Abstract

The failure or disruption of critical transport routes can have substantial impacts on the economy and societal wellbeing. Determining the criticality of transport routes is thus of crucial importance for infrastructure providers, city planners and emergency management officials as it enables appropriate resilience assessments and targeted improvement/intervention and investment strategies to be conducted.

We summarise the proposed criticality framework developed by Hughes (2016) for road networks, and apply and validate the framework as a trial to an area containing 907 km of roads in the central Auckland area of New Zealand. Following an initial trial of the framework, alterations were made to the framework logic, which included the introduction of a new criticality level to account for some roads providing minimal direct societal and economic benefit, and a rationalisation step to ensure that road sections always link to others with either an equal or higher criticality.

The modified framework and 5-level criticality scale, when applied to the study area in central Auckland, is suitable for determining critical roads, and can therefore assist with future assessments of road infrastructure resilience. The framework also has potential to be applied more widely and adapted so that it is applicable for determining the criticality of other infrastructure types, which would allow improved assessments within and across sectors.
1. Introduction

The recognition and protection of critical infrastructure is of increasing concern to national governments, infrastructure managers, and local authorities (Dvořák et al., 2017). Transport networks are one of the most critical infrastructure types for day-to-day activities in developed countries as they allow businesses, regions, and cities to be well connected and productive, as well as serving a variety of users (Ashrafi et al., 2017; MoT, 2017). They are also vital during emergencies because of their role in providing access for first responders and for allowing the restoration of all other infrastructure types (Cova and Conger, 2003; Blake, 2016). Critical transport routes are those that are especially important to societal wellbeing and/or those that have a high consequence of failure (Nicholson and Du, 1994; Jenelius et al., 2006; Hughes, 2016). The more critical the road link, the more severe the consequences (e.g. social, economic, environmental, health impacts) if that link is disrupted or fails (Theoharidou et al., 2011; FHWA, 2014; Jenelius et al., 2016). For example, the 2010-2011 floods in Queensland, Australia impacted 9,170 km of state owned road network including many critical components and links, causing an adverse effect on the country’s social and economic growth (Setunge et al. 2014). Criticality assessments can assist risk and resilience assessments by enabling the prioritisation of infrastructure maintenance and improvement activities through appropriate planning and investment decisions. Improvements to road infrastructure may be focussed in certain geographical areas and on particular assets that are the most important for end-user transportation functionality. This can be in the context of business-as-usual functionality or, indeed, during disasters when certain assets may be exposed to natural and technological hazards and/or reach higher-than-usual capacities. Criticality assessments also allow the implementation of performance based standards for recovery time (Hughes and Healy, 2014; FHWA, 2014; World Bank, 2015). Often, these assessments are achieved through the categorisation of assets into different levels of criticality.

Criticality assessments can be achieved through a combination of:

1) Desk reviews to identify critical assets (e.g. using traffic data and information on functional classification and proximity to emergency management resources); and

2) Stakeholder engagement to provide additional information that is not publically accessible and to address local concerns (Cabinet Office, 2011; FHWA, 2014; World Bank, 2015).

Despite established definitions of criticality and recognition by practitioners of its importance for informing resilience assessments, there are no consistent and agreed frameworks for establishing criticality within and across individual infrastructure sectors in New Zealand (Hughes, 2016). However, we note that three levels of criticality have been developed to broadly distinguish between nationally, regionally and locally critical infrastructure and community assets in New Zealand (see section 2.3), which take into account the number and type of customers affected directly and indirectly if an asset fails (AELG, 2014; ALG, 2017).

Some critical infrastructure providers in New Zealand, including regional and local authorities, have established their own frameworks for determining criticality. For example, some electricity distribution businesses, and councils responsible for water infrastructure, have developed asset criticality frameworks that underpin their investment programmes (e.g. Todd and Mitchell, 2018; Chisnall and Martin, n.d.; Cole, n.d.). However, these frameworks are often developed independently and in relative isolation from one another with different criteria which evolve slowly (e.g. to meet changing organisational requirements) and/or rapidly (particularly following a disastrous or high-profile emergency event). Additionally, the frameworks and criteria are not always accessible at a public or, indeed, inter-regional level beyond the organisation where they evolved. We recommend that a nationally consistent and impartial criticality framework be

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1 A link is a section of road that connects adjacent intersections.
developed, which can be adopted by infrastructure providers and governing authorities. Such a framework would enable improved comparative analysis within and across sectors, and ultimately enhance resilience assessments and infrastructure investment decisions.

