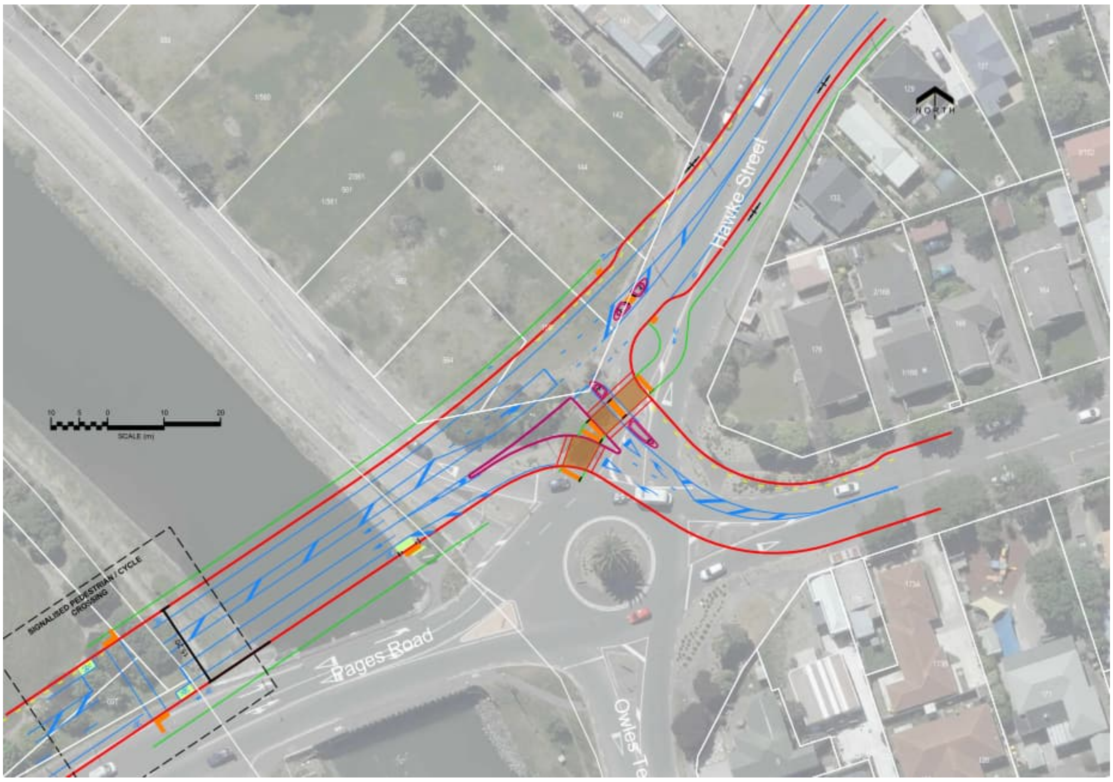


Figure 43: Option 4a: Signals scheme plus free left turn

Figure 44: Option 7 / 7a: Multi lane signals with second outbound evacuation lane

