Measuring the resilience of transport infrastructure

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An important note for the reader

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Abbreviations and acronyms

CDEM	Ministry of Civil Defence & Emergency Management (New Zealand)
IPCC	Intergovernmental Panel on Climate Change
NIAC	National Infrastructure Advisory Council (US)
NIP	National Infrastructure Plan
NIU	National Infrastructure Unit
TMP	traffic management plan
TOSE	technical, organisational, societal, economic
Transport Agency	New Zealand Transport Agency
UNDRO	United Nations Disaster Risk Organisation
UNISDR	United Nations International Strategy for Disaster Reduction
USDHS	United States Department of Homeland Security
VTPI	Victoria Transport Policy Institute

Contents

Executive summary

The New Zealand Transport Agency ('the Transport Agency') has a key interest in ensuring that transport infrastructure assets and services function continually and safely. This interest has led to a specific focus on the concept of *resilience* and how this can be defined, measured and improved across the transport system.

As a result, from late 2012 to mid-2013, the Transport Agency engaged AECOM to develop a framework to measure the resilience of the New Zealand transport system.

The project involved initial research and scoping to determine the project boundaries and definitions, and following this, the development of a practical framework and assessment tool.

The framework is applicable to the broad land transport system (road and rail) and allows consideration of various scales (asset/network/region).

Critical infrastructure and hazards

Infrastructure is recognised as a critical element to healthy economies and stable communities. It enables commerce, movement of people, goods and information, and facilitates society's daily activities.

In a transport context, societies rely on transportation networks for their daily economic and social wellbeing. The ability of the transport system to function during adverse conditions and quickly recover to acceptable levels of service after an event is fundamental to the wellbeing of communities.

Furthermore, the risks to critical infrastructure from hazards are, according to research, increasing globally. These hazards can include natural, technological, social and political hazards, each of which can occur with a varying degree of predictability.

The hazard scenarios are further amplified due to complex interdependencies between modern infrastructure networks, and the existence of many different failure modes – all of which can affect the functioning of infrastructure.

What is resilience?

Resilience is considered the ultimate objective in the context of hazard mitigation. There is a variety of definitions which have evolved as different disciplines have applied resilience thinking to their work and adapted the definitions to meet their focus.

A definition which is both applicable to the New Zealand transport context and is consistent with international literature is that provided within the Treasury's *National infrastructure plan* (NIP):

> *The concept of resilience is wider than natural disasters and covers the capacity of public, private and civic sectors to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions, including climate change, and grow over time.*

This definition acknowledges that the service the infrastructure delivers will be disrupted, due to damage to the infrastructure; however, the service is able to reduce the possibility of failure, adapt and recover from a disruptive event and/or gradual external changes over time. It also implies transformation, so not only is the infrastructure service able to survive or recover but it can adapt to a changing environment in which it operates. Finally, the definition is broad enough to encompass more recent approaches that allow for 'unknown' as well as 'known' hazards.

To further understand resilience, researchers have identified a number of dimensions, principles and measures of resilience. By defining and categorising these dimensions and principles, the broad framework elements can be built, from which meaningful and practical measures can then be developed.

The literature review identified two dimensions of resilience – technical and organisational – as being representative of the range of broad considerations for assessing resilience.

Similarly, in terms of resilience principles, the following were chosen, grouped under the two dimensions above. These principles form the basis for the framework development:

- technical principles: robustness, redundancy, safe-to-fail
- organisational principles: change readiness, leadership and culture, networks.

A framework for measuring transport system resilience

A broadly qualitative framework for measuring resilience was created, based on the dimensions and principles described above. Specific, detailed measurement categories were developed under each of the principles.

The framework involves an initial determination of the context of the resilience assessment, followed by a detailed assessment of resilience measures, which combine to generate a resilience score ranging from 4 (very high resilience) to 1 (low resilience). These measures can then be aggregated and weighted as required.

4 Very high resilience – meets all requirements

3 High resilience – acceptable performance in relation to a measure(s), some improvements could be made

2 Moderate resilience – less than desirable performance and specific improvements should be prioritised

1 Low resilience – poor performance and improvements required.

A number of cross-cutting themes were developed to influence the context and approach of the resilience assessment. These are summarised and discussed in the table below.

Table 1 Cross-cutting themes

Cross-cutting theme	Discussion
All hazards/specific hazard approach	The assessment can be undertaken in one of two ways: 1 An all-hazards assessment – based on an event due to any (unspecified) hazard/failure, which could be either known or unknown. 2 A hazard-specific assessment could be undertaken. This would involve identifying the relevant known hazard types and assessing the resilience to each.
Scale of assessment	The framework will allow assessment at various scales: regional, network or asset. Measures have been developed for each and the user can filter the questions accordingly. Regional assessments could be aggregated to a national indicator if desired.
Shock event or stress event	The framework will be able to evaluate both short-term shock events (eg earthquakes and tsunamis) and longer-term stress events (eg climate change related).

In summary, the approach to undertaking the resilience assessment is as follows:

1 Determine the context of the assessment:

   a all-hazards or specific hazards (including shock or stress event, rare events etc)

   b scale: asset/network/regional

   c shock or stress event

2 Undertake the assessment, using the relevant questions and assigning scores

3 Apply weightings to categories as required

4 Generate resilience scores for categories, principles and dimensions and a total score.

As a stand-alone assessment, the resilience measurement framework could be applied to generate a relative score for comparing resilience across assets/networks or regions. However, to provide additional rigour, other steps could be applied during implementation.

Implementation of the framework

To implement the measurement framework in a systematic manner, additional steps could be incorporated to determine priorities for intervention. These steps include determining:

1 Which infrastructure should be assessed for resilience?

2 What level of resilience is appropriate for a given asset/network?

In order to answer these questions, an understanding is required of both the criticality of a given asset, and the risk of a particular hazard occurring. Note, this corresponds directly to whether a general 'all-hazards' or 'hazard-specific' assessment has been chosen.

The all-hazards approach would involve an assessment of criticality to determine which assets should be focused on for the resilience assessment. The criticality assessment would identify which assets merit a certain 'desired' level of resilience, and then following a resilience assessment for these assets, related improvements or interventions could be targeted.

If further detail was required, a more detailed hazard-specific assessment could be undertaken. This would provide information on the relevant hazards and the likelihood of their occurring. In this case, the output of the risk assessment would determine the 'desired' level of resilience.

The Transport Agency currently has a risk assessment tool based on AS/NZS 31000, as well as a state highway classification system that could be utilised to determine criticality of assets. The rail system and local authorities may have similar methods for determining criticality.

In terms of application across different scales, the following approaches could be implemented. Any approach could be used at any scale; however, the following are considered the most appropriate.

- **Asset scale:** Either an 'all-hazards' approach using criticality as a first step, or a hazard-specific approach using risk assessment. Resilience assessment would be compared against 'desired' level of resilience for the asset to determine the need for intervention.
- **Network/route scale:** Either an 'all-hazards' approach for all critical assets within the network using criticality as a first step, or a hazard-specific approach using risk assessment. Resilience assessment would be compared against 'desired' level of resilience for the network to determine the need for intervention.
- **Regional scale:** Stand-alone resilience assessment either via an 'all-hazards' approach or a hazard-specific approach. This would enable regions to be compared, and actions and interventions to be prioritised across regions.

Conclusions and recommendations

The framework developed through this study is applicable to the broad land transport system (road and rail) and allows an assessment at various scales (asset/network/region). It also gives effect to the guiding principle of resilience within the NIP.

Due to project constraints, detailed real-scenario testing of the framework was not undertaken. Specific operator knowledge of assets and the relevant organisations would be required to undertake a meaningful assessment. As such, this and other recommendations for future work are made below.

- Undertake a real-scenario testing of the framework with key operational staff.
- Undertake further work to improve understanding of critical infrastructure and factors which may determine criticality – from both an economic and societal point of view.
- Undertake further economic and engineering research to better understand and quantify a suitable level of investment in technical (structural) resilience. This is generally where significant capital expenditure is required and is difficult to justify when funding is limited
- Improve understanding of linkages between resilience and sustainability. To date, conversations around infrastructure resilience have occurred largely in isolation of those which occur around sustainability.

Abstract

Internationally there is a growing call to improve the resilience of our critical infrastructure. This is in response to a realisation that the services we take for granted may be robust in the face of predictable hazards/failures, but are in fact extremely fragile in the face of unanticipated shocks.

In the context of transport infrastructure, operators strive to ensure that transport assets and services function continually and safely in the face of a range of existing and emerging hazards. This has led to a specific focus on the concept of resilience and how this can be defined, measured and improved across the transport system.

The theory of resilience was researched and a measurement framework has been proposed that broadly covers both technical and organisational dimensions of resilience and breaks these down into specific principles and measures which can be utilised to qualitatively assess resilience.

The measurement of resilience was approached from a view that a risk management approach alone is not sufficient and needs to be complemented by an awareness that resilience requires both consideration of events that fall outside of the realms of predictability and, importantly, that failure is inevitable.

1 Introduction

1.1 Background

The New Zealand Transport Agency (the 'Transport Agency') is primarily responsible for managing New Zealand's state highway network. It is actively involved in strategy and planning at a national and regional level, with a strong focus on integration with both rail and port services.

Additionally, the Transport Agency has a key interest in ensuring that transport infrastructure assets and services function continually and safely. This interest has led to a specific focus on the concept of resilience and how it can be defined, measured and improved across the transport system. This was highlighted by the *National infrastructure plan 2011* (National Infrastructure Unit 2011), which identifies 'resilience' as one of six guiding principles to 'provide a platform for infrastructure development' and 'signal how the country should move forward and make better decisions in the future'.

1.2 Purpose

The purpose of this research was to develop a framework and assessment tool to measure the resilience of transport infrastructure, which is practical and feasible to implement, and which:

- will be applicable to the wider land transport system (road and rail), and will allow consideration of various scales (asset/network/region)
- can link to broader criticality and risk management approaches allowing prioritisation of improvements and interventions.

1.3 Methodology

A three-staged approach was followed, as illustrated in figure 1.1:

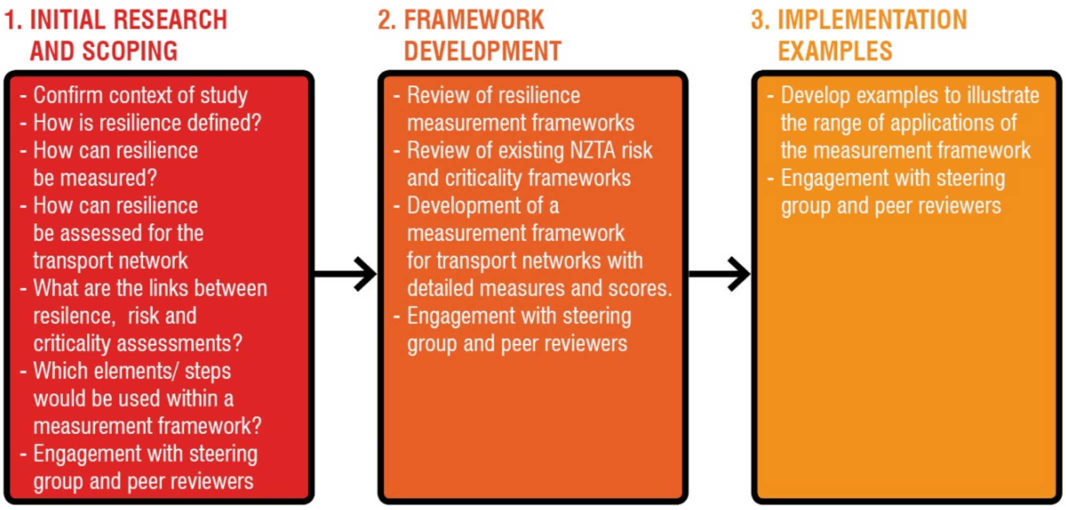
1 Initial research and scoping – including literature review and definition of the term 'resilience'

2 Development of a framework and assessment tool, which is practical and feasible to implement

3 Implementation example.

The project team consisted of New Zealand based and international AECOM staff. The review was undertaken both by key Transport Agency staff and steering group members consisting of staff from the Treasury and Ministry of Transport. Finally, two peer reviewers were engaged to provide input following each stage of the project.

Figure 1.1 Outline of project methodology



1.4 Report structure and target audience

This research report has been developed in-line with the three-stage methodology and designed to guide agency management and operators in their engagement with transport resilience in New Zealand.

Chapters 1 to 5 relate to work undertaken during stage one, and detail the objectives and background of the study, define key terms, context and key considerations for measuring resilience. More specifically:

- Chapters 1 and 2 provide introduction and context.
- Chapter 3 discusses the importance of resilience and different stakeholder perspectives.
- Chapter 4 defines resilience, and related dimensions and principles
- Chapter 5 discusses how resilience can be measured and also what hazards are of relevance
- Chapters 6 and 7 bring together the preceding work and cover the development of the proposed measurement framework and recommend specific measurements for resilience, as well as providing suggestions around implementation and linking to existing criticality and risk frameworks
- Chapter 8 gives some examples of implementation.
- Chapter 9 contains the conclusion and recommendations for future work.

2 Context of this study

This section covers the context in which the resilience framework and resilience measures must operate. The New Zealand government has released a number of publications which establish guidance principles, context and direction for the provision and management of infrastructure in New Zealand.

The first of these is *Working towards higher living standards for New Zealanders* (Treasury 2011b). This publication focuses on how improved economic performance can lead to enhanced living standards and outlines a series of dimensions which contribute to achieving this. These dimensions include ‘reducing risk’, and ‘improving New Zealand’s ability to withstand unexpected shocks’. In the context of physical or social infrastructure, this could be viewed as building resilience.

Additionally, Treasury has published *Better business cases* (Treasury 2012) and the *Better capital planning and decision making* (Treasury 2011a).

The purpose of these two complementary publications is to deliver better value for money through public investment and ultimately better outcomes and service delivery to the public. The key messages focus on robust planning, analysis, decision-making and implementation in order to ensure project success.

Treasury (2011a) covers the fundamental principles of good asset management and planning, which, in turn, incorporate an assessment of critical assets and business risk when developing business cases.