In this paper, we apply and validate a criticality framework for road networks proposed by Hughes (2016). This framework is based on an amalgamated scoring system for the classification of road links and access to lifeline utilities, evacuation routes and essential services, and is intended for application across New Zealand. The road network in central Auckland, New Zealand is selected as a case study for the application and validation process of this trial. The methodology section in this paper outlines the details of the approach we adopted, which incorporates desk reviews and stakeholder engagement. The results section contains both the initial findings and those following modification of the framework to account for some roads providing minimal essential service in terms of recovery function. A discussion of our findings follows, including a brief qualitative assessment of its success and recommendations for further work. Initially, however, we provide background information which includes a summary of the framework adopted and specifics on the road network and area chosen for its application and validation.

2. Background

2.1 Road Hierarchy and Criticality

Internationally, road authorities often use the concept of hierarchy, which generally infers a degree of criticality. A road hierarchy system typically classifies roads by type and allows the prioritisation for functional operational and asset management purposes; for example, the ‘Asset management hierarchy’ in Scotland (Transport Scotland 2009), and the ‘Functional hierarchy for South Australia’s land transport network’ (DPTI, 2013). The assigned levels of hierarchy are commonly used to guide design practice and speeds, as well as accessibility, amenity and safety requirements, among other factors. Assessments of criticality identify which assets merit a certain level of resilience, enabling resilience assessments and targeted improvement or intervention strategies (Hughes and Healy, 2014). The majority of systems used worldwide are hierarchy frameworks and few include criteria which specifically relate to criticality and the capacity to provide a level of service during natural hazard events.

Recent studies suggest various criteria to consider when determining the criticality of transport corridors. Factors identified by the ‘Critical land transport infrastructure risk management review’ by the Ministry of Transport in New Zealand relate directly to the consequences of impact or failure. This includes transport assets that carry high volumes of traffic, provide linkages between different modes and those that are vital to social and economic wellbeing and maintaining law and order (URS, 2005). The ‘Approach to evaluate resilience’ by the Victoria Transport Policy Institute in Canada also considers, among others, assets which provide for emergency response and the operation of public services, commercial and business travel, as well as high-value personal errands such as shopping and medical requirements (VTPI, 2017). For a more detailed review of existing methods to determine hierarchy and criticality, we refer the reader to the reports by Hughes and Healy (2014) and Hughes (2016).

Recent studies by lifeline utility groups in New Zealand (e.g. the Waimakariri Lifelines Resilience Study; AECOM, 2009) have identified priority transport routes based on:

1) Their existing function within the road network;
2) The connectivity that they provide to other critical lifelines and emergency service facilities; and
3) The need to provide a core system of functioning routes connecting communities and key services during an emergency event.

These criteria are of particular interest to this study and form the basis of the criticality framework. Additional specific measures outlined in other studies (e.g. “maintaining law and order or national security”, “freight and package delivery” and “lower-value personal errands” – URS, 2005; VTPI, 2017) are not considered in our study. This decision was taken with the intention of streamlining the criticality assessment process, primarily so that the original framework remains applicable and adaptable at a national level within New Zealand. This includes rural areas, on which the country relies for agricultural production and other primary economic activities (Spector et al., 2018).

2.2 Criticality Framework

The criticality framework developed by Hughes (2016), and chosen for this research, incorporates three key criteria and assigns a scoring system to each. This consists of an approach which suggests equal weighting to all three criteria, thus allowing simple aggregated criticality scores to be determined. Information on each of the criteria and the scoring system is summarised below.

2.2.1 One Network Road Classification (ONRC)

The ONRC is a classification system used by New Zealand Road Controlling Authorities to classify roads based on their importance as part of an integrated national network and allowing investment to be directed where it is needed most (NZTA 2013; NZTA, 2015). The ONRC system assists operational and culture change in road activity management, particularly through addressing end-user needs, with customer outcome measures including road safety, road smoothness and travel times. (NZTA, 2013; NZTA, 2014). The system accounts for road factors including vehicle and passenger numbers, economic criteria, accessibility and connectivity, and categorises roads based on their function: national, arterial, regional, primary collector, secondary collector, and access (NZTA, 2018).

