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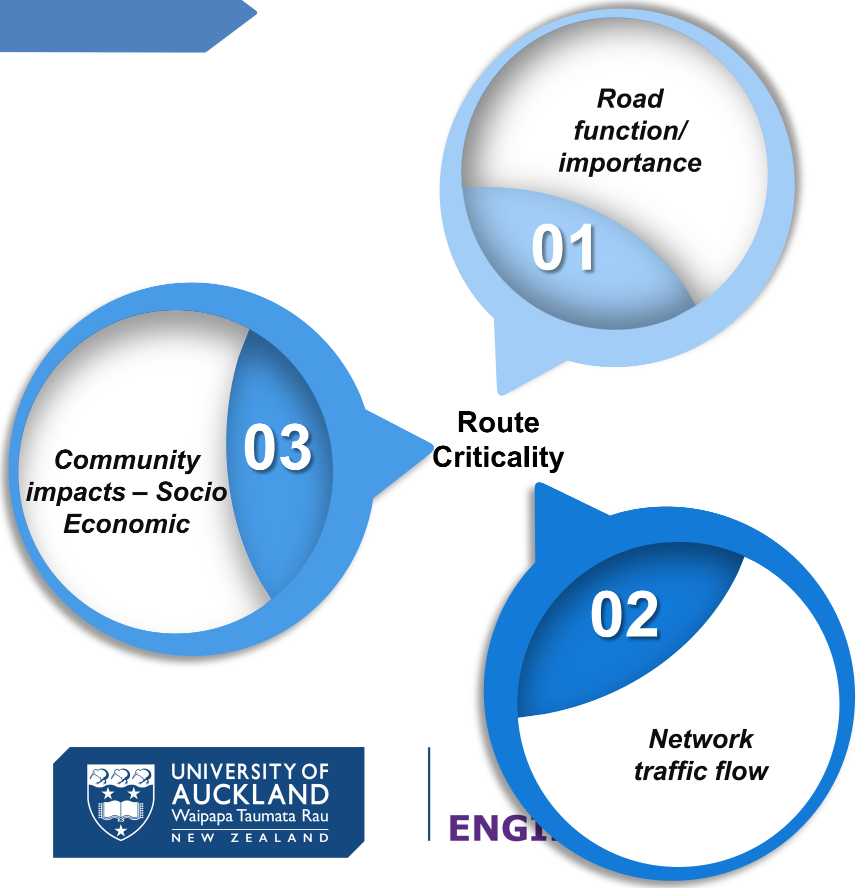
Contribution of Road Network Redundancy to Reducing Road Link Criticality

Eduardo Allen Binet & Theuns Henning

Supervisors: Seosamh Costello & Theuns Henning

Thursday, 26 September 2024

Objective – Setting the Context



- We will never have enough $$ to address resilience on an entire network
- Not all parts of the network are equally important:
  - to the community
  - carries equal risk (exposure and vulnerability)
- We need to focus on the parts that matter most

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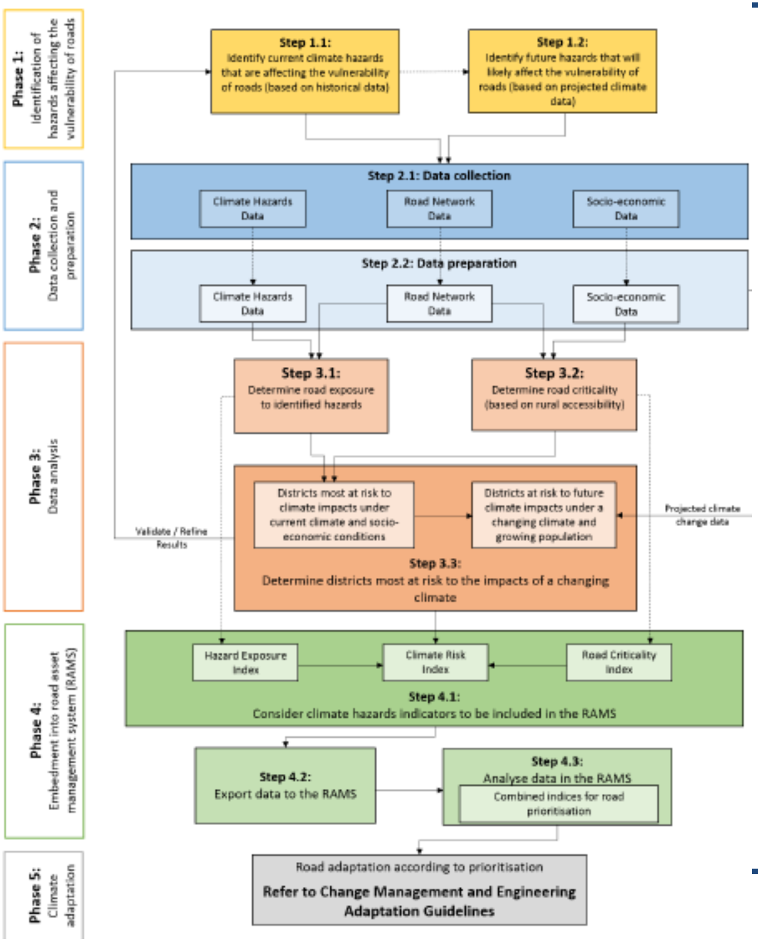
Climate Risk Planning Process



Understand hazard

Network and climate data

Determine Risk and criticality

Intergrade with RAMS

Source ReCAP -Le Roux 2019

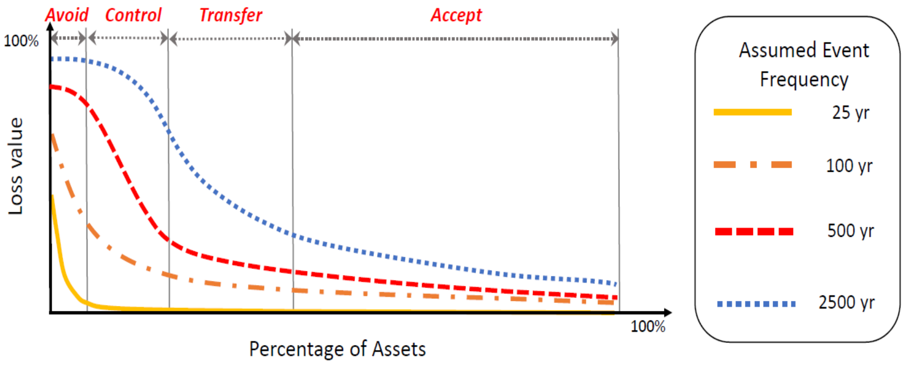
Context: Investment Decision for Resilience