Finally, Treasury has released the *National infrastructure plan* (NIP) (NIU 2011). This document establishes resilience as a key area of focus and is discussed further below.

2.1 National Infrastructure Plan 2011

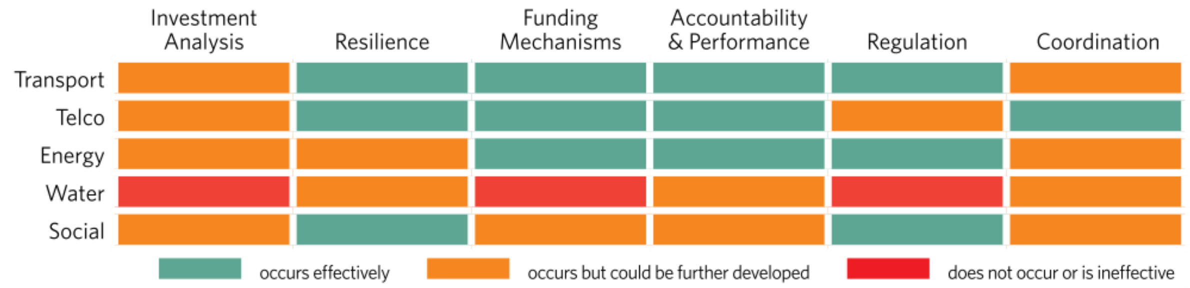
The NIP covers the transport, telecommunications, energy, water and social infrastructure sectors, and sets out a vision that ‘by 2030, New Zealand’s infrastructure is resilient and coordinated and contributes to economic growth and increased quality of life’.

The NIP establishes six guiding principles as a platform for infrastructure development: investment analysis, resilience, funding mechanisms, accountability and performance, regulation and coordination. For each of these principles a high-level assessment was undertaken for each sector (figure 2.1), with resilience within the transport sector assessed as ‘occurs effectively’. It is understood that this high-level assessment was not the result of a robust or evidence-based assessment (R Fairclough, pers comm).

In order to provide clarity and robustness to this high-level assessment, the NIP acknowledges that significant work is required to develop indicators for the assessment areas shown in figure 2.1, both within and across sectors. Agencies and industry bodies are therefore being encouraged to develop indicators which are relevant, transparent, replicable and can be standardised.

In this context, the Transport Agency commissioned this research project to develop a framework to measure resilience for the land transport system.

Figure 2.1 NIP high-level assessment of current infrastructure situation



Source: Treasury (2011)

Subsequent to the publication of the NIP, the NIU has further developed its thinking around resilience and how this applies to infrastructure. A series of eight resilience attributes have been developed which aim to achieve a common understanding of resilience as it applies to national infrastructure. These are: service delivery, adaptation, community preparedness, responsibility (voluntary and regulatory), interdependencies (consideration of linkages), financial strength, continuous (vigilance and assurance) and organisational performance (leadership and culture).

These attributes provide context to the measurement framework presented in this report and are discussed further in section 4.3. Effort has been made in developing the framework to be clear on a) how the framework elements 'map' to the NIU attributes, and b) how a specific assessment(s) could provide a national-level picture of resilience performance.

2.2 Responsibilities and perspectives on resilience

In New Zealand, those utilities responsible for delivering and maintaining critical infrastructure have been denoted 'lifeline utilities'. These have been defined as part of the Civil Defence and Emergency Management Act 2002. This act sets out which sectors are considered critical lifeline infrastructure (utilities) and includes: transport, water, wastewater, stormwater, energy and telecommunications services. All lifeline organisations have a direct interest in understanding and developing resilience to hazards across all the utility organisations both because of their operational interdependence, and in their desire to function to their fullest possible level of service. The framework set out in this report will allow consideration of these interdependencies and the framework principles will be broadly applicable across the range of sectors/utilities.

In addition to the lifeline utilities, there are a range of other stakeholders – each of whom may have a slightly different perspective on 'resilience'. These perspectives influence priorities and where investment is targeted to improve resilience. Table 2.1 below summarises these perspectives.

Table 2.1 Stakeholders and perspectives on resilience

Stakeholder	Perspective
User: The direct or indirect customer/user of the infrastructure, which may be for business or personal purposes. For example: • direct – freight companies, or commuters using the road network • indirect – those who receive goods and key supplies, such as supermarkets.	Users expect the level of service they are accustomed to, to be restored following an event. They may accept a lower level of service for a period of time that is proportional to the severity of an event; however, they may be less accepting of a lower level of service for extended periods. The owner and operator of the infrastructure need to understand the length of time the user will tolerate decreased levels of service.

Stakeholder	Perspective
Operator and maintainer: Government agency, local government, utility company or private contracted organisation.	Operators need to deliver resilience which does not adversely raise the cost of maintenance and operational expenditure. They have a key interest in interdependencies and potential cascade failure.
Government/owner: Both central and local government, related agencies and utilities.	Government and related agencies deliver resilience for the community, and therefore need to consider broader social as well as economic objectives, with a key interest in interdependencies. Infrastructure reliability has political significance through the way infrastructure disruptions are perceived by constituents. Robust business cases are required for investment in resilience.
Funding organisation: Private financier of capital and/or operations and maintenance.	Funding organisations need to deliver resilience to protect the investment in existing assets, with a focus on value for money and a robust business case.
Insurer:	The insurer has a vested interest in reducing the risk profile as a result of resilience improvements.

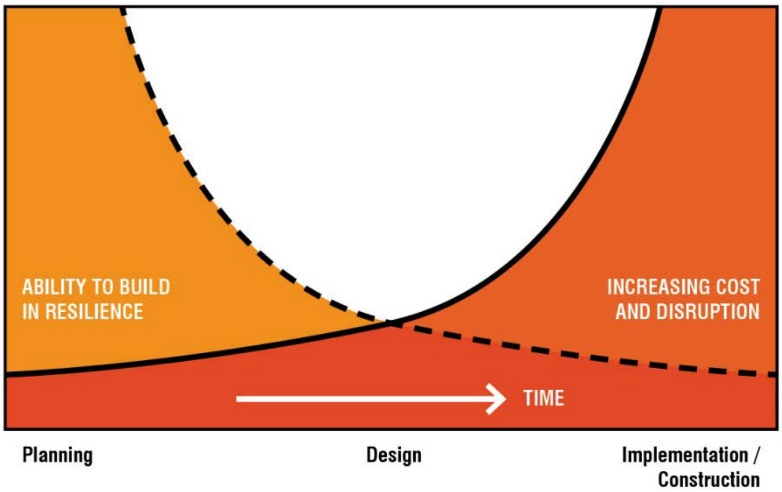
From a national transport perspective, the Transport Agency is considered to be the owner's representative, operator and funder, ultimately interested in the best resilience outcome for New Zealand as a whole. This report and the development of a measurement framework for resilience can be used by the transport sector and will be applicable across a range of scales from regional and national down to the asset level. Nonetheless, it is important that the perspectives of all stakeholders (especially users) are considered when determining criticality of elements of the transport network and the corresponding required levels of resilience (refer chapter 7).

2.3 Challenges in planning for resilience

Resource constraints and the requirement for robust business cases (refer above) put pressure on organisations to justify all expenditure, and when this expense involves mitigating the risk of future and uncertain hazard events, consensus among decision makers and stakeholders can be difficult to achieve. As such, a method to assess resilience of infrastructure and prioritise improvements is considered important and timely.

Ladbrook (2012) emphasises that building structural resilience requires deliberate choices early in the development of a project. Opportunities for resilience can be lost if not planned and designed for prior to implementation, as illustrated in figure 2.2. Decision making to build resilience requires a broad approach that considers long-term infrastructure resilience and economic optimisation, rather than the sole, narrow perspective of short-term 'return on investment' views.

Figure 2.2 Opportunity to build resilience in planning and design



Despite this agreed need to build resilience, there are, however, few (if any) practical methods for the application of resilience in engineering design. Park et al (2013) highlight a number of challenges that will need to be overcome in order to design for resilience:

- Engineering challenges need to be seen as conditions to be managed, rather than problems to be solved.
- Current approaches focus on known, identified hazards and ignore the significance of unidentified hazards either via assumption or because of cost constraints. This issue is fundamental when exploring resilience and risk, and one which is discussed further in subsequent sections.
- Current design practices are based on existing codes and are sanctioned by agencies. These codes ignore the possibility of unidentified or emergent hazards, and lead to incremental evolution of design, rather than encouraging innovative design.

While it will not establish parameters for engineering design, the framework set out in this report will address some of these challenges and provide a method for assessing and measuring the resilience of transport infrastructure, and identifying priority areas for improvement.

2.4 Summary

2.4.1 Main points

The NIP along with Treasury (2012) and Treasury (2011a; 2011b) all establish a context for understanding, assessing and building resilience in infrastructure. In particular, the NIP provides key attributes for resilient infrastructure.

There is a wide range of perspectives from which resilience can be assessed – ranging from user, through to owner, operator, funder and insurer. Each has different perspectives and views on priorities.

There are challenges in planning and designing for resilience and justifying expenditure for mitigating future, uncertain hazards. A long-term view is required and methods are needed that allow measurement of resilience.

2.4.2 Relevance to framework development

The framework needs to:

- give effect to the high-level objectives of the above plans and documents
- relate to the NIP attributes developed
- be applicable across a range of scales (regional – asset), while assuming a national perspective (ie the best outcome for New Zealand)
- address the challenge of unidentified hazards.

3 The importance of resilient infrastructure

In this section we cover reasons why resilient infrastructure is important to society. We discuss this in the context of increasing reliance on critical 'lifelines' infrastructure, increasing frequency of hazards and evolving, complex interdependencies within infrastructure systems. We also explore how different stakeholders can view resilience from different perspectives.

3.1 Why is resilience important?

Worldwide, infrastructure is recognised as a critical element for healthy economies and stable communities. It enables commerce, movement of people, goods and information, and facilitates society's daily activities. Infrastructure can be considered to include everything from the physical infrastructure of roads, bridges, airports, rail, water supply, telecommunications and energy services, to the social infrastructure of health care, education, banking and finance services, emergency services and the justice system.

Croope (2010) states 'Critical infrastructure not only responds to the needs of society for the smooth daily continuation of activities, but also provides the basis on which society exists and relies'.

Godshalk (2002) lists two reasons behind the importance of resilience.

1 Because the vulnerability of technological, natural and social systems cannot be predicted, the ability to accommodate change without catastrophic failure in times of disaster is critical.

2 People and property fare better in resilient cities when struck by disasters. Fewer buildings collapse, fewer power outages occur, fewer businesses are put at risk, and fewer deaths and injuries occur.

Societies have an increasing reliance on transportation networks for their daily activities. The ability of the transport system to function during adverse conditions and quickly recover to acceptable levels of service after an event is fundamental to the wellbeing of people within society.

The current increased focus on resilience is driven by a raised awareness of hazards due to recent natural disasters, such as the Christchurch earthquakes, and other natural and technological hazard events globally (eg the Fukushima nuclear disaster, Hurricane Katrina and the Deep Water Horizon oil spill). Climate change is also affecting the severity and frequency of events, and creating new hazards in its own right.

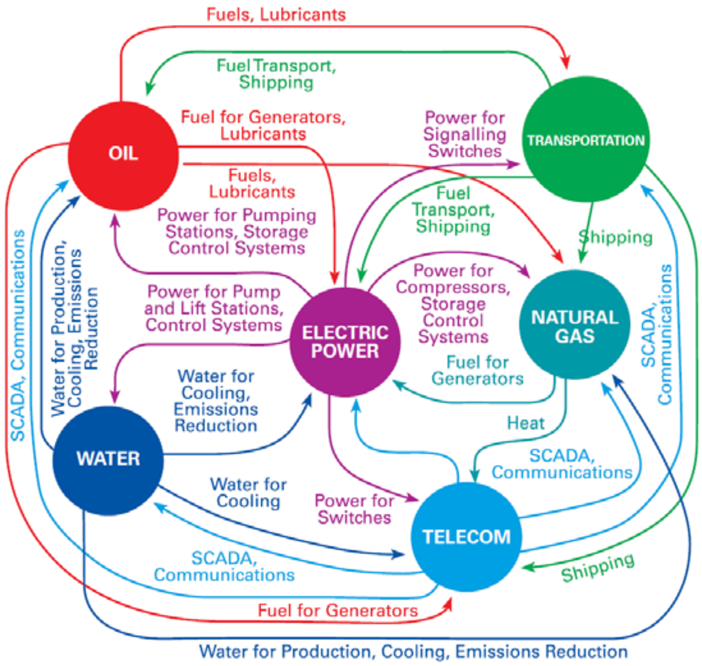
Additionally, awareness of unpredictable, 'rare' events is increasing, and there is a recognition that societies need to build resilience to these, in ways that may not have been used in the past.

Finally, complex interdependency in modern infrastructure networks means we need to look further afield than the principal sector (eg roading network) to other interdependent sectors (eg electricity, telecommunications) to identify potential failure modes and hazards. This is discussed further below.

3.2 Complex interdependencies

Modern infrastructure networks are increasingly complex and interconnected. These interdependencies and their many dynamic and multi-dimensional parts necessitate a 'system of systems approach' (Croope 2010 and USDHS 2009a) in order to fully understand and assess where vulnerabilities lie and where resilience can be improved. This is illustrated in figure 3.1.

Figure 3.1 Connections and interdependencies across the economy



Source: T O'Rourke

These complex, interconnected systems create benefits and efficiencies at times of normal operation, yet bring with them vulnerabilities and operational challenges, especially during unexpected circumstances or when faced with hazards. Extensive analysis of complex engineering systems has revealed that in many cases 'failure' is at best a statistical inevitability, or at worst a part of 'normal' operation (Perrow 1984).

Interdependencies can lead to a wide range of potential failure modes and the emergence of previously unidentified hazards which can cause failure. Hollnagel (2011) categorises the range of failure modes as simple-linear (or cascade) failure, complex-linear failure (caused through hidden interdependencies or latent conditions), or complex-nonlinear failure resulting from concurrence of unexpected events. These are discussed further in section 4.2.