The criticality framework adopted in this paper uses the ONRC as a proxy for road factors and assigns a score of 1-4 to road links as follows:

1. Access or low volume
2. Primary or secondary collector
3. Regional or arterial
4. National or high volume.

2.2.2 Access to lifeline utilities or evacuation route

In New Zealand, the CDEM Act (2002) requires every lifeline utility2 to ensure that it is able to function to the fullest possible extent, and, when requested, make available to the Director of Ministry of Civil Defence and Emergency Management its plan for functioning during and after an emergency. While it is important that lifeline utilities themselves remain functional, it is equally important that roads leading to these utilities remain functional to allow access for inspections and repairs. The criticality framework used in this paper assigns a score which is based on the total number of lifeline utilities on a route. This element of the framework includes physical assets such as

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2 We use the definition in the New Zealand CDEM Act (2002) for lifeline utilities: “entities that provide essential infrastructure services to the community such as water, wastewater, transport, energy and telecommunications”.

substations, ports and airports, which require access to maintain essential services. It also includes any routes which are considered essential for evacuation:

1. No access to utilities
2. 1-2 local lifeline utilities
3. 3-4 local lifeline utilities, ≥1 regional lifeline utilities, or an essential evacuation route
4. >5 local lifeline utilities, >3 regional lifeline utilities, or ≥1 national lifeline utilities.

2.2.3 Access to essential services

Essential services refer to those that would be required for response and recovery during a natural hazard event. The criticality framework uses priority scores for essential services, which have been adapted from AECOM (2009). All essential services are categorised by typology and given a score based on their priority (Table 1); the higher the score, the higher the priority.

Table 1. Priority scores for access to essential services (adapted from AECOM 2009).

<table>
<thead>
<tr>
<th>Essential Service</th>
<th>Score (based on priority)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospitals and large aged-care facilities</td>
<td>3</td>
</tr>
<tr>
<td>Ambulance, fire, police and emergency operation centres</td>
<td>2</td>
</tr>
<tr>
<td>Major utility control centres (e.g. councils, electricity, telecoms)</td>
<td>0.5</td>
</tr>
<tr>
<td>Welfare facilities</td>
<td>0.25</td>
</tr>
<tr>
<td>Key retail outlets (e.g. hardware, supermarkets)</td>
<td>0.25</td>
</tr>
<tr>
<td>Schools, sector posts and major industry</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The total priority score for each road link is calculated by summing the scores in Table 1 when multiple essential services can be accessed. Based on the total priority score, the classification framework assigns a new score from 1-4:

1. <1 total priority score
2. 1-2 total priority score
3. 3-4 total priority score
4. >5 total priority score.

2.2.4 Overall criticality

By default, and until further consultation with road transport authorities indicates an alternative system, the scores for each of the three criteria are assigned an equal weighting (0.3333). They are then aggregated to provide an overall criticality level, with Criticality 1 being the most critical and Criticality 4 being the least (Table 2).

Table 2. Criticality level scores (adapted from Hughes, 2016).

<table>
<thead>
<tr>
<th>Criticality level</th>
<th>Overall (weighted) score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criticality 1 (vital)</td>
<td>&gt;3.17 to ≤4.00</td>
</tr>
<tr>
<td>Criticality 2 (major)</td>
<td>&gt;2.33 to ≤3.17</td>
</tr>
<tr>
<td>Criticality 3 (substantial)</td>
<td>&gt;1.50 to ≤2.33</td>
</tr>
<tr>
<td>Criticality 4 (minor)</td>
<td>≥1.00 to ≤1.50</td>
</tr>
</tbody>
</table>

2.3 Auckland Road Network
Auckland, New Zealand has an increasing regional population – currently ~1.6 million, which accounts for 34% of the national population (Statistics New Zealand, 2015). Various societal challenges stem from this increasing population and the geographical constraints of the city area; the Waitemata and Manukau Harbours (to the north-east and south-west respectively; Figure 1), restrict all ground transport infrastructure through two isthmuses and limit evacuation routes (Auckland CDEM, 2015). Furthermore, Auckland is susceptible to various natural and technological hazards including floods, volcanic hazards, tsunami and electricity failure (Auckland CDEM, 2016). Determining the criticality of transport network links, is thus of particular importance in Auckland to enable continued functionality on both a ‘typical’ daily basis and following hazardous events (CDEM Act, 2002). The only criticality classification system applied widely to Auckland’s road network to date that we have identified from a review of the literature, is that by the Auckland Lifelines Group (ALG), which uses the system to identify critical infrastructure in the Auckland region, distinguishing between national, regional and local critical infrastructure (section 1; AELG, 2014). This approach designates the majority of State Highways (SHs) through Auckland as Criticality 1, as they are the main routes through and across the region (ALG, 2017). A number of roads, which provide access to lifelines and essential services (e.g. Ports of Auckland Waitemata site, Auckland Airport and Auckland Hospital) are classified as Criticality 1 or 2 using this system (ALG, 2017). While this criticality classification approach has many advantages, it could be argued that it is somewhat broad, subjective and non-systematic, with decisions on designation ultimately made by individual transport infrastructure managers. Assessing what is critical to local areas requires the consideration of other criteria including community and economic factors (FHWA 2014).