AVOID - Reduce exposure

CONTROL - Mitigate physical impact

TRANSFER – Limit financial loss and aid recovery

ACCEPT - Adaptive response arrangements



Consider multiple possible futures, where risk(s) change with time

Avoid ->Very small portion of the infrastructure where avoiding the risks may be appropriate – e.g. coastal infrastructure that gets damaged with every storm or high tidal event.

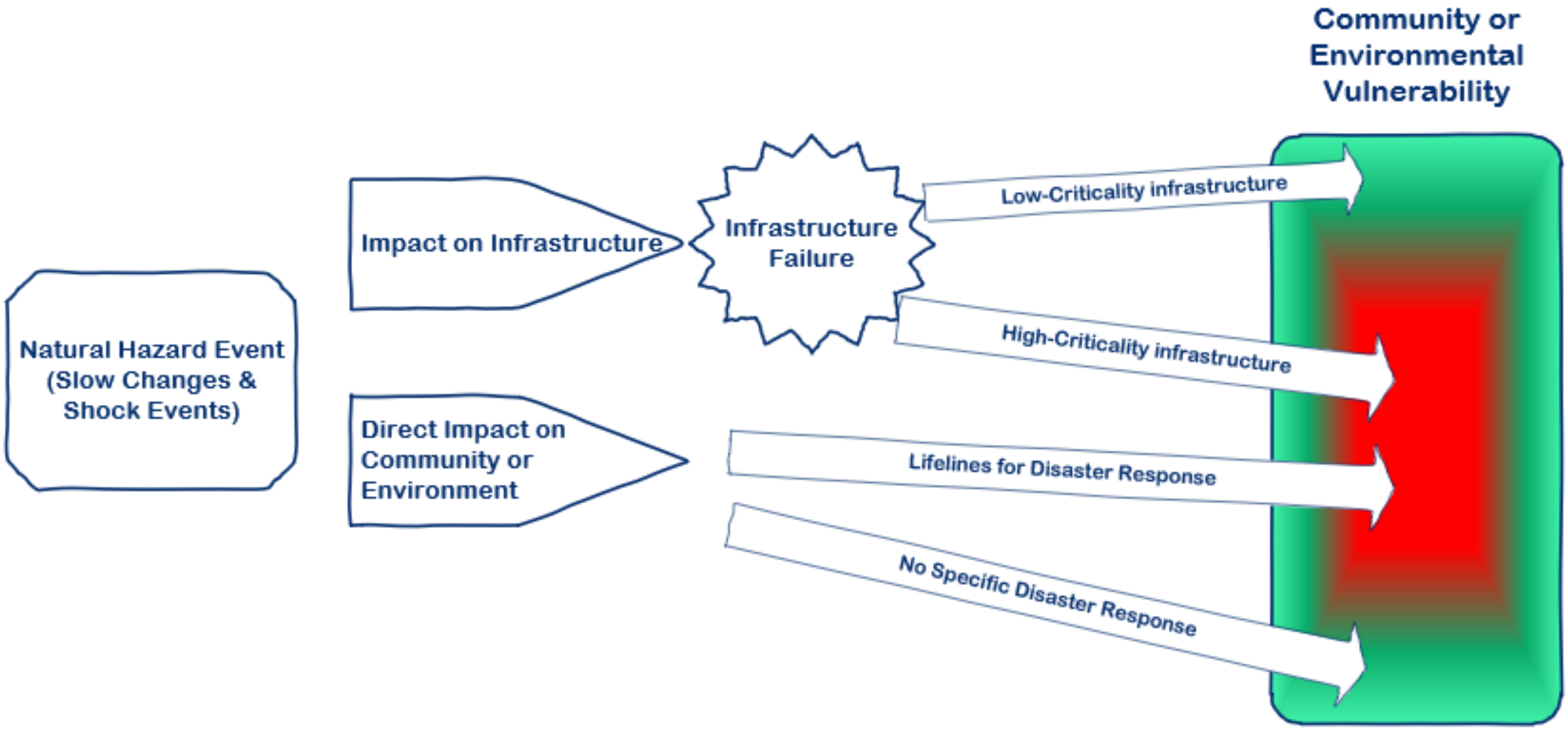
Accept ->large portion of most infrastructure networks where the likely loss would be minimal and investing in adaptation for these parts would be uneconomical or even unnecessary.

Control vs Transfer -> AM system helps us answer

- Control->portion of the infrastructure where adaptation projects will control the potential losses from events. (Good return on investment)
- Transfer - different financing instruments such as insurance or bonds may be more practical

Source Hugh Cowen

Asset Criticality



Common ADB Criticality Framework

Category	Criticality Criteria	Rationale
Economic	Commercial/ Vehicle Flow	Indicator of the importance of the route or asset to industry and commerce
	Strategic Roads	To indicate the importance of route or asset to industries e.g. agriculture, fishing, etc. Could also use criteria such as the number of businesses within 'X' km.
	Supporting Tourism	Indicator of how important the route or asset is in supporting tourism. Number of major tourist attractions within 'x' km of asset
Social/Wellbeing	Health	Hospitals or health centres within 'x' km - i.e. access to health facilities are vital to the welfare of the community.
	Populations served (>5,000)	To indicate the importance of the asset/route in linking large population centres
	Community accessibility/ Redundancy	An indicator of the importance of the route for providing access to important local facilities.
Integrated Transport	Airports	Airports are major transportation hubs, and their location can be an important influence on adjacent road assets.
	Ferry ports	Ferry ports are key links to other islands and can therefore have a significant influence on roads and associated assets which serve them.
	Lifelines	Connection to Emergency Services Evacuation Routes and Facilities High Infrastructure Interdependencies No Redundancy

Criticality Factors to Consider

Strategic importance/significance – Indication of the strategic importance at a national, regional or local level.