Interdependence can be considered in a number of ways, including physical proximity, operational interaction and interdependency of stakeholders (owner, funder, operator, insurer). Operational interdependence can be assessed in terms of both upstream and downstream dependencies. As an example, *upstream* for the Transport Agency are those systems/utilities whose failure would impact on the functioning of its transport network (eg failure of electricity for signals), and *downstream* being the systems/utilities which would be affected by failure of the Transport Agency transport network (eg a road providing access to a power station fails, causing shut down). In the context of measuring resilience for the transport system, the upstream dependencies are those that should be considered in terms of hazard identification (with the downstream being important in assessing criticality).

It is considered vital that a detailed consideration and understanding of interdependencies and potential failure modes is included in any assessment of resilience.

3.3 Summary

3.3.1 Main points

Resilient infrastructure and specifically resilient *transport* infrastructure is vital to our modern society and economy. The increased frequency, intensity and awareness of global hazard events mean that building resilience is a justified and important goal.

Awareness of unpredictable, 'rare' events is increasing and there is a recognition that societies need to build resilience to these.

Complex interdependencies in modern infrastructure systems necessitate a wide-ranging approach to assessing hazards and potential failure modes.

3.3.2 Relevance to framework developments

The framework needs to consider the complete range of hazards, including rare events, and complex failure modes as a result of inter-related, upstream dependencies.

4 What is resilience?

This section provides a working definition for 'resilience' as well as recommending a series of appropriate dimensions and principles which will feed into the measurement framework.

4.1 Defining resilience

Resilience is considered the ultimate objective of hazard mitigation, that is, 'action taken to reduce or eliminate long-term risk to people and property from hazards and their effects' (Godschalk 2002).

The term resilience has evolved as different disciplines have applied resilient approaches to their work and adapted the definitions to meet their focus.

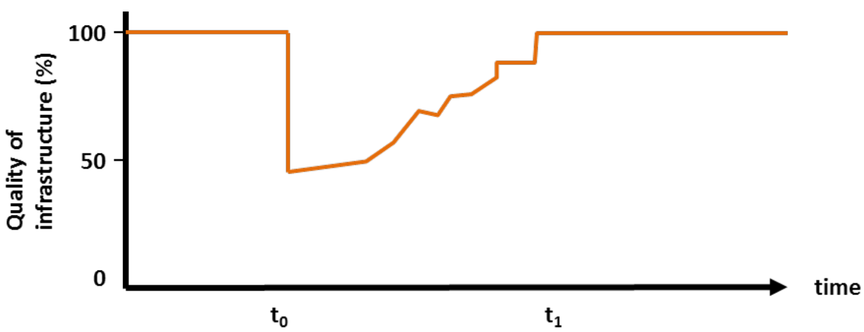
Levina and Tirpak (2006) propose two key differentiators in resilience definitions, the first being the ability of a system to withstand a disturbance without changing (whether by improvement or deterioration), implying that no damage is done, and the second differentiator is the ability of the system to recover when damage has occurred.

Maguire and Cartwright (2008) identify three views of resilience: resilience as *stability*, resilience as *recovery* and resilience as *transformation*.

Manyena et al (2011) highlight that disasters are accompanied by change, and that instead of resilience involving 'bouncing back' after an event, it should involve 'bouncing forward' and 'moving on'. They argue that 'bouncing back' does not signal change, and may involve returning to the conditions that may have caused the disaster in the first place. They conclude that resilience can be viewed as the 'intrinsic capacity of a system, community or society predisposed to a shock or stress to bounce forward and adapt in order to survive by changing its non-essential attributes and rebuilding itself'.

Bruneau et al (2003) illustrate the notion of resilience as it relates to the measure of seismic resilience. Figure 4.1 demonstrates conceptually the measure of resilience over time from a single event (at t_0) and the restoration of '100%' level of service (at t_1). The diagram is a simplistic depiction as it does not show the impacts from gradual changes over time (stress events), nor does it demonstrate adaptation (ie return to an improved or altered state).

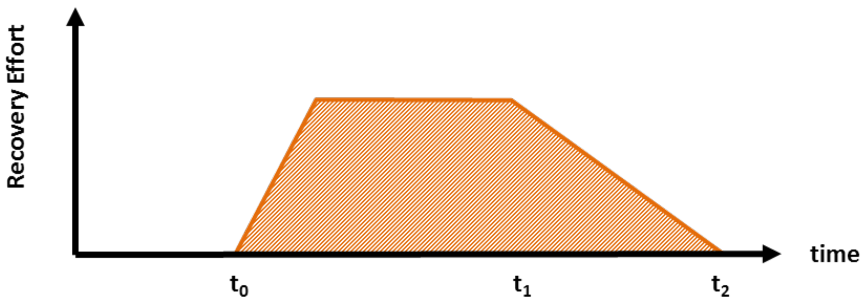
Figure 4.1 Conceptual measure 1 of resilience



Source: Bruneau et al (2003)

Other authors also quantify resilience as a function of the effort and resources required to recover from the disaster as depicted in figure 4.2. This shows a rapid increase of effort after an event at t_0 followed by a constant effort until the infrastructure is restored (t_1) and then a gradual decrease.

Figure 4.2 Conceptual measure 2 of resilience (recovery effort)



Recent work by Park et al (2013) describes resilience as an emergent property of what an engineering system *does*, rather than a static property the system *has.* This viewpoint leads to different approaches to dimensioning and building resilience, and focuses on continuous management, adaptation and new approaches to design. This view is shared by Snowdon (2011) who contends 'a resilient system accepts that failure is inevitable and focuses instead on early discovery and fast recovery from failure'. A fundamental factor in their respective approaches to resilience is the consideration of *risk* in the context of 'unknown' hazard events, and the differentiation between a 'resilience' approach and a 'risk' approach. This is discussed further in section 4.2.

With the above conceptualisations and views in mind, we have summarised a range of definitions:

- 'Resilience is the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must' (Allenby and Fink 2005).
- 'Resilience is the ability of systems, infrastructures, government, business and citizenry to resist, absorb, and recover from or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance' (USDHS 2009a).
- 'Resilience is the ability to survive a crisis and to thrive in a world of uncertainty' (Seville 2009).
- '[Resilience is the ability of] a locale to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life and without a large amount of assistance from the outside community' (Mileti 1999).
- 'The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change' (Solomon et al 2007).

Finally, it is necessary to highlight the NIP definition, which is as follows:

> *The concept of resilience is wider than natural disasters and covers the capacity of public, private and civic sectors to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions, including climate change, and grow over time* (NIU 2011).

This definition acknowledges that the service the infrastructure delivers will be disrupted, due to the infrastructure undergoing damage; however, the service is able to reduce the possibility of failure, adapt and recover from a disruptive event and/or gradual external changes over time. It is considered the definition is broad enough to encompass an approach consistent with the more recent views of Park (2013) and Snowdon (2011) who recommend an approach that allows for 'unknown' as well as 'known' hazards, as discussed above. It also could cover the 'bounce forward' idea proposed by Manyena et al (2011).

As such, and for the purposes of this study, the NIP definition is considered appropriate.

4.1.1 Resilience, vulnerability and sustainability

There is a vast array of literature available on defining resilience and the relationship of resilience to other commonly used (and often misunderstood) terms such as *vulnerability* and *sustainability*.

There are a variety of views on how they interact.

Vulnerability is a key concept for both disaster risk and climate change adaptation. It can be described as a deficit concept (Malone 2009) and as such, resilience and vulnerability could be considered as two ends of a spectrum (Levina and Tirpak 2006) with resilience being a positive measure. Folke et al (2002) termed vulnerability the 'flip-side' of resilience.

On the other hand, vulnerability can be viewed as a component of resilience (Maguire and Cartwright 2008), or indeed as suggested by Brabhaharan (2006), resilience is a function of vulnerability (and other factors). Therefore, the infrastructure can be assessed as vulnerable but *still* have a level of resilience due to other influencing organisational, financial and social dimensions.

The following definition of vulnerability, adapted from UNDRO (1980) and UNISDR (2004), was adopted for this study.

> *Vulnerability refers to the propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events.*

As for sustainability and resilience, Grubinger (2012) argues that the concepts overlap over a time scale, with resilience being achieved in the short term via *adaptation*, and leading into sustainability over the medium term through *mitigation* and ultimately reaching sustainability through *transformation*. This could be illustrated through considering the example of sea-level rise due to climate change. Resilience to sea-level rise-related hazards could be achieved in theory through a variety of structural, planning and response activities/adaptations (such as relocation of houses and building of defences). Mitigation could be achieved by lowering carbon dioxide emissions through reducing or substituting fossil fuel use. Finally, sustainability would be the outcome of a long-term transition to a low (zero) carbon society.

Zolli (2012) proposes a relationship along similar lines and suggests that where sustainability aims to put the world back into balance, resilience looks for ways to manage an imbalanced world. He goes on to suggest that resilience is a more pragmatic and politically inclusive response to pressures – 'rolling with the waves instead of trying to stop the ocean'.

Sustainability has not been considered in this study, due to the specific focus on transport systems and a desire to simplify the approach where possible. Recommendations are made, however, for future work in this area in order to generate more clarity on the subject and identify opportunities to deliver benefits in both a sustainability and resilience context (refer chapter 9).

For further discussion on the above relationships, refer to appendix C.

4.2 Hazards, risk and resilience

In order to further understand resilience, it is useful to consider its significance to both hazards and risk.

Recent natural and technological catastrophes have highlighted a) a failure to predict extreme events, and b) an inability to understand the complex systems involved and the potential range of failure possibilities. Park et al (2013) emphasise our ignorance: 'not the assumption that future events are expected, but that they will always be unexpected'.

In general, hazards can be categorised into three general types: natural, technological and social/political in nature. These can be further broken down into 'stress' events, that are long-term and gradual change processes, and 'shock' events, that are short-term and sudden change processes. Appendix E contains examples of the various types of hazards in these categories.

Hazards can also be classified as 'known' (or predictable) and 'unknown'. Unknown' hazards are also called 'rare events', or in some instances, 'black swans'. Taleb (2008) developed three characteristics to describe black swan events:

1 They lie outside the realm of regular expectations, because nothing in the past can convincingly point to their possibility.

2 They carry an extreme impact.

3 In spite of their outlier status, human nature causes people to concoct explanations for the occurrence after the fact, making it explainable and predictable.

Furthermore, due to the range of complex interdependencies involved, there is a wide variety of possible failure modes. In general, we have a poor understanding of how failures can propagate and amplify within and across complex systems. Risks can emerge through non-linear interactions among system components and generally only become observable after they occur. Hollnagel (2011) classifies failure modes into three general types as summarised below (and discussed further in appendix E):

- simple, linear failure: failure of one asset triggering the failure of an interconnected and successive asset (cascade)
- complex, linear failure: failure results from a combination of failures and latent conditions – often hidden dependencies
- complex, non-linear failure: failure results from expected or unexpected combinations (concurrence) of events.

Historically, a risk analysis approach has been used to identify risks and then develop management/mitigation approaches. However, as many hazards and failure modes are unknown, risk analysis becomes inadequate, and arguably impossible (Park et al 2013). In short, risk analysis requires the hazards to be identifiable, and therefore, to prepare for the *unexpected*. An alternative (and complementary) approach is required to consider these unpredictable events.

Some key differences in a traditional 'risk-based' approach versus a 'resilience' approach are as follows:

1 A risk-based approach looks to mitigate failure through probability and scenario-based analysis of known hazards. A resilience approach looks to minimise the consequences of failure through investigating scenarios with unidentified causes.

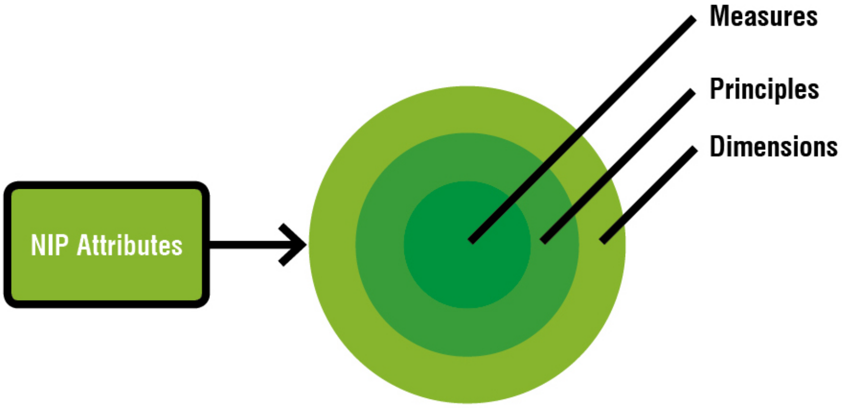
2 A risk-based approach would involve incrementally modifying existing designs in response to emerging hazards, whereas a resilience approach would involve adapting to changing conditions, and potentially allowing controlled failure ('safe-to-fail' design) at a sub-system level to reduce the possibility of broader loss of function within the larger system (Park et al (2013) and Snowden (2011).

These ‘risk’ and ‘resilience’ approaches are considered complementary and applicable in different circumstances. They are not considered mutually exclusive, and their use will depend on the context of the analysis being undertaken and the understanding of the relevant hazard. This is discussed in section 5.1.

4.3 Dimensions and principles of resilience

To further understand resilience, researchers have developed a range of dimensions, principles and measures of resilience. Their relationship to the NIP attributes is indicated below. By defining and categorising these dimensions and principles, the broad framework elements can be built, from which meaningful and practical measures can then be developed. This section discusses dimensions and principles, with chapter 5 addressing measures.

Figure 4.3 Relationship between NIP attributes and dimensions, principles and measures of resilience



The NIP 2011 defines a series of eight ‘attributes’ which help guide the definition and application of resilience in practice. These are summarised in table 4.1.

Table 4.1 National Infrastructure Plan resilience attributes

NIP 2011 attribute	Description
1 Service delivery	There is a focus on national, business and community needs in the immediate and longer term. Resilient infrastructure delivers a level of service sufficient to meet public and private needs, ensuring community viability.
2 Adaptation	National infrastructure has the capacity to withstand disruption, absorb disturbance, act effectively in a crisis, and recognises changing conditions over time.
3 Community preparedness	Infrastructure providers and users understand the infrastructure outage risks (hazards) they face and take steps to mitigate these. Aspects of timing, duration, regularity, intensity and impact tolerance differ over time and between communities, and must be taken into account.
4 Responsibility	Individual and collaborative responsibilities are clear between owners, operators, users, policy-makers and regulators. Responsibility gaps are addressed.
5 Interdependencies	A systems approach applies to identification and management of risk (including consideration of interdependencies, supply chain and weakest link vulnerabilities).
6 Financial strength	There is financial capacity to deal with investment, significant disruption and changing circumstances. This includes available funds, the awareness of financiers and insurers, continuing capital investment and maintenance expenditure.