For the purpose of this research, we chose a study area of Central Auckland, which is a densely populated location in New Zealand and contains a high number of essential services and lifeline utilities (Figure 1). This enabled us to thoroughly test the different components of the Hughes (2016) criticality framework on the 907 km of roads contained within.

3. Methodology

In this section we describe the details of how we applied the criticality framework, including choices for the selection of key criteria. ArcGIS was used for mapping purposes, as this software is also used by many of the organisations where geospatial data was sourced.

3.1 Application of ONRC scores

The Hughes (2016) scores for the ONRC system (see section 2.2.1) were allocated to all road links in our Central Auckland study location to act as a proxy for different road factors. ONRC rankings for each road in the study area were obtained from Auckland Transport.

3.2 Location of lifeline utility access points

Lifeline utility locations in the Central Auckland study area were determined from existing research conducted by the ALG (AELG, 2014) and as part of the Auckland Unitary Plan (Auckland Council, 2018). Google Maps and Auckland Council’s GeoMaps (Auckland Council, 2017) were both used to obtain the access routes to the identified lifeline utilities (i.e. a road, street, access way or walkway.

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3 Auckland Transport is a Council Controlled Organisation (of Auckland Council) responsible for Auckland’s transport services. This includes the roads in the region excluding the State Highway network.
which provides access to the utility and is considered essential to maintain service continuity as usual and in the case of an emergency).

3.3 Location of essential services access points

Various data sources were used to obtain the location of essential service facilities in Central Auckland. In addition to data from the ALG and Auckland Unitary Plan, the Ministry of Education’s database provided information on the location of schools, and the locations of all emergency service stations (Police, Fire and Ambulance) were obtained from their respective websites.

3.4 Scoring and weighting

After determining the ONRC system allocations, and access points for lifeline utilities and essential services in Central Auckland, each road link was scored based on the scoring criteria in section 2.2. The scores were then weighted equally and aggregated to provide overall criticality scores (Table 2).

3.5 Alterations to the criticality framework

As this was the first trial of the Hughes (2016) criticality framework, an important step in our study was to assess the validity of the overall criticality map. This process included stakeholder engagement and expert advice from those within the Asset Management team at Auckland Transport to check the rationale behind the application, ensure that the objectives were met and check that findings would be useful for management purposes. This was achieved by focusing on the roads around a selection of key known lifeline utilities and essential services and manually checking that the assigned criticality is logical based on their experience and knowledge of the area. Two alterations were made to improve the existing framework, which are discussed further in section 4 following the initial results.

4. Results and Discussion

4.1 Application of the original criticality framework

Figure 2 shows the ONRC rating modified by Hughes (2016) for each road link in our study site.

Access routes to 57 lifeline utilities and 172 essential services were considered for this project, all of which are shown in Figure 3.

Figure 4 shows the overall criticality of Central Auckland’s road network, directly determined using all three key criteria from the criticality framework. Every road link was designated a level of at least Criticality 4, which was due to every link having an ONRC ranking assigned, so each link will always obtain a score of at least 1 for the ONRC criterion. Additionally, due to the scoring system design for lifeline utilities and essential services, every road link will be assigned a score of at least 1 for each of these criteria, even without a lifeline utility or essential service on the link. Indeed, as Table 3 shows, out of the 6669 road links in Central Auckland, 4212 links are assigned a level of Criticality 4. However, analysis showed that out of the 6669 links, 5029 did not have any access to lifeline utilities or essential services.
Table 3. Original criticality framework outputs, excluding the motorways (managed by the New Zealand Transport Agency).

<table>
<thead>
<tr>
<th>Criticality</th>
<th>No. of road links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criticality 2</td>
<td>41</td>
</tr>
<tr>
<td>Criticality 3</td>
<td>2416</td>
</tr>
<tr>
<td>Criticality 4</td>
<td>4212</td>
</tr>
<tr>
<td>TOTAL</td>
<td>6669</td>
</tr>
</tbody>
</table>

As the criticality assessment is intended to guide which roads contain critical assets and ultimately inform resilience assessments, and since investments to improve road resilience are often capped, we decided that it would be more appropriate to have a criticality scale which included a zero criticality rating for roads which offer only minor societal and economic benefit (i.e. no essential services). An alteration to the criticality framework was suggested as a result.