Dependencies with other infrastructure – In itself, an asset component may not be deemed critical, but there may be codependency with another asset component that is critical.

Lifelines – The significance of infrastructure in terms of linking emergency services, hospitals and essential utilities. Lifeline considerations also include emergency response activities such as evacuation routes and temporary safe-havens. "***a utility that is required to function 'to the fullest possible extent (even at a diminished level) during and after an emergency, participate in emergency management planning***" (New Zealand Government, 2002)

Redundancy – The capacity and redundancy in the system to cope with the losing specific links in the services system.

Fosters understanding of interdependencies – both network and site level

Auckland Lifelines

Dependence on	Electricity	Gas	Fuel	Telecomms	Transport	Water / Waste
Lifeline Utility Sector Reliance						
Electricity	Red	Red	Red	Orange	Orange	Orange
Gas	Red	Green	Orange	Orange	Orange	Green
Fuel	Red	Orange	Red	Red	Red	Red
Telecommunications	Red	Green	Orange	Red	Orange	Orange
Road Transport	Orange	Green	Orange	Orange	Red	Orange
Other Transport	Red	Orange	Red	Orange	Red	Orange
Water	Red	Green	Orange	Orange	Orange	Green
Wastewater	Red	Orange	Orange	Orange	Orange	Green
Stormwater	Orange	Green	Orange	Orange	Orange	Green
Community Sector Reliance						
Health	Red	Orange	Orange	Orange	Red	Red
Police	Orange	Green	Red	Red	Red	Green
Fire	Orange	Green	Red	Red	Red	Red
Banking	Red	Green	Orange	Red	Orange	Green
Fast Moving Consumer Goods	Red	Green	Red	Red	Red	Green

Legend	Critical requirement to maintain service continuity during business-as usual. (Red)	Some impact on ability to function. Utility becomes more critical in an emergency. (Orange)	Not required for network operation, though may require for staff needs. (Green)

Content

- Impacts of Natural Hazard Events on Road Networks
- Criticality Measures: Review
- Contribution of Road Network Redundancy to Reducing Criticality
- Final Comments

Impact of Natural Hazard Events on Road Networks

Kaikoura Earthquake New Zealand (2016)

More than $600 million dollars in transportation related infrastructure (MCDonald et al, 2017)

Hurricane Dorian, Bahamas (2019)

More than $87 million US dollars in the transportation sector alone (IDB, 2019)

Flooding Brazil (2024)

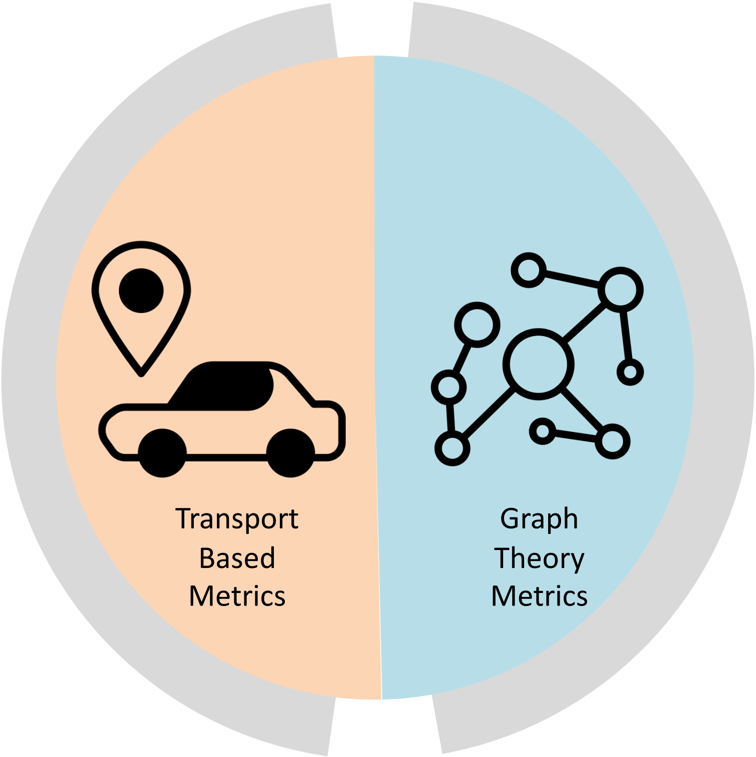
More than $780 million US dollars in the transportation sector alone (GRADE World Bank, 2024)

Volcanic Eruption Tonga (2022)

More than $90 million US dollars in the infrastructure sector (GRADE-World Bank, 2022)

How do we measure criticality?

- Origin of quantifying road criticality
- Quantifying road network criticality has become a major focus for mitigation recovery planning (Tian et al., 2021)
- There is not a unique and single formalization of road link criticality



Transport model based metrics

- This approach considers transport studies to determine road link criticality

- Examples:

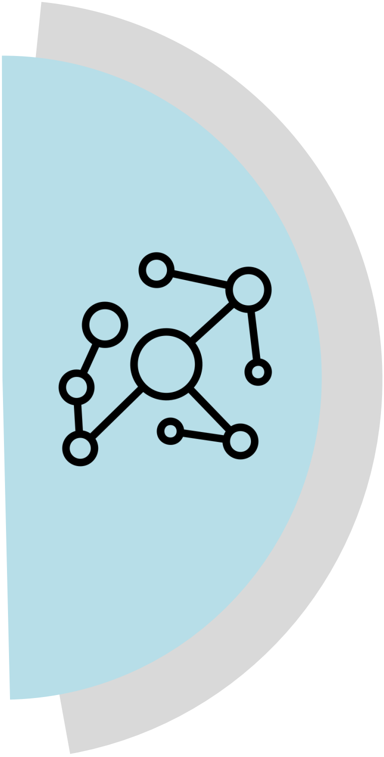
  - Increases in Travel time (Jenelius et al., 2006; Gauthier et al., 2018)
  - Impacts on user experiences (Jenelius, 2009; Rokneddin et al., 2013)
  - Fragility Indices (Koks et al., 2019)
  - Congestion models (Aydin et al., 2019)
  - Accessibility provided by road links to critical infrastructure (Hughes, 2017; Rabello, 2019)

Graph theory based metrics

- This approach considers topological metrics to describe network criticality. It could be applied to any type of network.