NIP 2011 attribute	Description
7 Continuous	On-going resilience activities provide assurance and draw attention to emerging issues, recognising that infrastructure resilience will always be a work in progress. Includes effective, on-going monitoring and auditing processes feeding back into continuous improvement.
8 Organisational performance	Leadership and culture are conducive to resilience, including resilience ethos, situational awareness, management of keystone vulnerabilities and adaptive capacity. Future skills requirements need to be addressed.

Source: NIU (2012)

These attributes are considered the over-arching considerations that then guide the development of a resilience framework. The dimensions, principles and measures developed in this study will necessarily be more specific and quantifiable. These are discussed further in the following sections.

4.3.1 Dimensions of resilience

It is important to understand different dimensions in order to develop an appropriate approach to measuring and improving resilience.

USDHS (2009a) divides resilience dimensions into 'hard' and 'soft' systems, hard systems pertaining to the technical and mechanical capabilities of infrastructure and organisations, and soft relating to the human needs, behaviours and psychology within organisations and communities.

VTPI (2010) adopts a slightly different approach and breaks down dimensions of transport resilience into five levels: individual, community, design, economic and strategic planning.

Bruneau et al (2003) developed four dimensions of resilience: technical, organisational, social and economic (TOSE). They note that these four TOSE dimensions cannot be measured by any single performance measure, instead they require different measures for each system under analysis.

A final, more simplistic, example is that developed by the US National Infrastructure Advisory Council (NIAC 2010), which distinguishes between those practices related to people and processes and those related to the structure of infrastructure and assets.

Both the NIAC dimensions and the TOSE dimensions serve as useful and relevant constructs for understanding the high-level dimensions of resilience. They effectively encompass and summarise the dimensions developed by VTPI (2010) and USDHS (2009a).

It is proposed that of the four TOSE dimensions, only the technical and organisational elements be utilised, as illustrated in table 4.2. Because of the narrow focus on the transport system, the social and economic dimensions are considered implicit as the network itself provides a vital social and economic service, and its technical or organisational resilience will inherently provide flow-on social and economic resilience. Economic considerations relating to the operator, and funding to deliver resilience, will be covered within the organisational dimension.

Significant work has been undertaken in Australia (Governmental Resilience Expert Advisory Group) and New Zealand (Resilient Organisations) to understand and develop more resilient organisations, especially within the critical infrastructure and lifelines sectors.

It is vital that organisational resilience is given equal consideration to the resilience of the physical infrastructure (technical resilience). Not only does this provide for improved outcomes for the overall sector, but can also deliver enhanced leadership, enhanced reputation, lower costs, increased innovation and many other tangible benefits (Commonwealth of Australia 2011).

Table 4.2 Dimensions of resilience

Resilience dimension	Description
Technical	The ability of the physical system(s) to perform to an acceptable/desired level when subject to a hazard event (Bruneau et al 2003).
Organisational	The capacity of an organisation to make decisions and take actions to plan, manage and respond to a hazard event in order to achieve the desired resilient outcomes (adapted from Bruneau et al 2003). Seville et al (2006) write that a resilient organisation is one that is 'still able to achieve its core objectives in the face of adversity'. They identify three aspects to building resilience in organisations: a) reducing the size and frequency of crises (vulnerability), b) improving the ability and speed of the organisation to manage crises effectively (adaptive capacity), and c) an acute awareness of risk and an ability to manage strategic risks as a process and not an event.

Source: Bruneau et al (2003)

The next section discusses specific principles of resilience that may apply to the dimensions above.

4.3.2 Principles of resilience

In previous sections we have outlined the complexity involved in understanding and defining resilience, as well as the complexity in types of hazards and failure modes that can affect infrastructure. A number of authors have developed comprehensive lists of principles for achieving resilience to enable common understanding and direct efforts to improving resilience. This section discusses general principles of resilience and then provides further detail specifically around organisational resilience principles.

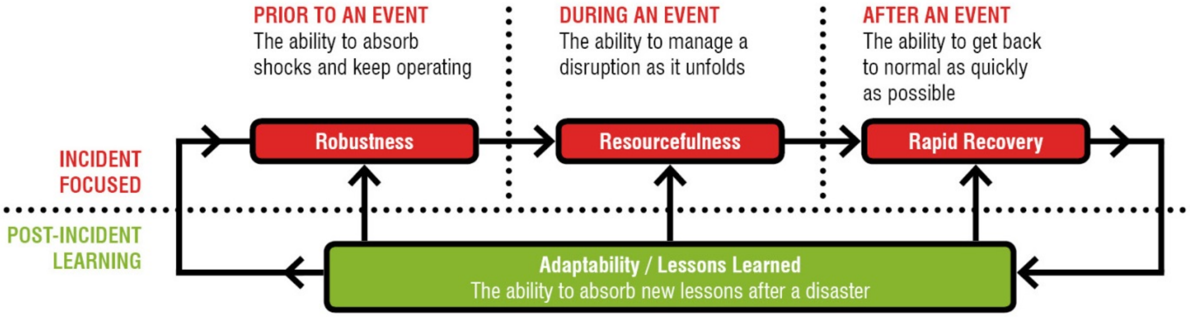
4.3.2.1 General resilience principles

Foster (1997) identifies that in general, resilient systems are independent, diverse, renewable and functionally redundant, with reserve capacity achieved through duplication, interchangeability and interconnections.

VTPI (2001), Comfort (1999) and Foster (1997) have developed principles which include: redundant, diverse, efficient, autonomous, strong, adaptable and collaborative.

Bruneau et al (2003) determine four principles: robustness, redundancy, resourcefulness and rapidity. To these, NIAC (2010) adds the principle of 'adaptability' into incident response planning. Figure 4.4 clarifies how these can apply prior, during and after an event.

Figure 4.4 Resilience principles in sequence



Source: NIAC 2010

CDEM (2005) has established 4 R's which are reduction, readiness, response and recovery. While these overlap, they are more applicable to the field of emergency management and the cycle before, during and after an event than to a specific resilience assessment.

Madni et al (2009) emphasise that resilience in engineering systems is more properly thought of as a characteristic of how the system *behaves* (process), as opposed to a property that the system *has* (state). Park et al (2013) acknowledge this and have established three overarching principles as follows, spanning both the technical and organisational dimensions:

- *Continuous management*: Due to the unpredictability of complex systems, a resilience assessment demands a constant, recursive process, often across multiple organisations. This process involves four components: sensing, anticipation, adaptation and learning.
- *Recognition of incompleteness:* Complex systems are characterised by inherent uncertainty and incompleteness across a variety of areas: internal and external factors affecting design and operation, uncertainty in variability of shocks, and types and visibility of interdependencies.
- *New approaches to design:* Resilience requires a new approach to design thinking. Standard design approaches tend to be based on incremental adaptations of previous approaches in response to a failure. These approaches are generally inflexible and are difficult to change if unexpected conditions are found. Resilient design requires new thinking and a departure from existing practices. Where a traditional 'risk-based' design would result in a design that is resistant to hazards, a resilient design would embrace uncertainty and failure via anticipation and adaptation (Anderies et al 2007). Additionally, whereas a risk-based approach would typically generate a 'fail-proof' design (able to withstand a range of known hazards), a resilience-based approach would account for unpredictability through a 'safe-to-fail' design (Snowden 2006; Park et al 2013). This would entail planned, predictable modes of failure that have been anticipated and designed for, as opposed to failure modes in a fail-proof design which can often be brittle and catastrophic.

As can be seen many common themes run through the types of principles associated with resilience. However, paradoxically many of these are combinations of apparent opposites: redundancy and efficiency, diversity and interdependence, robustness and safe-to-fail, autonomy and collaboration, planning and adaptability – adding weight to the importance of careful definitions and delineation between assessment areas when building a framework.

4.3.2.2 Organisational resilience principles

In regard specifically to organisational resilience, Commonwealth of Australia (2011) and Resilient Organisations (various papers) have identified three core behavioural principles (with a range of indicator subsets) which help define resilient organisations, as summarised in table 4.3 below.

Table 4.3 Organisational resilience – behavioural principles

Behavioural principle (and indicators)	Description
Leadership and culture (Leadership, staff engagement, decision making, situational awareness, innovation and creativity)	A resilient organisation: • develops an organisational mind-set/culture of enthusiasm for challenges, agility, flexibility, adaptive capacity, innovation and taking opportunity • fosters the above through developing trust, clear purpose and empowerment of employees • promotes a consistent and transparent organisational commitment to a resilience culture, values and vision, including a belief of 'one in – all in' • encourages increased personal resilience by employees • has board members and senior executives who engage and provide leadership appropriate to their position on organisational resilience.
Networks (Breaking silos, leveraging knowledge, effective partnerships, internal resources)	A resilient organisation: • establishes relationships, mutual aid arrangements and regulatory partnerships • understands an organisation's community interconnectedness and its vulnerabilities across all aspects of supply chains and distribution networks • promotes open communication and mitigation of internal/external silos.
Change ready (Planning strategies, unity of purpose, proactive posture, stress testing plans, innovation and creativity)	A resilient organisation: • promotes proactive anticipation and preparation for future challenges • develops a forewarning of disruption threats and their effects through sourcing a diversity of views, increasing sensitivity and alertness, and understanding social vulnerability • promotes empowered and broadly embraced organisational and individual self-efficacy, as well as enthusiasm for finding effective solutions to complex challenges • promotes requisite decision making using both rational and intuitive abilities • promotes critical reflective learning, lesson retention, knowledge sharing and continuous improvement.

Source: Resilient Organisations (2012)

4.3.2.3 Summary of chosen resilience principles

To conclude this section, the following broad principles have been summarised which encompass the views of the various authors across both technical and organisational dimensions, and which are proposed to form the basis of the framework to measure the resilience of the transport system.

From a technical perspective, Bruneau's principles of robustness and redundancy are considered to broadly encapsulate the range of ideas proposed by other authors, while the concept of 'safe-to-fail' proposed by Park et al and Snowden is included as a third technical principle. The concept of 'independent' as proposed by Foster (or 'autonomous') has not been included explicitly as a technical principle. For transport infrastructure, this may, in theory, be applicable to powered systems (eg lights) which could be powered by independent supplies; however, it is suggested (for practical reasons) that the provision of independent supplies be considered instead in a back-up context as 'redundancy.

From an organisational perspective, the three principles developed by Resilient Organisations have been adopted. These are considered to broadly encompass the principles developed by others, as discussed above.

Table 4.4 Proposed principles of resilience for the transport system

Dimension	Principle	Definition and justification
Technical	Robustness	Strength, or the ability of elements, systems and other units of analysis, to withstand a given level of stress or demand without suffering degradation or loss of function (Bruneau et al 2003).
	Redundancy	The extent to which elements, systems, or other infrastructure units exist that are substitutable, ie capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality (Bruneau et al 2003). For simplification, this is assumed to include considerations of 'diverse' and 'reserve capacity'. The concept of 'independent/autonomous' is included here, only in the context of back-up provision, as discussed above.
	Safe-to-fail	The extent to which innovative design approaches are developed, allowing (where relevant) controlled, planned failure during unpredicted conditions, recognising that the possibility of failure can never be eliminated. This may involve new approaches to design, to complement traditional, incremental risk-based design (Park et al 2013).
Organisational	Change readiness*	The ability to sense and anticipate hazards, identify problems and failures, and to develop a forewarning of disruption threats and their effects through sourcing a diversity of views, increasing alertness, and understanding social vulnerability (Resilient Organisations 2012). Also involves the ability to adapt (either via redesign or planning) and learn from the success or failure of previous adaptive strategies (Park et al 2013). This learning is also conceptualised by Manyena et al (2011) who in their 'bounce-forward' idea of resilience, identify moving from single-loop or error-corrective learning, to double-loop, organisational learning, where the values, assumptions and policies that led to the actions in the first place are questioned. The capacity to mobilise resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis; resourcefulness can be further conceptualised as consisting of the ability to apply material (ie monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals (Bruneau et al 2003).
	Networks	The ability to establish relationships, mutual aid arrangements and regulatory partnerships, understand interconnectedness and vulnerabilities across all aspects of supply chains and distribution networks, and; promote open communication and mitigation of internal/external silos (Resilient Organisations 2012).
	Leadership and culture	The ability to develop an organisational mind-set/culture of enthusiasm for challenges, agility, flexibility, adaptive capacity, innovation and taking opportunity (Resilient Organisations 2012).

*Readiness encompasses the change-ready concepts developed by Resilient Organisations (2012), along with the concept of 'resourcefulness' developed by Bruneau et al (2003) and Park et al (2013).

4.4 Summary

4.4.1 Main points

The NIP resilience definition is considered appropriate: 'The concept of resilience is wider than natural disasters and covers the capacity of public, private and civic sectors to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions, including climate change, and grow over time' (NIU 2011).

The NIP attributes are considered relevant; however, we do not suggest they be used to categorise resilience dimensions and principles. In subsequent sections, the NIP attributes are mapped to the chosen framework principles for completeness.

It is suggested that the broad dimensions of technical and organisational be used, along with the principles of robustness, redundancy, safe-to-fail, change readiness, networks, leadership and culture.

4.4.2 Relevance to framework development

The framework has been built around the broad dimensions as follows:

- technical (robustness, redundancy, safe-to-fail)
- organisational (change readiness, networks, leadership and culture).

5 How can we measure resilience?

As illustrated in figure 4.3, measures for resilience can be distilled from an analysis of dimensions and principles. In general terms, measures need to be broad enough to allow application across a variety of scales, including transport modes. They also need to be transparent and quantifiable (although, this may be in a relative sense as opposed to being an exact determination).