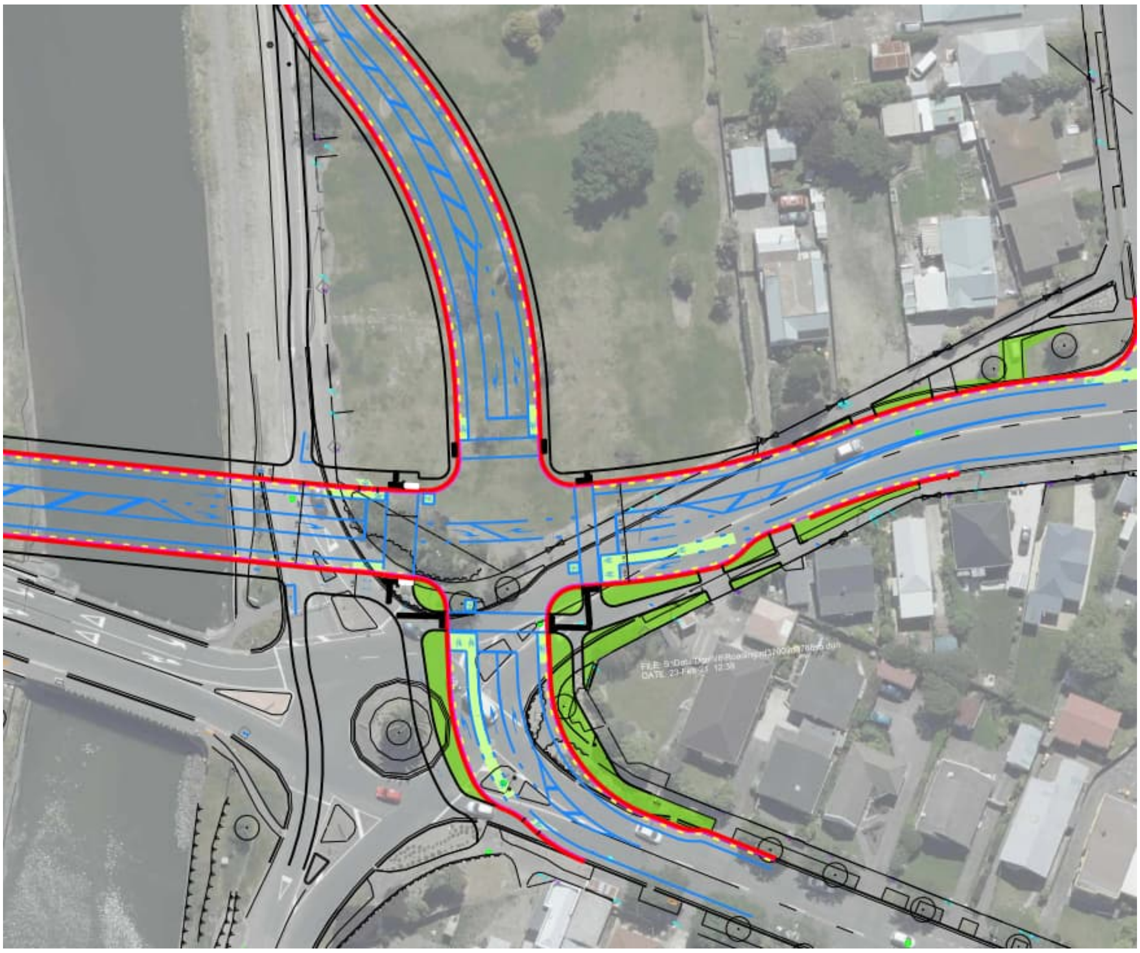


Figure 45: Option 8: Signals scheme plus fourth arm (New Brighton Road),

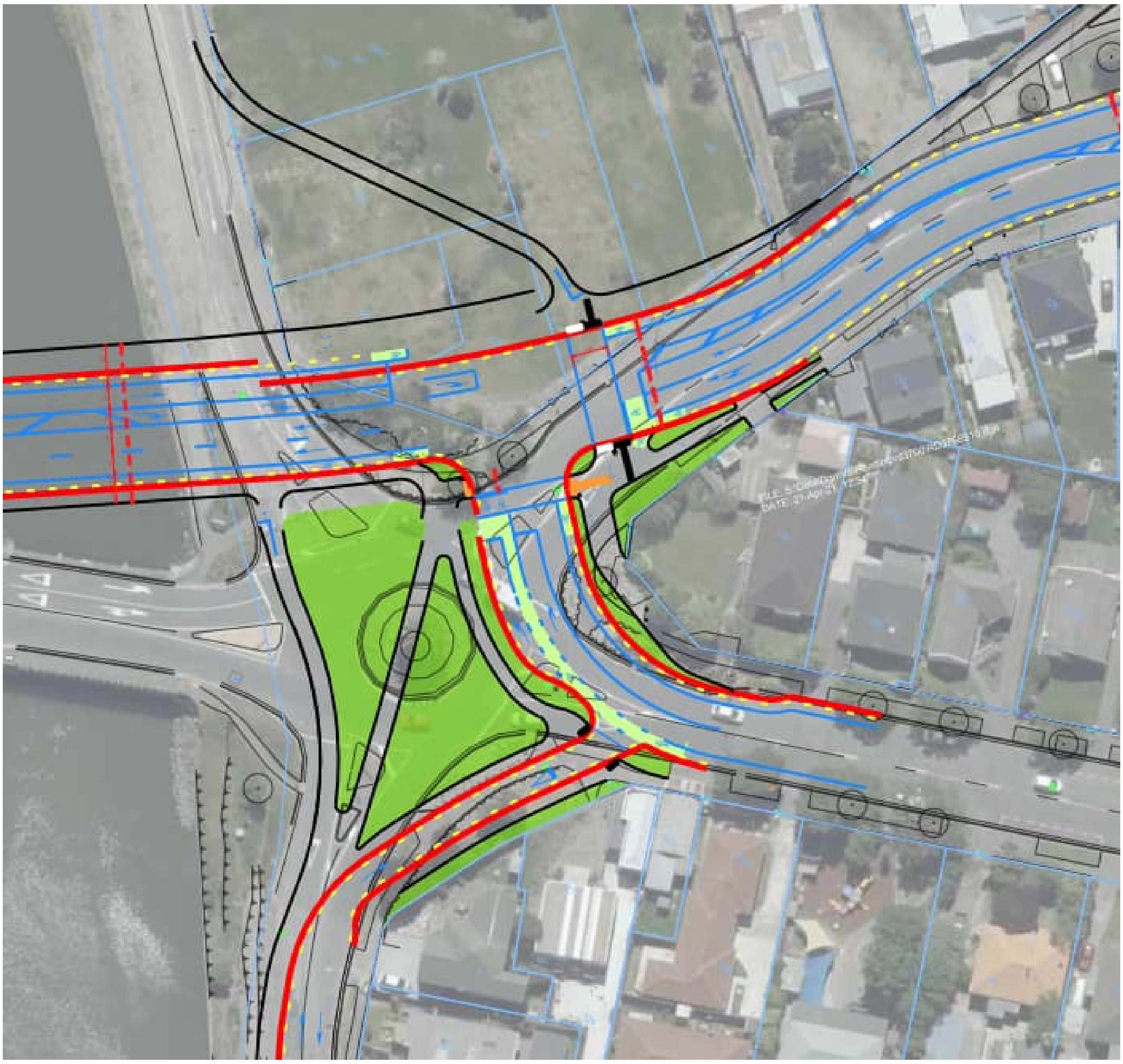


Figure 46: Option 9: Signals plus retained access from Owles Terrace