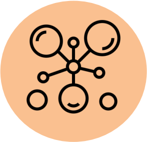
- Examples:

  - Betweenness Centrality (Chen et al., 2023)
  - Network Efficiency (Dehgani et al., 2014)
  - Connectivity (Yan-Jin and Xia, 2018)
  - Minimum link cut calculation (Ford and Fulkerson, 1956)



How to quantify each road’s criticality

How to evaluate criticality?



Full Scan Analysis

This method calculates consequences given the disruption of each road. It successively evaluates various instances of the network in which, every time a different road link is removed

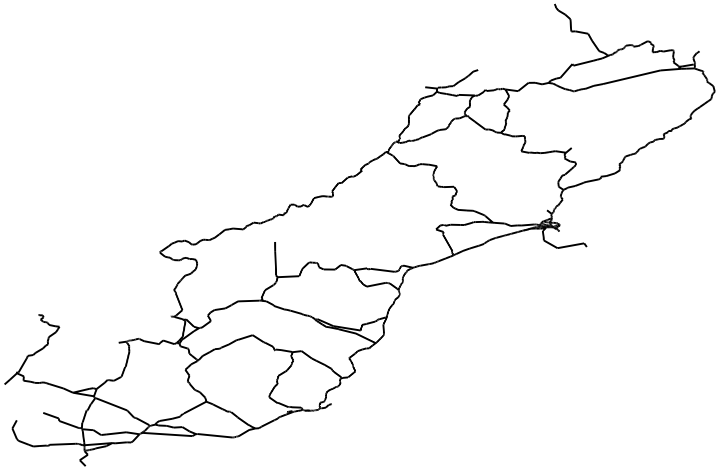
Monte Carlo Simulation

This method is a statistical technique that evaluates numerical results using random samplings and probability distributions to analyze complex networks

Does Network Resilience Play Any Role in Road Criticality?

Should a Redundant Network be More Resilient to Network Disruptions?

Would we have any difference in these two networks?



State Highway Network of New Zealand's South Island
4982 kms

Graph:
4119 Nodes
4204 Links/edges

Combined Road Network (CRN)
State Highways + Local Roads
11814 kms

Graph:
12982 Nodes
14049 Links/edges

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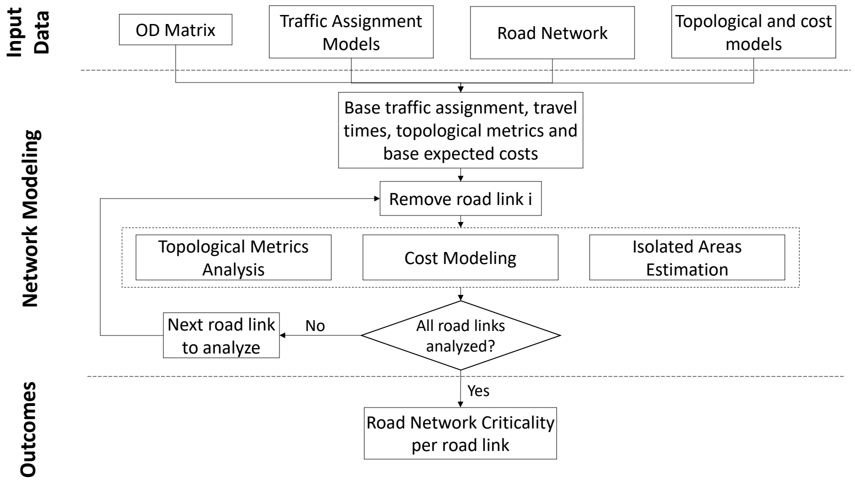
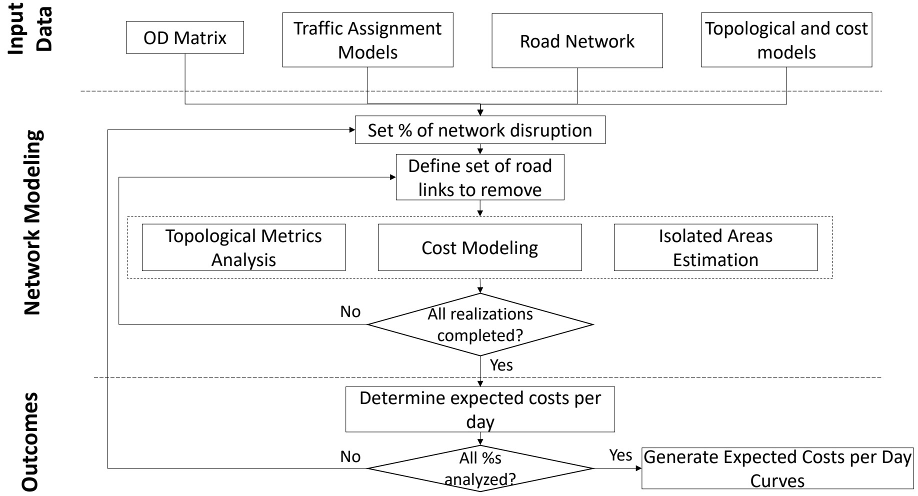
What are the consequences of interrupted road networks