Past studies have fallen generally into two groups – those which develop a conceptual (qualitative) framework for measuring resilience, and those which have attempted to develop quantitative metrics (indices) through more detailed analysis and modelling. We also note the difference between frameworks that assess resilience *after* a hazard event, and those that assess resilience *before* an event.

Initially, however, we explore the question 'resilience to what?' We discuss what types of hazards are relevant and how a resilience assessment could consider *consequence* as opposed to the hazard itself.

5.1 Resilience to what?

As discussed in section 4.2, there is a wide range of hazards, hazard types and failure modes that could affect a given piece of infrastructure or the transportation network. However, a resilience assessment also requires an awareness that the hazard itself may be unpredictable (Park et al 2013) and the organisation needs to think beyond typical disaster scenarios (Brunsdon and Dalziell 2005).

As such, it is useful to move from consideration of hazards (either via probability or scenario analysis) to consideration of consequences which specifically relate to the loss of service as well as other impacts. These consequences can relate to a non-specified hazard event, which could apply to any (or all) hazard types. Brunsdon and Dalziell (2005) provide some consequence scenarios which are considered applicable and have been adapted for the transport context:

- Regional event: significant physical damage to transport infrastructure, coupled with severe disruptions to other lifeline services such as electricity, water and telecommunications. An example of this type of event may be a major earthquake or flood.
- Localised event: a transport-specific incident resulting in loss of life, severe disruption to normal operations and reputation impacts. The intense focus of media and regulatory agencies requires the organisation to focus on managing stakeholder perception as well as the physical response and recovery from the event. Examples may be a collapse of a transport structure, or a hazardous spill affecting the immediate locality.
- Societal event: a societal event which may cause unexpected impacts or demand on the transport system. In this case, all physical infrastructure is intact; however, the transport system is unable to cope with demand. Examples may include: 1) a surge in traffic demand due to a specific event, or a major gathering of people, 2) growth in demand over time, 3) growth in public transport demand due to, say, fuel price rises, 4) an illness pandemic (eg influenza or SARS), meaning operational staff are unavailable.
- Distal event: impacts transport operations through key suppliers or interdependencies. This consequence scenario can identify the ways the transport system and related organisations may be affected through its networks of inter-organisational relationships. Examples may be the failure of a key dependent utility (power, telecommunications, water), failure of a key supplier, or an international shortage of key resources.

Note that such an approach to considering the consequences of unpredictable events should not necessarily replace an assessment of known (or predictable) hazards using a more standard risk-based approach.

There may be certain situations where a specific hazard assessment would be appropriate, for example, where critical assets or sections of network are required to be assessed and hazards are well understood. In these cases both approaches are required within the overall resilience framework. These have been distinguished into two categories called 'all-hazards' and 'specific-hazard'.

5.1.1 An all-hazards vs specific hazard approach

To summarise the above discussion, we consider there is merit in undertaking both an all-hazards approach as well as a specific-hazard approach, depending on the context of the evaluation.

An all-hazards approach to resilience would involve a high-level assessment looking at resilience measures in response to all hazards in general, and would consider a relevant event scenario as detailed above (regional, local, societal, distal).

A specific-hazard assessment would be more detailed, however, and therefore might be appropriate for certain critical assets. This would involve identifying the complete range and type of potential scenarios as described above, and assessing the risk (likelihood and consequence) of them occurring. The resilience assessment and response could then be tailored accordingly. Appropriate methods could be used to identify hazards due to known 'rare events' and also non-linear modes of failure involving interdependencies.

The following sections outline approaches to measurement of resilience in both a qualitative and quantitative context, and recommend a preferred approach.

5.2 Conceptual/qualitative frameworks

These frameworks typically remain at a higher level and set out principles (such as those outlined in section 4.3) from which resilience can be assessed. Some examples are described below.

Bruneau et al (2003) developed a range of performance criteria (measurement categories) relating to seismic resilience. Measures were developed specifically for each dimension (TOSE) and related to each principle (robustness, redundancy, resourcefulness and rapidity) as summarised in table 5.1.

Table 5.1 Seismic resilience measures example

	Performance criteria			
Performance measures	**Robustness**	**Redundancy**	**Resourcefulness**	**Rapidity**
Technical	Damage avoidance and continued service provision	Backup/duplicate systems, equipment and supplies	Diagnostic and damage detection technologies and methodologies	Optimising time to return to pre-event functional levels
Organisational	Continued ability to carry out designated functions	Backup resources to sustain operations (eg alternative sites)	Plans and resources to cope with damage and disruption (eg mutual aid, emergency plans, decision support systems)	Minimise time needed to restore services and perform key response tasks
Social	Avoidance of casualties and disruption in the community	Alternative means of providing for community needs	Plans and resources to meet community needs	Optimising time to return to pre-event functional levels

Performance criteria				
Performance measures	**Robustness**	**Redundancy**	**Resourcefulness**	**Rapidity**
Economic	Avoidance of direct and indirect economic losses	Untapped or excess economic capacity (eg inventories, suppliers)	Stabilising measures (eg capacity enhancement and demand modifications, external assistance, optimising recovery strategies)	Optimising time to return to pre-event functional levels

Source: Bruneau et al 2003

Brabhaharan (2006) also developed a method to establish 'performance criteria' and example metrics by which elements of the transport system could be measured after an event. These were based on specific levels of service requirements following hazard events, and performance criteria developed for specific critical sections of the network by relevant stakeholders. Some example criteria are shown in table 5.2. These serve as useful example measures; however, it is noted that these apply to a post-event situation. Similar, qualitative measures could be developed for use before an event.

Table 5.2 Example performance criteria

Service provided	Priority/criticality of relevant road link	Level of service	Measure
1a. Temporary access to emergency services for emergency service vehicles	Very high	Restore temporary road access to hospitals and emergency centres.	Within two hours
1b. Temporary access to emergency services for emergency service vehicles	High	Restore temporary road access to hospitals and emergency centres identified by the district health board	Within two days
2a. Access to lifeline utilities	N/A (all are assumed equal)	Restore 4x4 road access to power, water and telecommunication utilities for inspection and repair.	Within three days.
3a. Network availability	High	Re-open one lane for heavy trucks and buses	Within 24 hrs.
3b. Network availability	Medium	Re-open one lane for heavy trucks and buses	Within 36 hrs.
3c. Network availability	Low	Re-open one lane for heavy trucks and buses	Within one week

Source: Brabhaharan (2006)

Other examples of conceptual transport-related frameworks include those developed by Heaslip et al (2009), Murray-Tuite (2006), Mostashari et al (2009). All of these are qualitative in nature and propose a range of subjective criteria to assess.

Dantas and Giovinazzi (2010) developed a benchmarking framework to measure the readiness of road controlling authorities to meet their obligations under the Civil Defence and Emergency Management Act 2002. The self-assessment tool developed, included a set of key performance indicators, which are representative of the critical success factors in emergency management, and benchmarked performance in relation to the 4Rs (reduction, readiness, response and recovery).

Lee et al (2013) developed a framework and survey tool for organisations to use to identify their strengths and weaknesses and to develop and evaluate the effectiveness of their resilience strategies and investments. The survey consisted of a range of questions across 13 indicators which are shown as subsets within table 4.3.

5.3 Quantitative approaches

A number of authors have developed detailed quantitative methods for measuring the resilience of specific networks. In many cases these have produced a 'resilience index' resulting from the modelling of networks and possible failure modes.

In general terms, many of the methods set out to a) evaluate the failures in levels of service due to the impact of an event, b) evaluate the time to restore an acceptable level of service to a network and c) compare the recovered system performance as a result of a strategy (intervention) with the system performance without the strategy.

Approaches used to undertake the analysis vary and include the use of network models, GIS analysis, fuzzy systems approaches and others. Urena Serulle (2010) summarised a range of previous analyses undertaken and related field and methodology employed, which is shown in table 5.3.

Table 5.3 Summary of previously proposed quantitative assessments of resilience

Author	Field	Proposed methodology
Hamad and Kikuchi (2002)	Transportation engineering	Developed a measure of traffic congestion based on two conventional transportation metrics, travel speed and delay. A fuzzy inference approach was implemented to combine travel speed and delay into one single index. The result was a congestion index that ranges from 0 to 1, where 0 is the best condition and 1 the worst.
Brenkert and Malone (2004)	Social study	Proposed a set of 17 quantitative indicators that allow comparisons of different levels of localities (regional, states, cities, etc) in terms of their vulnerability and resilience to current and changing climate.
Mayunga (2007)	Social study	Obtained a weighted average of the resilience elements (social capital, human capital, economic capital, physical capital and natural capital) to obtain a single community disaster resilience index.
Heaslip et al (2010)	Transportation engineering	Ten measurable variables were used to define four basic network performance indexes (network availability, traveller perception, transportation cost and network accessibility). These four indexes were then combined using fuzzy inference logic into a single network service performance index, which served as a base resilience index.

Source: Serulle 2010

5.4 Recommended measurement approach

Based on the above research of measurement approaches, table 5.4 summarises each type of approach.

Table 5.4 Summary of qualitative and quantitative measurement approaches

	Qualitative approach	**Quantitative approach**
Flexibility	Provides a flexible approach that can be adapted to a range of situations, scales and conditions.	Is typically applied only at a smaller geographical scale and at a more detailed level.
Data requirements	Can be applied with complete or incomplete data sets. Relies on subjective assessments in many cases.	Typically requires large, accurate data sets.
Computational requirements	None/minimal.	Requires significant computational effort.
Results	A relative, subjective assessment – often using a ranking scale	Typically delivers a discrete resilience index or measure by way of network modelling or fuzzy logic modelling.
Ease of implementation	Simple	Difficult
Use in targeting resilience improvements	Useful; however, is very much related to the design of the framework, how it is implemented, and subjectivity of the scores given.	Can be accurate for the network analysed.
Useful in wider organisational resilience assessments and engagement	Yes	No
Useful in assessing physical network asset resilience	Yes	Yes

Based on the above, we suggest that a broadly qualitative approach would better suit the Transport Agency's requirements for a practical and flexible framework. We note that there may be some quantitative measures within the overall framework; however, generally speaking, we propose a qualitative assessment.

The approach will be based around:

- dimensions of resilience – technical and organisational
- principles of resilience – robustness, redundancy, safe-to-fail, readiness, continuous management, leadership and culture, networks.

5.5 Summary

5.5.1 Main points

Either an 'all-hazards' or 'hazard-specific' approach could be used for measuring resilience. The latter would be much more detailed and it may be appropriate in certain situations where specific hazards are well understood.

Historically, both qualitative and quantitative approaches have been used for measuring resilience. Quantitative approaches tend to be less flexible, time consuming and appropriate for more narrow assessments of networks and systems. They are data intensive and can be difficult to implement.

Qualitative assessments are, by nature, more subject to interpretation, but are flexible in terms of scale and context, and can provide wider process and organisational benefits due to the necessary involvement of operators and managers.

There are also broadly qualitative frameworks which contain measures that are more quantitative in nature.

5.5.2 Relevance to framework development

A broadly qualitative approach to measuring resilience is proposed, with a range of specific measures/categories based on the dimensions and principles developed in the previous section.

The framework should be able to be implemented at a general ‘all-hazards’ level or a ‘specific-hazard’ level.

6 A proposed measurement framework for transport system resilience

This chapter summarises a proposed practical framework for measuring resilience based on the dimensions and principles developed in previous sections. For each step, explanation and detail is provided to justify the chosen approach.

The process described in figure 6.1 includes an initial determination of the context of the resilience assessment, followed by a detailed assessment using a wide range of resilience measures, which combine to generate a resilience score from 4 (very high resilience) to 1 (low resilience):

4 Very high resilience – meets all requirements

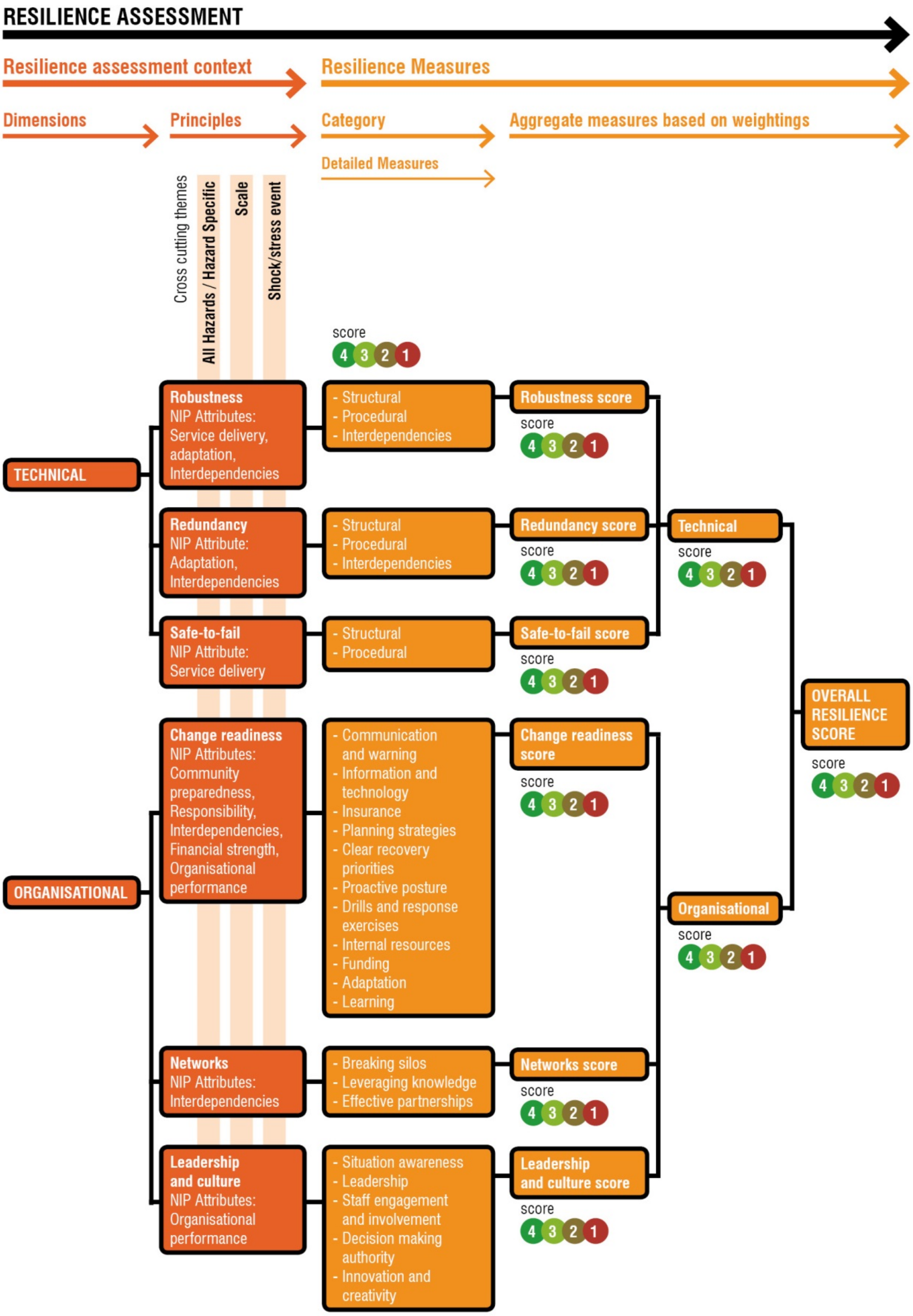
3 High resilience – acceptable performance in relation to a measure(s), some improvements could be made

2 Moderate resilience – less than desirable performance and specific improvements should be prioritised

1 Low resilience – poor performance and improvements required.

The following sections describe each of these processes in more detail.