4.2 Alterations to the criticality framework

4.2.1 New zero score for essential services
The updated scoring system for essential services, with additional zero score, is outlined below. Although a relatively minor adjustment from the original scoring system (with the same priority score system; Table 1), it provides a crucial distinction between links that have low priority essential services and no essential services:

0. No essential services
1. <1 total priority score
2. 1-2 total priority score
3. 3-4 total priority score
4. >5 total priority score.

4.2.2 New criticality level and amended scores
The second alteration to the original framework involved changing the weighted scoring ranges for each overall criticality level and the introduction of a new criticality level – Criticality 5. Like the above alteration, this one was partially undertaken to account for roads that offer little societal and economic benefit. Additionally, the ranges for the top three most critical levels, were narrowed so that fewer road links fall into these categories, highlighting their importance, with those that are least critical falling into the Criticality 4 and 5 levels. The amended criticality levels and weighted scores are shown in Table 4.

Table 4. Amended criticality level scores. Changes to the original criticality level scores are shown as bold text.

<table>
<thead>
<tr>
<th>Criticality level</th>
<th>Overall (weighted) score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criticality 1 (vital)</td>
<td>≥3.25 to ≤4.00</td>
</tr>
<tr>
<td>Criticality 2 (major)</td>
<td>≥2.50 to &lt;3.25</td>
</tr>
<tr>
<td>Criticality 3 (substantial)</td>
<td>≥1.75 to &lt;2.50</td>
</tr>
<tr>
<td>Criticality 4 (minor)</td>
<td>≥1.00 to &lt;1.75</td>
</tr>
<tr>
<td>Criticality 5 (minimal)</td>
<td>≥0.00 to &lt;1.00</td>
</tr>
</tbody>
</table>
4.3 Rationalisation and final outputs

During and following emergencies when disruption to lifeline utilities has occurred, it is imperative that service providers have access to critical assets so that repairs and maintenance can be conducted. However, as shown in Figure 5A, the direct outputs from applying the criticality framework show that some road links are not connected to links with an equal or higher criticality level. In this situation, if the roads which surround these higher criticality links were damaged so that they were inaccessible, then the critical asset would be compromised. Therefore a rationalisation step is introduced so that all road links are connected to others with a higher criticality (up to Criticality 1 / motorways). Figure 5B shows the same area of the network as Figure 5A where the rationalisation step has been completed, and Figure 6 shows the entire Central Auckland study area post-rationalisation.

Table 5 shows the amended criticality framework outputs by number of road links. Comparisons to outputs from the original framework application (Table 3) shows a decrease in the number of links with Criticality levels of 1-4. In particular, a substantial drop has occurred for Criticality 4 road links which decreased from 4212 to 1681 links. This is attributed to roads which provide minimal societal and economic benefit being assigned the new Criticality 5 level, suggesting that the amended and calibrated framework is successful in highlighting the most critical roads in Central Auckland.

Table 5. Amended criticality framework outputs. All motorways are again manually assigned a Criticality 1 rating as they act as primary evacuation routes.

<table>
<thead>
<tr>
<th>Criticality</th>
<th>No. of road links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criticality 2</td>
<td>32</td>
</tr>
<tr>
<td>Criticality 3</td>
<td>884</td>
</tr>
<tr>
<td>Criticality 4</td>
<td>1681</td>
</tr>
<tr>
<td>Criticality 5</td>
<td>4072</td>
</tr>
<tr>
<td>TOTAL</td>
<td>6669</td>
</tr>
</tbody>
</table>