Full Scan Analysis



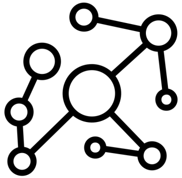
Monte Carlo Simulation



Metrics

Transport Based Metrics

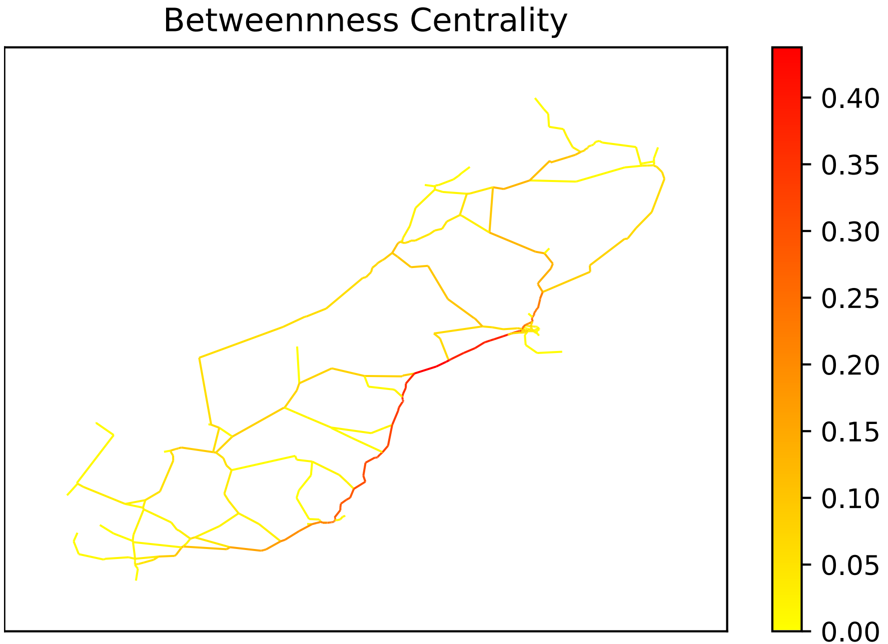
- Vehicle Operational Costs (e.g. tyre consumption, gas consumption, etc)
- Travel Time Cost for Users
- Monetarized Gas Emissions (Hydrocarbons, Carbon Monoxide, Nitrous Oxide, Particulates)

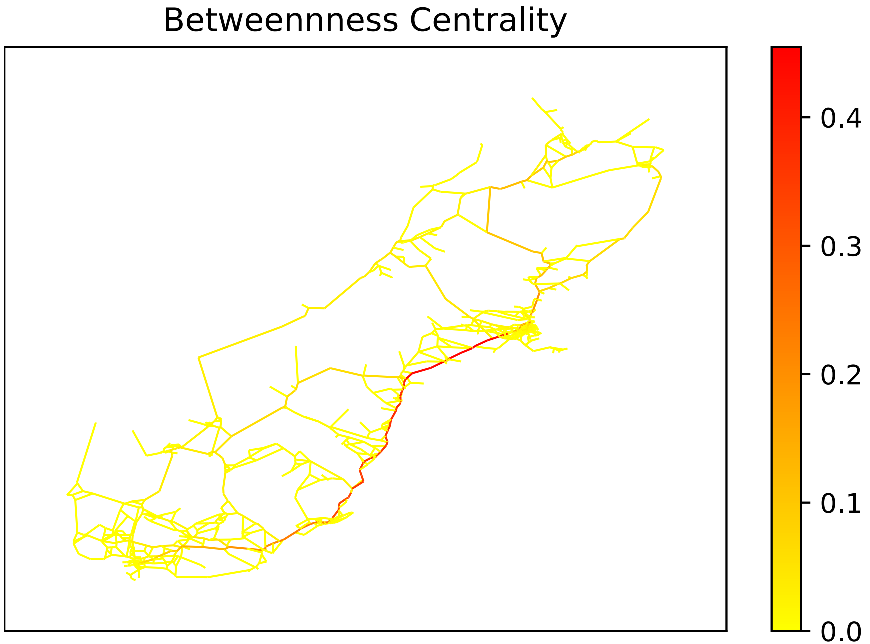


Graph Theory Metrics

- Betweenness Centrality
- Centrality
- Distance to big urban areas
- Average node degree