Figure 6.1 Proposed resilience assessment



6.1 Resilience assessment context

The resilience assessment has been divided into dimensions and principles as determined in chapter 4.

The broad level dimensions used are technical and organisational. Principles of resilience have been taken as robustness, redundancy, safe-to-fail, change-readiness, networks, and leadership and culture. Robustness, redundancy and safe-to-fail relate to technical, asset or network considerations while the remainder relate to the organisational considerations (refer to figure 6.1).

Each of the above four principles has been mapped to the NIP 2011 attributes to ensure that the framework links to and aligns with the NIU process.

There are a number of cross-cutting themes that influence the context and approach of the resilience assessment. These are summarised and discussed in the table below.

Table 6.1 Cross-cutting themes

Cross-cutting theme	Discussion
All hazards/specific hazard approach	The assessment can be undertaken in one of two ways: 1 An all-hazards assessment – based on an event due to any (unspecified) hazard/failure, which could be either known or unknown. The event could be regional, local, societal or distal (section 5.1). 2 A hazard-specific assessment could be undertaken. This would involve identifying the relevant known hazard types and assessing the resilience to each.
Scale of assessment	The framework will allow assessment at various scales: regional, network or asset. Measures have been developed for each and the user can filter the questions accordingly. Regional assessments could be aggregated to a national indicator for NIU purposes.
Shock event or stress event	The framework will be able to evaluate both short-term shock events (eg earthquakes and tsunamis) and longer-term stress events (eg climate change related). Stress events should be considered as part of a hazard-specific assessment (see above) and if required, a risk-assessment could be undertaken as well to understand likelihood and consequence of occurrence.

6.2 Resilience measures

A range of measurement categories are suggested based on the six resilience principles – as discussed in section 5.2. Within these categories, specific measures have been developed. It is important to note that each category covers a range of parameters associated with that measure.

The measurement categories are described in table 6.2 and map to the NIP resilience attributes as shown. Each technical principle has been divided into categories of structural, procedural and interdependencies as these are thought to encapsulate the main types of relevant measures. Organisational principles have been divided into categories based on those proposed by Resilient Organisations (2012) and Lee et al (2013), as well as some additional categories suggested by the authors of this report.

Table 6.2 Summary of measurement categories

Principle	Measurement category	Description
Technical		
Robustness (NIP attributes: service delivery, adaptation, Interdependencies)	Structural	Physical measures relating to asset/network design, maintenance and renewal
	Procedural	Non-physical measures relating to existence, suitability and application of design codes, guidelines
	Interdependencies	This relates to upstream dependencies (refer section 3.2) and their relative robustness in both a structural and procedural sense
Redundancy (NIP attribute: adaptation, Interdependencies)	Structural	Physical measures relating to network redundancy, alternate routes and modes and backup supplies/resources
	Procedural	Non-physical measures relating to existence of diversion and communication plans
	Interdependencies	This relates to upstream dependencies and their relative redundancy in both a structural and procedural sense.
Safe-to-fail (NIP attribute: adaptation)	Structural	The extent to which innovative design approaches are implemented, allowing (where relevant) controlled failure during unpredicted conditions. This may complement traditional, incremental risk-based design (Park et al 2013).
	Procedural	The extent to which safe-to-fail designs are specified in design guidelines.
Organisational		
Change readiness (NIP attributes: community preparedness, responsibility, interdependencies, financial strength, organisational performance)	Communication and warning	This relates to the existence and effectiveness of communication and warning systems
	Information and technology	This relates to the use of technology to monitor events, communicate, share data, assess resilience etc.
	Insurance	This relates to the adequacy of insurances for hazard events.
	Internal resources	The management and mobilisation of the organisation's resources to ensure its ability to operate during business-as-usual, as well as being able to provide the extra capacity required during a crisis. Also relates to ensuring roles and responsibilities of all internal stakeholders are clear and that coordination is effective.
	Planning strategies	The development and evaluation of plans and strategies to manage vulnerabilities in relation to the business environment and its stakeholders.
	Clear recovery priorities	An organisation-wide awareness of what the organisation's priorities would be following a crisis, clearly defined at the organisation level, as well as an understanding of the organisation's minimum operating requirements.
	Proactive posture	A strategic and behavioural readiness to respond to early warning signals of change in the organisation's internal and external environment before they escalate into crisis.
	Drills and response exercises	The participation of staff in simulations or scenarios designed to practice response arrangements and validate plans.

Principle	Measurement category	Description
	Funding	Extent to which funding is available for all elements of resilience planning including technical and organisational.
	Adaptation	Constant vigilance and situation awareness (see below) allows adaptation strategies to be developed. These may be procedural/planning focused/organisational or technical (increased robustness, redundancy, or designing for 'safe-to-fail' modes).
	Learning	Past actions and adaptation strategies are observed and evaluated in terms of their success in mitigating hazards. Appropriateness of actions can be assessed and iterations and changes made.
Networks (NIP attributes: interdependencies)	Breaking silos	Minimisation of divisive social, cultural and behavioral barriers, which are most often manifested as communication barriers creating disjointed, disconnected and detrimental ways of working.
	Leveraging knowledge (internal and external)	Critical information is stored in a number of formats and locations and staff have access to expert opinions when needed. Roles are shared and staff are trained so that someone will always be able to fill key roles.
	Effective partnerships (external)	An understanding of the relationships and resources the organisation might need to access from other organisations during a crisis, and planning and management to ensure this access. Also relates to clear coordination and understanding between organisations, and clarity of roles and responsibilities.
Leadership and culture (NIP attributes: organisational performance)	Situation awareness (sensing and anticipation)	Staff are encouraged to be vigilant about the organisation, its performance and potential problems. Staff are rewarded for sharing good and bad news about the organisation. Early warning signals are quickly reported to organisational leaders. Newly incorporated knowledge gained from vigilance is used to foresee/anticipate crises. This can be used to develop adaptation strategies.
	Leadership	Strong crisis leadership to provide good management and decision making during times of crisis, as well as continuous evaluation of strategies and work programs against organisational goals.
	Staff engagement and involvement	The engagement and involvement of staff who understand the link between their work, the organisation's resilience, and its long-term success. Staff are empowered and use their skills to solve problems.
	Decision-making authority	Staff have the appropriate authority to make decisions related to their work and authority is clearly delegated to enable a crisis response. Highly skilled staff are involved in, or are able to make, decisions where their specific knowledge adds significant value, or where their involvement will aid implementation.
	Innovation and creativity	Staff are encouraged and rewarded for using their knowledge in novel ways to solve new and existing problems and for utilising innovative and creative approaches to developing solutions.

A detailed database (spreadsheet) has been developed which describes measurements and captures scores on a scale of 4 (very high level of resilience) to 1 (low resilience). Some example measures for 'robustness' are shown in figure 6.2 below, with the complete lists contained in appendix B. The measures can then be weighted at the discretion of the user to give an aggregate score for a principle (eg robustness) or dimension (eg technical), or overall.

A summary 'dashboard' allows the user to view the various scores and weightings used.

Figure 6.2 Example of resilience measures (for the 'robustness' principle)

ROBUSTNESS			Weighted robustness score				2.3
Category	**Measure**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**
Structural	Maintenance	Processes exist to maintain critical infrastructure and ensure integrity and operability – as per documented standards, policies & asset management plans (eg roads maintained, flood banks maintained, stormwater systems are not blocked. Should prioritise critical assets as identified.	4 – Audited annual inspection process for critical assets and corrective maintenance completed when required. 3 – Non-audited annual inspection process for critical assets and corrective maintenance completed when required. 2 – Ad hoc inspections or corrective maintenance completed, but with delays/backlog. 1 – No inspections or corrective maintenance not completed.	3.0	2.8	33.33%	94.4
	Renewal	Evidence that planning for asset renewal and upgrades to improve resilience into system networks exist and are implemented.	4 – Renewal and upgrade plans exist for critical assets, are linked to resilience, and are reviewed, updated and implemented. 3 – Renewal and upgrade plans exist for critical assets and are linked to resilience, however no evidence that they are followed. 2 – Plan is not linked to resilience and an ad hoc approach is undertaken. 1 – No plan exists and no proactive renewal or upgrades of assets.	4.0			
	Design	Percentage of assets that are at or below current codes	4 – 80% are at or above current codes 3 – 50-80% are at or above current codes 2 – 20-50% are at or above current codes 1 – Nearly all are below current codes	3.0			
		Assessment of general condition of critical assets across region	4 – 80% are considered good condition 3 – 50-80% are considered good condition 2 – 20-50% are considered good condition 1 – Nearly all poor condition	3.0			
		Percentage of assets that are in zones/areas known to have exposure to hazards	4 – <20% have some exposure to known hazards 3 – 20-50% are highly exposed, or >50% are moderately exposed 2 – 50-80% are highly exposed 1 – 80% are highly exposed to a hazard	2.0			
		Percentage of critical assets with additional capacity over and above normal demand capacity	4 – 80%+ of critical assets have >50% spare capacity available 3 – 50-80% of critical assets have >50% available 2 – 20-50% of critical assets have >50% spare capacity 1 – 0-20% have spare capacity.	2.0			

In summary, the approach to undertaking the resilience assessment is as follows:

1 Determine the context of the assessment:

   a all-hazards or specific hazards (including shock or stress event, rare events etc)

   b scale: asset/network/regional context

   c shock or stress event.

2 Undertake the assessment using the questions relative to the context above and select scores for each.

3 Apply weightings to the scores, as required.

4 This will generate resilience scores for categories, principles and dimensions and a total score.

As a stand-alone assessment, the resilience measurement framework can be applied to generate a relative score that could be used to compare resilience across assets/networks or regions. However, to provide additional rigour, other steps could be applied. This is discussed in chapter 7.

6.2.1 Application of weightings

The resilience measurement framework consists of a range of questions across the categories shown in figure 6.1. Once the relevant questions have been answered, weightings can be applied at the category, principle or dimension level. These weightings are a percentage and must add to 100% across each group.

The weightings allow the user to place importance to (say) one principle over another. For example, one may determine that 'robustness' is more important than 'redundancy' or 'safe-to-fail' and as such, allocate a weighting of 40%:30%:30%.

It is important to note that the weightings are subjective and will be based on user preference. In all instances, the individual scores for each question can be viewed and interrogated to determine reasons behind a specific principle or dimension score.

Further guidance on the use of the framework is provided in appendix F.

6.3 Summary

6.3.1 Main points

The resilience measurement framework relates to the dimensions, principles and categories outlined in previous sections. Specific measures for each category have been developed and are included in appendix B.

Each measure is scored from 4 (very high resilience) to 1 (low resilience), and weightings can be applied at the category, principle and dimension level to generate aggregate scores if required.

The approach can be applied at various scales and to an 'all-hazards' or 'hazard-specific' context.

7 Implementation of the framework

As mentioned in chapter 6, the resilience assessment could be applied as a stand-alone assessment for a particular asset or region.

However, in order to implement the measurement framework in a systematic manner, additional steps could be incorporated to determine priorities for intervention. This would include determining:

1 Which infrastructure should be assessed for resilience?

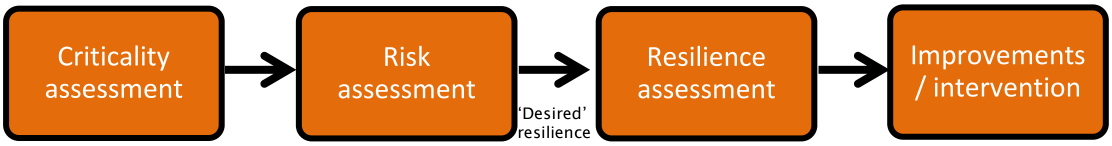
2 What level of resilience is appropriate for a given asset/network?

In order to answer these questions, we need to have an understanding of the criticality of a given asset, and, if required, an understanding of the risk of a particular hazard occurring. Note, this links directly with the choice of whether a general ‘all-hazards’ or a ‘hazard-specific’ assessment is chosen.

Figures 7.1 and 7.2 summarise the two alternative approaches.

Figure 7.1 All-hazards: criticality and resilience assessment

Figure 7.2 Hazard specific: detailed risk assessment and resilience assessment



The all-hazards approach would involve an assessment of criticality to determine which assets should be focused on for the resilience assessment. The related questions within the measurement framework (appendix B) would be those applicable across all hazard types (or, in other words, as the consequence of a regional, local, societal or distal event – refer section 5.1). The criticality assessment would identify which assets merited a certain ‘desired’ level of resilience, and then following a resilience assessment for these assets, related improvements or interventions could be targeted. The translation from criticality to ‘desired’ level of resilience is summarised in table 7.1.