4.4 Limitations

Incorporating both desk reviews and stakeholder engagement processes in criticality assessments can be time consuming and resource intensive (World Bank, 2015). Our criticality framework employs a hybrid of the two processes. It is largely desk-based in that it assesses road hierarchy and access to essential services and lifeline utilities by employing existing research and systems such as the ONRC and work by the ALG which identifies critical assets. Other than collaboration with Auckland Transport officials to check the validity of outputs, no direct stakeholder engagement was undertaken. However, the systems and research that were integrated into the framework did consist of stakeholder engagement processes (e.g. collaborations with infrastructure providers to identify critical infrastructure assets). The level of stakeholder engagement is thus deemed sufficient for an initial trial and modification of the criticality framework. Nevertheless, if the framework is applied to other regions or adapted for other infrastructure types besides road transport, we recommend a thorough stakeholder engagement process to check that key criteria adopted are suitable and that results are appropriate based on their experience and knowledge. We also suggest engaging with multiple stakeholders through organised workshops where possible to reduce subjectivity and improve the quality of criticality outputs (FHWA, 2014; World Bank, 2015).
As with all models, the quality of output data is dependent on the quality and availability of input data. We particularly note the importance of data that is used to identify lifeline utilities and essential services, and that which informs the ONRC (the three key criteria of the criticality framework). For example, fuel stations are often identified as critical lifeline sites. No specific importance is given to fuel stations in the existing framework, although many are located on major access routes that are classified as relatively critical through other criteria. Fuel priority during events is addressed by emergency management authorities (e.g. Auckland CDEM, 2013), which may impact response and recovery activities by transport authorities.

The existing framework does not currently consider alternative road routes in detail. For example, detailed analysis could consider the likelihood of alternative routes being affected by multiple hazards, the capacity of alternative routes to take additional vehicles, and the additional duration of travel along alternative routes (Hughes, 2016). While increasingly accurate results may be generated, the time required to conduct a modified assessment which incorporates a detailed assessment of alternative routes would increase. Therefore, a simpler assessment of alternative routes is preferable, and incorporating the ONRC is an appropriate technique to achieve this.

Asset criticality designations can ignore the low-level risks that face an extended road network and instead prioritise high value assets (World Bank, 2015). This is somewhat true for the Hughes (2016) criticality framework, which adopts existing research that focuses on high value assets such as access to key utilities and essential services. However, the lowest levels of criticality (Criticality 4 and 5) do imply a degree of criticality through their descriptions (termed minor and minimal respectively), so the low-level risks that may face an extended network are not ignored in this respect. This is also reflected in the scoring system of the amended framework, although opportunities remain for follow-up work to explore low-level and widespread aspects of criticality.

5. Conclusion

The criticality framework developed by Hughes (2016) was applied to a trial area of the road network in Central Auckland – an area chosen due to its relatively high population density and scope to vigorously test all three key criteria of the framework. Analysis of the findings from the initial application of the framework and engagement with a road transport service provider revealed that improvements may be beneficial to better account for some road links providing minimal societal and economic benefits with no access to essential services. Subsequent changes to the criticality framework included an additional (zero) score for the essential services criteria, new overall criticality level (Criticality 5), and alterations to the weighted score ranges for each overall criticality level. Application and rationalisation of the amended framework, again to Central Auckland roads, enabled the production of a viable criticality map for the network.

The application of the criticality framework in this trial was considered to be successful and it is thus deemed an important mechanism for guiding investment decisions for road maintenance and improvement activities, and for implementing performance based standards for recovery times. This ultimately allows optimum transportation functionality for end-users, whether on a daily basis or during disasters. The application of the framework has also demonstrated many opportunities for future research in this field. A rural application of the framework would be advisable, as rural networks can present different challenges to those in urban environments. This would help guarantee the framework’s applicability at a national level. We also suggest that the criticality framework could be adapted to assess the criticality of other infrastructure types besides road (e.g. electricity, water supply and wastewater networks). We particularly recommend that a thorough stakeholder engagement process is incorporated into future projects to ensure that findings remain
applicable for infrastructure providers and to appropriately guide resilience assessments and investment decisions within and across infrastructure sectors.

Acknowledgements

The authors wish to acknowledge the support provided by Resilience to Nature's Challenges, a National Science Challenge funded by the Ministry of Business Innovation and Employment (MBIE) in New Zealand. The authors also wish to thank Auckland Transport for their contributions and continued engagement in this research.

References


Figure Captions

**Figure 1.** The Auckland road network and selected area for criticality framework application and testing.

**Figure 2.** One Network Road Classification (ONRC) for links in Central Auckland.

**Figure 3.** Lifeline utilities and essential services considered in this study.

**Figure 4.** Overall criticality for Central Auckland using original framework. Note that the data provided by Auckland Transport did not contain motorways (as these are managed by the New Zealand Transport Agency). However, all motorways were manually assigned a Criticality 1 rating as they act as primary evacuation routes in the case of natural disasters in Auckland.

**Figure 5.** Example of the amended framework criticality outputs (A) pre-rationalisation, and (B) post-rationalisation. The rationalisation process ensures that the previously ‘isolated’ Criticality 2 (blue) road link is connected to links of equal or higher criticality.

**Figure 6.** Criticality map for the Central Auckland area using the amended framework and following rationalisation.