Topological Analysis





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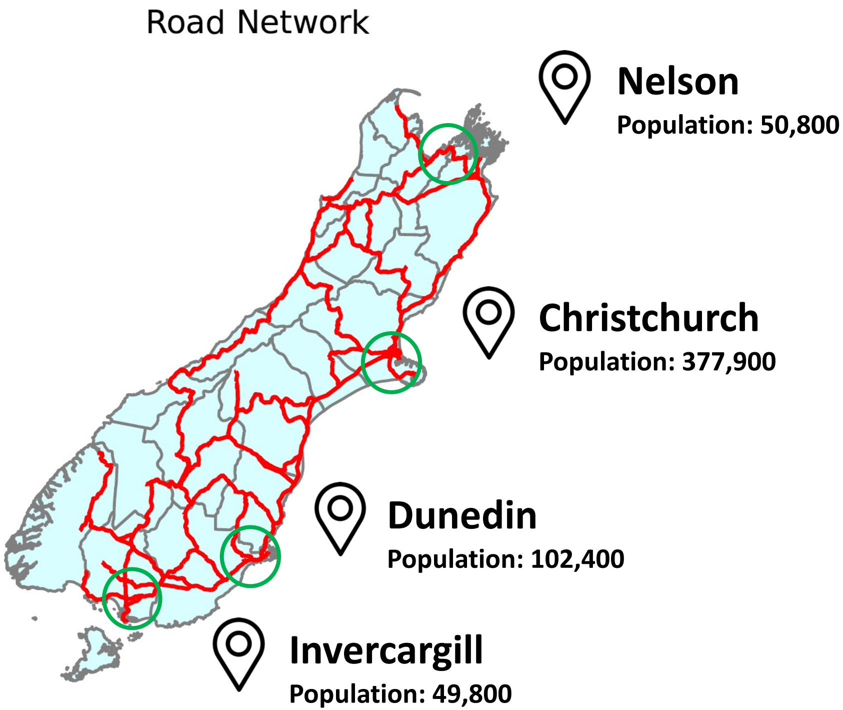
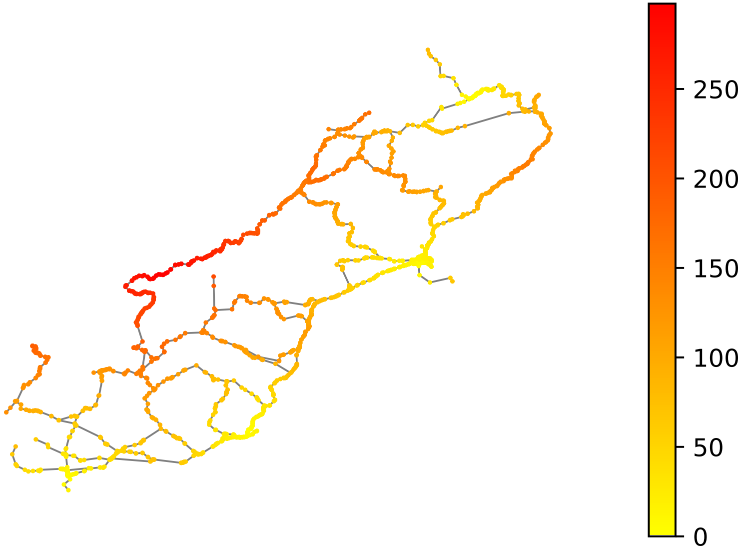
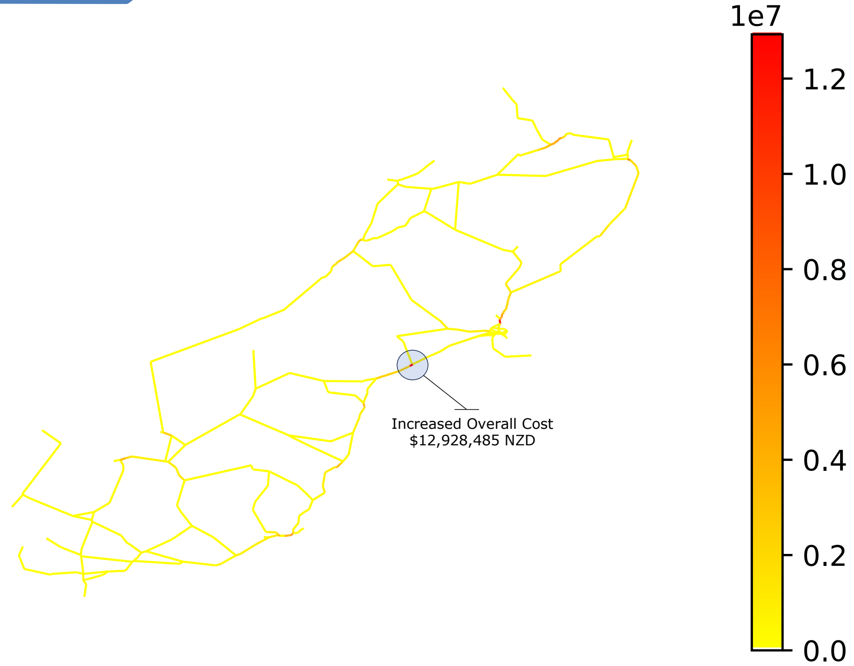
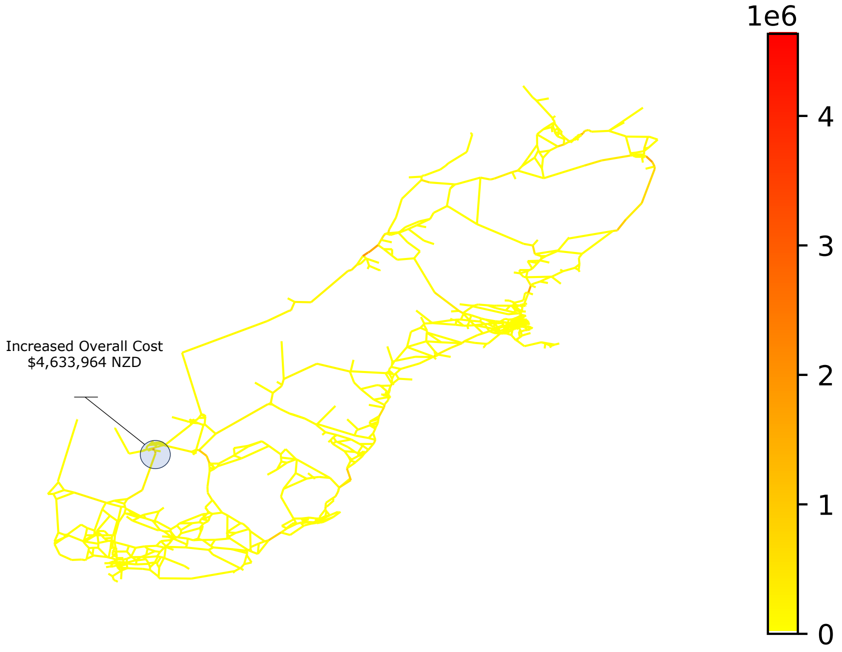