Table 7.1 Example translation of criticality score to ‘desired’ level of resilience

Criticality score	Desired level of resilience
Highly critical	Very high (4)
Medium	High (3)
Low	Moderate (2)
Not critical	Low (1)

If further detail was required, a hazard-specific assessment could be undertaken. This would require understanding which types of hazards would be relevant and their associated likelihoods. In this case, the output of the risk-assessment would determine the ‘desired’ level of resilience.

The Transport Agency currently has a state highway classification system that could be utilised to determine criticality of assets. Rail system operators and local authorities may also have similar methods for determining criticality. There are, however, a range of additional considerations that can be incorporated into a criticality assessment, relating to operational considerations, interdependencies and specific user/community requirements. More information on this is provided in appendix D.

The Transport Agency also has an established risk assessment approach based on the joint Australian/New Zealand standard AS/NZS 31000:2009, which could be utilised to determine an overall risk score relating to the likelihood and consequence of a particular hazard occurring (refer to appendix A for further detail). Other transport system operators may also have similar approaches.

In order to link to the resilience assessment, the risk assessment would need to specifically address:

1 The likelihood of a particular hazard occurring in a given location/region and the likelihood that it would impact on a given asset.

2 The consequence of failure of the asset, which would be related to the criticality assessment (ie a critical asset would have a high consequence if it fails).

The resultant risk score derived from a risk assessment could then translate to a ‘desired’ level of resilience, as illustrated in table 7.2 (example).

Table 7.2 Example translation of risk score to ‘desired’ level of resilience

Risk score (Transport Agency tool)	Desired level of resilience
4 (Extreme)	Very high (4)
3 (High)	High (3)
2 (Moderate)	Moderate (2)
1 (Low)	Low (1)

As outlined above, a risk assessment would be undertaken as part of a hazard-specific assessment. In this case, specific attention would need to be given to the types of hazards and failure causes/modes that may eventuate (refer sections 4.2 and 5.1).

Types of hazards would include, by definition, known hazards and also, where relevant, an assessment of ‘rare event’ possibilities. This assessment could include a range of activities with experienced operational staff to:

- identify linkages and interdependencies
- think the unthinkable in terms of rare events and failure modes
- consider the combinations of events that might occur
- consider what is happening elsewhere (horizon scanning)
- be more creative in risk identification and identify events that might be known by others but a ‘black swan’ to the Transport Agency.

Table 7.3 summarises the ranges of scales of application and the suggested relevant approaches which could be implemented.

Table 7.3 Approaches to implementation

Scale	Suggested approach	Application
Asset	1 Hazard-specific: would involve assessing the resilience of an asset, and comparing with a desired level based on risk. 2 All-hazards: would involve assessing the resilience of an asset, and comparing with a desired level based on criticality of the asset.	1 This would enable actions and interventions to be prioritised across assets in relation to specific identified hazards. 2 This would enable actions and interventions to be prioritised across assets more generally and in relation to 'all hazards'.
Network/route	1 Hazard-specific: would involve assessing resilience of various elements within the network/route, and comparing with a desired level based on risk. 2 All-hazards: would involve assessing resilience of various elements within the network/route to 'all-hazards', and comparing with a desired level based on criticality of the network/route.	1 This would enable actions and interventions to be prioritised across the broader transport system in relation to specific identified hazards. 2 This would enable actions and interventions to be prioritised across the broader transport system in relation to 'all-hazards'.
Regional*	1 Hazard-specific: would involve assessing resilience of various critical elements within the region, and developing a stand-alone score. 2 All-hazards: would involve assessing resilience of various critical elements within the region to 'all-hazards', and developing a stand-alone score.	1 This would enable regions to be compared, and actions and interventions to be prioritised across regions in relation to specific identified hazards. 2 This would enable regions to be compared, and actions and interventions to be prioritised across regions in relation to 'all hazards'. (A national assessment could be generated by aggregating regional scores that could then be utilised by the NIU.)

*An alternative approach to assessment at a regional level would be to undertake individual asset or network assessments, and aggregate individual resilience scores into a regional score. This would require more detail, and it is suggested that the approach above is implemented in the first instance.

7.1 Summary

The resilience measurement framework could be applied as a standalone assessment; however, in practice the framework should be implemented either via an 'all-hazards' approach or a 'hazard-specific' approach – either at an asset, network or regional scale.

The 'all-hazards' approach would involve an initial criticality assessment.

The 'hazard-specific' approach would involve a risk assessment and a more detailed understanding of potential hazards and failure possibilities.

It is important to emphasise here that this is a resilience assessment tool and not a risk assessment tool, although risk does form an important part of implementation.

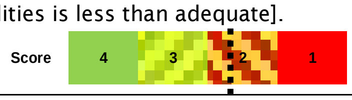
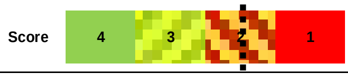
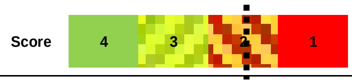
8 Example assessments

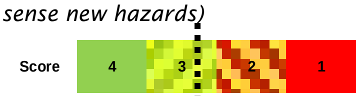
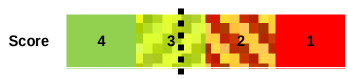
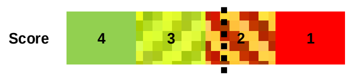
This section covers two high level examples through which the measurement framework is illustrated. The examples are fictitious, but serve to illustrate the application of the framework.

8.1 Regional all-hazard assessment

Table 8.1 summarises the assessment approach. The detailed questions for the assessment are included within appendix B.

Table 8.1 Example all-hazard assessment

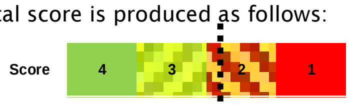
Assessment context and approach:	Regional, all hazard, pre-event. Assessment to be undertaken initially as a stand-alone assessment.
Assessment example:	Regional event (significant physical damage to transport infrastructure, coupled with severe disruptions to other lifeline services such as electricity, water and telecommunications). [An organisation that has experienced a few major disasters some time ago and has some resilience responses in place but is just starting to re-invigorate its resilience preparation and integration].
Technical resilience assessment:	**Robustness:** Robustness is assessed via a series of measures across the categories of structural, procedural and interdependencies. An example assessment is given below. Note: all categories are weighted equally. *Structural:* Across the five measures, the average score is 2.8, which is 'moderate'. [Rationale: maintenance and renewal of assets is acceptable, however most critical assets (such as bridges) are not up to current design code levels, as they were built in the 1960's]. *Procedural:* Across the one measure, the average score is 2.0, which is 'moderate'. [Rationale: design codes and guidelines do not adequately address resilience issues]. *Interdependencies:* Across the two measures, the average score is 2.0, which is 'moderate'. [Rationale: planning for resilience by interdependent utilities is less than adequate]. Overall robustness score of 2.3 (moderate). 
	Redundancy: Redundancy is assessed via a series of measures across the categories of structural, procedural and interdependencies. An example is given below. Note: all categories are weighted equally. *Structural:* Across the four measures, the average score is 2.0, which is 'moderate'. [Rationale: indicates that availability and capacity of alternative routes and modes is less than adequate]. *Procedural:* Across the one measure, the average score is 2.0, which is 'moderate'. [Rationale: indicates planning for diversions to alternate routes is less than adequate]. *Interdependencies:* Across the two measures, the average score is 2.0, which is 'moderate'. [Rationale: supplier awareness of redundancy issues, and implementation of improvements is less than adequate]. Overall redundancy score of 2.0 (moderate). 
	Safe-to-fail: Safe-to-fail is assessed via two single measures. An example is given below. Note: all categories are weighted equally. *Structural:* Across this measure, the score is 2.0, which is 'moderate'. [Rationale: indicates safe-to-fail design and planning is less than adequate]. *Procedural:* Across this measure, the score is 2.0, which is 'moderate'. [Rationale: indicates safe-to-fail design and planning is less than adequate]. Overall safe-to-fail score of 2.0 (moderate). 

Organisational resilience assessment:	**Change readiness:** Change readiness is assessed across 11 categories as summarised in table 6.2. A range of measures are assessed for each category – as summarised below: Note: all categories are weighted equally. *Communication and warning* *1.5 (note poor communication and warning)* *Information and technology* *2.0* *Insurance* *3.0 (good insurance cover)* *Internal resources* *2.3* *Planning strategies* *2.1* *Clear recovery priorities* *2.5* *Proactive posture* *2.0* *Drills and response exercises* *3.2 (note well prepared)* *Funding* *1.7 (note poor funding)* *Situation awareness (sensing)* *1.5 (note poor ability to sense new hazards)* *Learning* *2.5*  Overall change readiness score of 2.7 (high).
	Networks: Networks are assessed across three categories as summarised in table 6.2. A range of measures are assessed for each category – as summarised below: Note: all categories are weighted equally. *Breaking silos* *3.0 (good score)* *Leveraging knowledge (internal and external)* *1.5 (poor score)* *Effective partnerships (external)* *2. 1*  Overall networks score of 2.2 (moderate).
	Leadership and culture: Leadership and culture is assessed across four categories as summarised in table 6.2. A range of measures are assessed for each category – as summarised below: Note: all categories are weighted equally. *Leadership* *3.0 (good score)* *Staff engagement and involvement* *3.0 (good score)* *Decision making authority* *3.0 (good score)* *Innovation and creativity* *2.0*  Overall leadership score of 2.8 (high).
Summary	As a result of the assessment the following aggregate scores are produced: Technical: 2.1, Organisational: 2.6 **Overall resilience score: 2.3**  While both scores are near the middle of the range, this indicates the priority may be to invest in the technical response. However, there are significant areas for improvement across both technical and organisational. While this is a fictitious example, it clearly illustrates the usefulness in being able to: 1 Interrogate individual scores to explain/understand the outcomes 2 Clearly communicate areas for improvement 3 Generate an overall resilience score to give a broad understanding.

8.2 Asset, hazard-specific assessment

In order to illustrate an example relevant to a particular asset, and for a given hazard type, it is useful to expand on the above example. We have not presented an entirely new assessment, as this would give little value. We have, however discussed what the additional steps and considerations would be in this situation.

Table 8.2 Example hazard-specific assessment

Assessment context and approach	Asset, hazard-specific, pre event. Assessment to be undertaken as per figure 7.2, and consisting of an initial criticality and risk assessment to determine 'desired' level of resilience, followed by resilience assessment.
Assessment example	Major connecting road to port, determined as a highly critical asset. Hazard to assess is flooding.
Risk assessment	Risk implication of flooding includes: • damage to pavement or other assets (eg embankments, structures, drainage assets etc) • transport delays of goods from facilities to the export port, as well as delays to general traffic • short-term loss of port access leading to increased service disruptions due to increased maintenance regimes • back-up of goods that cannot leave or access the port generating a financial burden on importers and exporters • increased coastal flooding from extreme rainfall events and sea level rise as water cannot drain into the sea due to outfall pipes being below sea level. Risk assessment as per the Transport Agency risk tool generates an 'extreme risk' score (requires urgent attention). Therefore a 'very high' level of resilience is required.
Technical resilience assessment	A similar assessment would be undertaken as per the previous example; however, questions would relate to the specific asset in question, and the specific hazard (flooding) being assessed. No further detail is provided.
Organisational resilience assessment	A similar assessment would be undertaken as per the previous example; however, questions would relate to the organisation's ability to respond to the specific hazard (flooding) being assessed, and the specific type and location of the asset. No further detail is provided.
Summary	As a result of the assessment it is assumed an identical score is produced as follows: **Overall resilience score: 2.3**  The desired 'very high' level of resilience is 4.0, and therefore interventions are required to improve the score, both in a technical and organisational sense. As discussed above, interrogation of the individual scores will identify where improvements can be made.

9 Conclusions and recommendations

9.1 Conclusions

The Transport Agency has a key interest in ensuring that transport infrastructure assets and services function continually and safely. This interest has led to a specific focus on the concept of resilience and how this can be defined, measured and improved across the transport system.

In a transport context, societies rely on transportation networks for their activities. The ability of the transport system to function during adverse conditions and quickly recover to acceptable levels of service after an event is fundamental to the wellbeing of communities.

The framework developed through this study gives effect to the guiding principle of resilience within the NIP and links to the NIP resilience attributes developed by the Treasury. It is applicable to the broad land transport system (road and rail), and allows assessments at various scales (asset/network/region). The assessment can be applied as both a non-specific 'all-hazards' approach or a 'hazard-specific' approach.

A key difference between these approaches is the incorporation of a risk assessment component. An all-hazards approach accounts for the unpredictability of future extreme events and emergent hazards. As these events are inherently unknowable, a likelihood of occurrence cannot be estimated, and as such, a risk assessment is not applicable. However, if specific hazards are well known and are required to be assessed, then a risk-based assessment can be undertaken.

A broadly qualitative framework was developed, which provides the user with a flexible, simple and practical tool to understand resilience of the transport system and as a result, prioritise investment decisions. The framework utilises the following dimensions and principles, developed from a variety of sources, and which encapsulate the key considerations both from a technical and, importantly, an organisational point of view.

Dimension	Principle
Technical	Robustness, redundancy, safe-to-fail
Organisational	Change readiness, networks, leadership and culture

The assessment process consists of a range of questions within each principle, and to which the user can assign scores. Each individual score can be weighted at the discretion of the user, and scores aggregated to the principle or dimension level if required. In addition, if applied at a regional level, the overall regional scores could be further summarised to give a picture of national resilience for use within NIU reporting.

Due to project constraints, detailed real-scenario testing of the framework was not undertaken (instead, a hypothetical example assessment was provided to illustrate the application of the framework). Specific operator knowledge of assets and the relevant organisations would be required to meaningfully undertake an assessment and it is recommended that this be considered as a subsequent stage.