Distance to Big Cities
Average: 87 kms
Median: 77 kms
Max: 297 kms



Increased overall Costs





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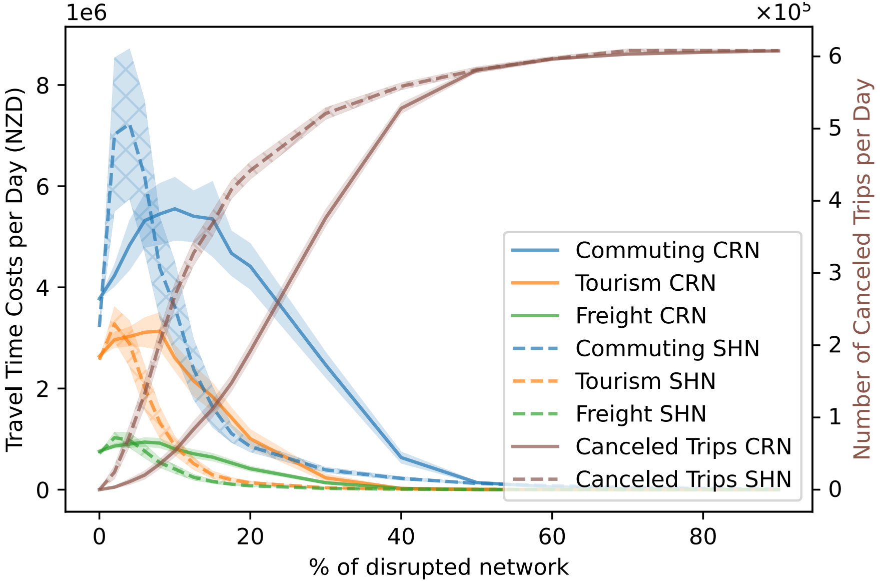
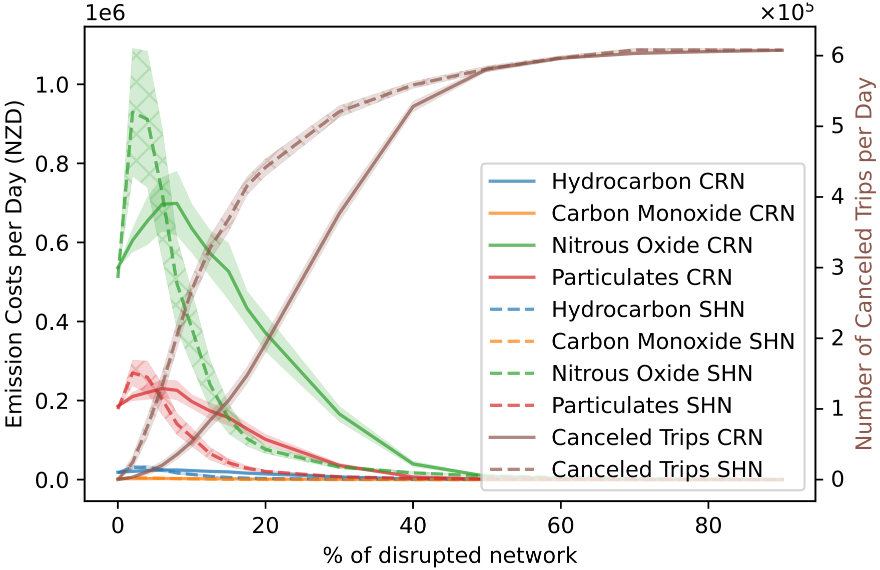
Combined Road Network (CRN) State Highways + Local Roads 11814 kms	Graph: *12982 Nodes* *14049 Links/edges*

Expected Costs

Expected Increased Travel Time Costs

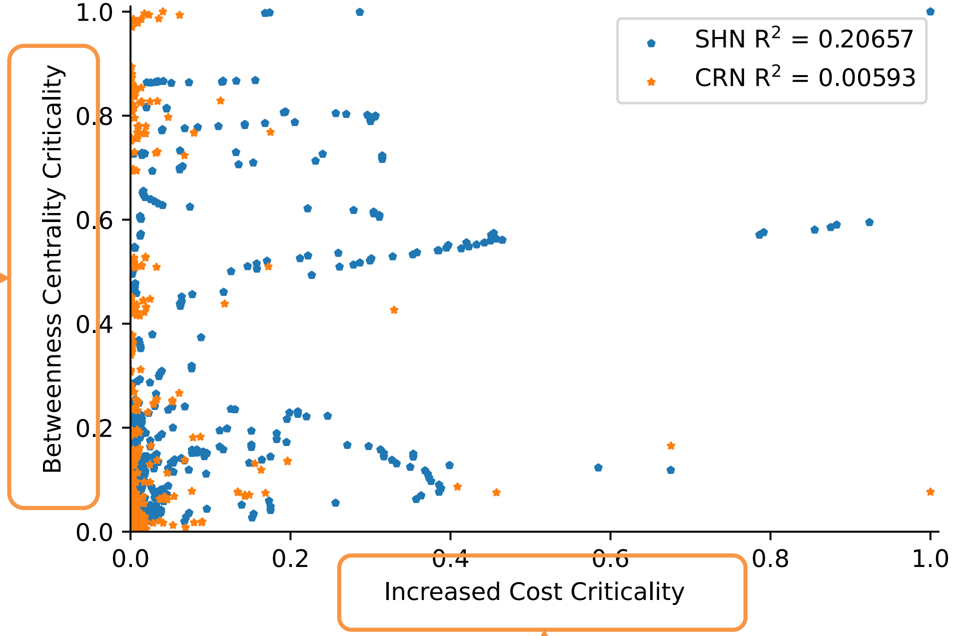


Expected Increased Gas Emission Costs



Road Criticality Measures

Normalized Betweenness Centrality per Road Link



Normalized Overall Increased Cost per Road Link

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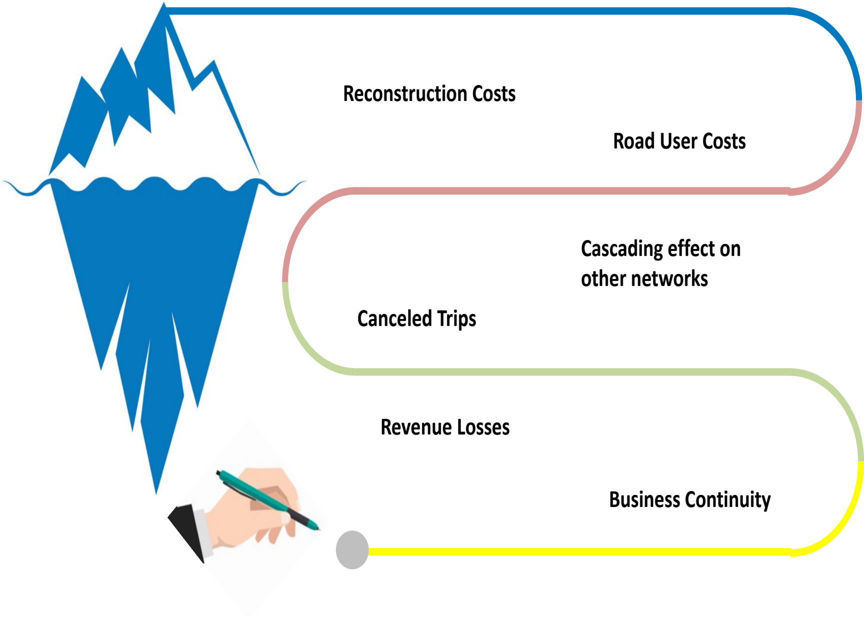
Conclusions and Final Comments

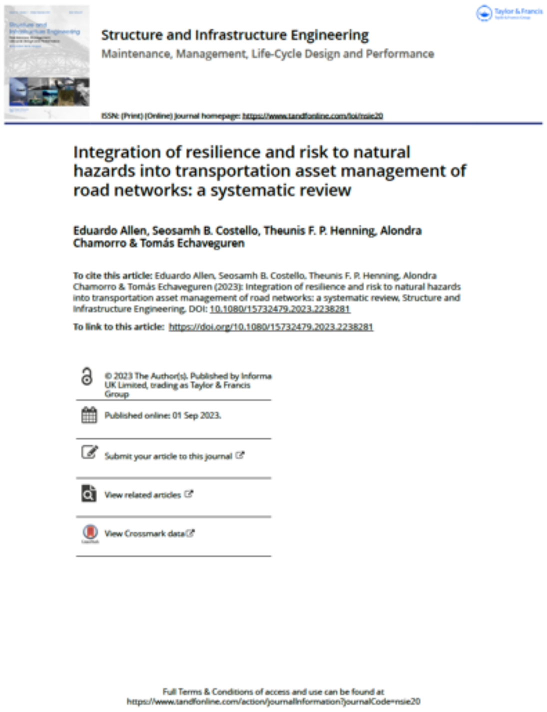
- Increasing redundancy in road networks results in significant reductions in expected consequences and, therefore, criticality

- Redundant network generate more alternative routes to areas of interest, making them less susceptible to being isolated

- Comparing different criticality metrics resulted in a weak correlation, demonstrating that the different methods lead to different results and, therefore, investment decisions



Papers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Integration of resilience and risk to natural hazards into transportation asset management of road networks: a systematic review

Eduardo Allen, Seosamh B. Costello, Theunis F. P. Henning, Alondra Chamorro & Tomás Echaveguren

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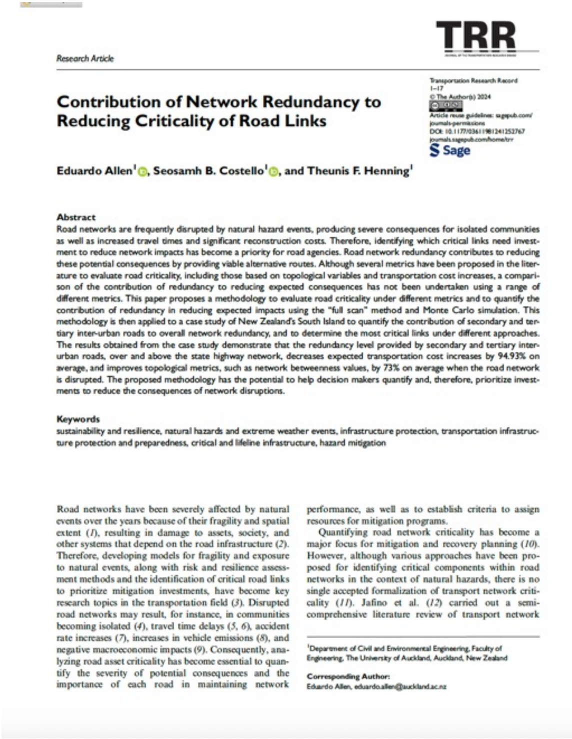
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Research Article

Transportation Research Record
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Contribution of Network Redundancy to Reducing Criticality of Road Links

Eduardo Allen[1], Seosamh B. Costello[1], and Theunis F. Henning[1]

Abstract
Road networks are frequently disrupted by natural hazard events, producing severe consequences for isolated communities as well as increased travel times and significant reconstruction costs. Therefore, identifying which critical links need investment to reduce network impacts has become a priority for road agencies. Road network redundancy contributes to reducing these potential consequences by providing viable alternative routes. Although several metrics have been proposed in the literature to evaluate road criticality, including those based on topological variables and transportation cost increases, a comparison of the contribution of redundancy to reducing expected consequences has not been undertaken using a range of different metrics. This paper proposes a methodology to evaluate road criticality under different metrics and to quantify the contribution of redundancy in reducing expected impacts using the "full scan" method and Monte Carlo simulation. This methodology is then applied to a case study of New Zealand's South Island to quantify the contribution of secondary and tertiary inter-urban roads to overall network redundancy, and to determine the most critical links under different approaches. The results obtained from the case study demonstrate that the redundancy level provided by secondary and tertiary inter-urban roads, over and above the state highway network, decreases expected transportation cost increases by 94.93% on average, and improves topological metrics, such as network betweenness values, by 73% on average when the road network is disrupted. The proposed methodology has the potential to help decision makers quantify and, therefore, prioritize investments to reduce the consequences of network disruptions.

Keywords
sustainability and resilience, natural hazards and extreme weather events, infrastructure protection, transportation infrastructure protection and preparedness, critical and lifeline infrastructure, hazard mitigation

Road networks have been severely affected by natural events over the years because of their fragility and spatial extent (*1*), resulting in damage to assets, society, and other systems that depend on the road infrastructure (*2*). Therefore, developing models for fragility and exposure to natural events, along with risk and resilience assessment methods and the identification of critical road links to prioritize mitigation investments, have become key research topics in the transportation field (*3*). Disrupted road networks may result, for instance, in communities becoming isolated (*4*), travel time delays (*5*, *6*), accident rate increases (*7*), increases in vehicle emissions (*8*), and negative macroeconomic impacts (*9*). Consequently, analyzing road asset criticality has become essential to quantify the severity of potential consequences and the importance of each road in maintaining network performance, as well as to establish criteria to assign resources for mitigation programs.

Quantifying road network criticality has become a major focus for mitigation and recovery planning (*10*). However, although various approaches have been proposed for identifying critical components within road networks in the context of natural hazards, there is no single accepted formalization of transport network criticality (*11*). Jafino et al. (*12*) carried out a semi-comprehensive literature review of transport network

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