9.2 Recommendations

A number of other improvements are suggested that may enhance resilience understanding and aid in the implementation of the framework. These are:

- Identify ways to improve understanding of critical infrastructure and factors which may determine criticality - from both an economic and societal point of view. These may include factors such as: providing access to critical infrastructure nodes (eg control centres or substations), access to critical community facilities (eg hospitals), or sections of road that have no alternative routes.
- Undertake further economic and engineering research to better understand and quantify a suitable level of investment in technical (structural) resilience. This is generally where significant capital expenditure is required, and is difficult to justify when funding is limited. A recent Australian study *Building our nation's resilience to natural disasters* (Deloitte 2013) compared investment in pre-disaster resilience with post-disaster expenditure on relief and recovery – through a number of case studies. General findings showed that for a vast majority of pre-disaster resilience initiatives, the benefit–cost ratio was favourable, highlighting that the policy response to building resilience to natural disasters must focus on prevention. Similar work is required in a New Zealand context.
- Improve understanding of linkages between resilience and sustainability. To date, conversations around infrastructure resilience have occurred largely in isolation of those which occur around sustainability. However, it is clear that many resilience measures are also measures that may be implemented to improve sustainability (such as green infrastructure, decentralised systems). Bringing the two fields of study together may lead to improved outcomes for both and should be explored further in both an academic and practical sense.

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Appendix A: NZ Transport Agency risk tool

Table A.1 Consequence rating

The outcome to the organisation from the risk event if it is not mitigated/treated more than it is currently

		Minimal	Minor	Moderate	Major	Substantial
Category	**Sub-category**	**1**	**10**	**40**	**70**	**100**
Financial (operational/ capital funding)	–	Minor variance able to be absorbed within budget	$100,000 to <$1m	$1m to <$10m	$10m to <$50m	$50m+
Service delivery (processes/ outputs	**Highway network efficiency**	Highway outage resulting in addition of <30k vehicle-minutes on the affected route	Highway outage resulting in additional 30k–300k vehicle-minutes on the affected route	Highway outage resulting in additional 0.3m–3m vehicle-minutes on the affected route	Highway outage resulting in additional 3m–30m vehicle-minutes on the affected route	Highway outage resulting in addition of >30m vehicle-minutes on the affected route
	Highway network availability	Highway outage resulting in addition of <40k vehicle-minutes on an alternative route	Highway outage resulting in additional 40k–400k vehicle-minutes on an alternative route	Highway outage resulting in additional 0.4m–4m vehicle-minutes on an alternative route	Highway outage resulting in additional 4m–40m vehicle-minutes on an alternative route	Highway outage resulting in additional >40m vehicle-minutes on an alternative route
Reputation (customer/ intermediate outcomes)	**Customer relationships** (includes internal or external customers)	Minor disagreement with customer/ community stakeholder	Relationship issues with customer group/community stakeholder	Ongoing relationship issues with customer group/community stakeholders	Strained relationships with customer group/community stakeholders requiring independent arbitration	Breakdown in relationships with customer group/community stakeholders resulting in public impasse
	Media exposure	Local media coverage for one day	Local media coverage for one to five days	Regional media or short-term (days) national media coverage	Sustained national media coverage (weeks)	Sustained national media coverage (months) or international media coverage
	Ministerial interest	Ministerial comment that is successfully resolved	Negative feedback from Minister requiring executive response/official information requests	Parliamentary/ministerial questions	Potential for loss of ministerial confidence/formal enquiry by AOG or statutory agency	Loss of ministerial confidence/Commission of Inquiry/sacking of Board or intervention by Minister
Asset and infrastructure integrity and maintenance		No damage to asset or need for changes to the maintenance regime	Localised asset damage, such as temporary flooding of a road or expansion of rail track due to hear. No permanent damage. Some minor restoration work required. *Infrastructure will need to be renewed 5% earlier than its original life expectancy	Widespread damage to assets such as structural damage to bridge due to a storm event or washout of a road due to intense rainfall. Damage recoverable by maintenance and repair. Partial loss of local asset or infrastructure. Infrastructure will need to be renewed 15–50% earlier than its original life expectancy. Significant increased	Extensive infrastructure damage requiring extensive repair. Permanent loss of regional infrastructure services, eg a port facility washed away by a storm surge. Infrastructure will need to be renewed 15–50% earlier than its original life expectancy. Significant increased maintenance requirement	Permanent damage and/or loss of infrastructure service across extended region or country, eg permanent inundation and erosion of a critical transport route due to sea level rise and storm surge event. Retreat of infrastructure and asset.

Table A.2 Likelihood rating

The probability of the worst consequence occurring

	Rare	Highly unlikely	Unlikely	Possible	Likely
Description	1	2	3	4	5
Frequency	Consequence may occur in exceptional circumstances (11+ years)	Consequence may occur in the next 6-10 years	Consequence may occur in the next 3-5 years	Consequence is expected to occur in the next 1-2 years	Consequence is expected to occur in the next 12 months
Probability	Probability <1%	Probability 1-9%	Probability 10-19%	Probability 20-50%	Probability greater than 50%

Table A.3 Risk rating

	Likelihood				
	Rare	Highly unlikely	Unlikely	Possible	Likely
Consequence	1	2	3	4	5
Substantial 100	2 (100)	3 (200)	3 (300)	4 (400)	4 (500)
Major 70	2 (70)	2 (140)	3 (210)	3 (280)	4 (350)
Moderate 40	1 (40)	2 (80)	2 (120)	2 (160)	3 (200)
Minor 10	1 (10)	1 (20)	1 (30)	1 (40)	1 (50)
Minimal (1)	1 (1)	1 (2)	1 (3)	1 (4)	1 (5)

Table A.4 Risk scores

Risk score	1	2	3	4
Risk description	Low risk Risk is tolerable	Moderate risk Risk requires attention	High risk Risk requires close attention	Extreme risk Requires urgent attention

Appendix B: Resilience assessment example

This fictitious example, set out in this appendix, is characterised as follows:

- A regional event (significant physical damage to transport infrastructure, coupled with severe disruptions to other lifeline services such as electricity, water and telecommunications).
- An organisation that has experienced a few major disasters some time ago and has some resilience responses in place but is just starting to re-invigorate its resilience preparation and integration.

Table B.1 Summary dashboard for resilience scores

Change weightings as required in blue cells
Check total weightings add to 100%

Score: 4.0 = Very high (3.51 – 4) | 3.0 = High (2.51 – 3.50) | 2.0 = Moderate (1.51 – 2.50) | 1.0 = (0 – 1.50)

			Category score				Principle score				Dimension score				Total resilience score
	Dimension	Principle	Category	Average score	Weighting	Weighted score	Principle	Average score	Weighting	Weighted score	Dimensions	Average score	Weighting	Weighted score	
Summary resilience assessment	1. Technical resistance	Robustness	Structural	2.8	33%	94	Robustness	2.3	33%	76	Technical resilience	2.1	50%	105	2.3
			Procedural	2.0	33%	67									
			Interdependencies	2.0	33%	67									
		Redundancy	Structural	2.0	33%	67	Redundancy	2.0	33%	67					
			Procedural	2.0	33%	67									
			Interdependencies	2.0	33%	67									
		Safe to fail	Structural	2.0	50%	100	Safe to fail	2.0	33%	67					
			Procedural	2.0	50%	100									
								Check (100%)	100%						
	2 Organisational resilience	Change readiness	Communication and warning	1.5	9%	14	Change readiness	2.7	33%	90	Organisational resilience	2.6	50%	128	
			Information and technology	2.0	9%	18									
			Insurance	3.0	9%	27									
			Internal resources	2.3	9%	21									
			Planning strategies	2.1	9%	19									
			Clear recovery priorities	2.5	9%	23									
			Proactive posture	2.0	9%	18									
			Drills and response exercises	3.2	9%	29									
			Funding	1.7	9%	15									
			Situation awareness (sensing and anticipation)	1.5	9%	14									
			Learning	2.5	9%	23									
		Networks	Breaking silos	3.0	33%	100	Networks	2.2	33%	73					
			Leveraging knowledge (internal and external)	1.5	33%	50									
			Effective partnerships (external)	2.1	33%	70									
		Leadership and culture	Leadership	3.0	25%	75	Leadership and culture	2.8	33%	92					
			Staff engagement and involvement	3.0	25%	75									
			Decision making authority	3.0	25%	75									
			Innovation and creativity	2.0	25%	50									
								Check (100%)	100%			Check (100%)	100%		

Table B.2 Technical resilience

All-hazard assessment
Based on the principles of robustness, redundancy and safe-to-fail
Only score those elements that are relevant or of interest
Before beginning assessment, unfilter all cells and delete previous scores (to ensure no hidden cells are scored)

Select filter for asset/region, ie whether the assessment is for an asset or wider region (do not filter blanks)
At least one rating is required for each category
User to complete columns highlighted in blue only

Score				
Score	4.0 = Very high (3.51 – 4)	3.0 = High (2.51 – 3.50)	2.0 = Moderate (1.51 – 2.50)	1.0 = (0 – 1.50)

ROBUSTNESS									Weighted robustness score	2.3	
Category	**Measure**	**Filter: asset or regional (network) assessment**	**Item #**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/ justification**
Structural	Maintenance	Region		Effectiveness of maintenance for critical assets	Processes exist to maintain critical infrastructure and ensure integrity and operability – as per documented standards, policies & asset management plans (eg roads maintained, flood banks maintained, stormwater systems are not blocked. Should prioritise critical assets as identified.	4 – Audited annual inspection process for critical assets and corrective maintenance completed when required. 3 – Non-audited annual inspection process for critical assets and corrective maintenance completed when required. 2 – Ad hoc inspections or corrective maintenance completed, but with delays/backlog. 1 – No inspections or corrective maintenance not completed.	3.0	2.8	33.33%	94.4	
	Renewal	Region		Establish asset renewal plans and upgrade plans to improve resilience	Evidence that planning for asset renewal and upgrades to improve resilience into system networks exist and are implemented.	4 – Renewal and upgrade plans exist for critical assets, are linked to resilience, and are reviewed, updated and implemented. 3 – Renewal and upgrade plans exist for critical assets and are linked to resilience, however no evidence that they are followed. 2 – Plan is not linked to resilience and an ad hoc approach is undertaken. 1 – No plan exists and no proactive renewal or upgrades of assets.	4.0				
	Design	Region		Suitability/robust-ness of critical asset designs across region	Percentage of assets that are at or below current codes	4 – 80% are at or above current codes 3 – 50-80% are at or above current codes 2 – 20-50% are at or above current codes 1 – Nearly all are below current codes	3.0				
		Region		Condition of critical assets	Assessment of general condition of critical assets across region	4 – 80% are considered good condition 3 – 50-80% are considered good condition 2 – 20-50% are considered good condition 1 – Nearly all poor condition	3.0				
		Region		Location of critical assets in areas known to be vulnerable to a known hazard (eg land slip, coastal erosion, liquefiable land, etc)	Percentage of assets that are in zones/areas known to have exposure to hazards	4 – <20% have some exposure to known hazards 3 – 20-50% are highly exposed, or >50% are moderately exposed 2 – 50-80% are highly exposed 1 – 80% are highly exposed to a hazard	2.0				
		Region		Spare capacity of critical assets within region (in the event of partial failure, or surge in demand)	Percentage of critical assets with additional capacity over and above normal demand capacity	4 – 80%+ of critical assets have >50% spare capacity available 3 – 50-80% of critical assets have >50% available 2 – 20-50% of critical assets have >50% spare capacity 1 – 0-20% have spare capacity.	2.0				
Procedural	Standards/ codes	Region		Existence of design codes to address resilience issues and risks. Update codes/standards to include resilience design principles into modern methods and materials (part of ongoing updates)	Existence of applicable updated design codes for all physical assets – which incorporate resilient design approaches	4 – Codes exist, have been implemented, are up-to-date and are applicable to all asset types 3 - Codes have been developed and updated, however, not implemented 2 – Codes are in existence but not updated 1 – No codes	2.0	2.0	33.3%	66.7	

ROBUSTNESS continued									**Weighted robustness score**	2.3	
Category	**Measure**	**Filter: asset or regional (network) assessment**	**Item #**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/ justification**
Interdepend-encies (upstream dependencies only)	Supplier utility robustness	Region		Awareness of robustness issues (vulnerabilities) in supplier utilities	Supplier staff and NZ Transport Agency staff aware of robustness issues within suppliers utilities (power, telecom, other)	4 – Good awareness and have been followed up 3 – Some awareness 2 – Minor awareness 1 – No awareness	2.0	2.0	33.3%	66.7	
	Supplier utility procedures	Region		Suppliers have implemented procedures to measure/improve robustness	Evidence that suppliers have implemented procedures and improvements and that these are effective	4 – Suppliers have developed and implemented procedures and there is strong dialogue 3 – Initial dialogue and plans are being prepared 2 – Initial dialogue 1 – No action or evidence	2.0				

REDUNDANCY									**Weighted redundancy score**	2.0	
Category 1	**Category 2**	**Filter: asset or regional (network) assessment**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Structural	Network redundancy	Region		Availability and capacity of alternate route for critical assets that would probably not be affected by the specific hazard event	Percentage of critical assets within region that have alternate routes – that may not be affected, considering travel time difference and capacity	4 – 80%+ critical assets have alternate, unaffected routes with minimum travel time difference and similar capacity 3 – 50%+ have alternate routes with min travel time difference and similar capacity or 80%+ have alternate routes, however, involve greater travel time or have much lower capacity 2 – 20%+ have alternate routes with min travel time difference and similar capacity or 50%+ have alternate routes, however, involve significantly greater travel time or have much lower capacity 1 - <20% have alternate routes	2.0	2.0	33.3%	66.66	
	Alternate mode choice	Region		Availability of alternate mode choices within region	Existence of alternate modes serving critical elements of the regional network, considering accessibility and travel time difference	4 – Alternate modes exist for 80%+ of critical assets, with minimum travel time difference 3 – Alternate modes exist for 50-80% of critical assets, with minimum travel time difference 2 – Alternate modes exist for 20-50% of critical assets, with minimum travel time difference 1 – No alternate modes N/A – Provide no score					N/A
	Redundancy/ alternate routes and modes capacity	Region		Capacity that non-car modes have to accept a demand shift from car to other modes (eg rail/bus)	Capacity of alternate modes that may not be affected in relation to failure of the critical assets in the region being assessed	4 – Alternate, unaffected modes have >75% capacity of failed mode(s) 3 – Alternate modes have 50-75% capacity of failed mode(s) 2 – Alternate modes have 25-50% capacity of failed mode(s) 1 – Alternate modes have >25% capacity of failed mode(s) N/A - Provide no score					N/A
	Back up inventories and equipment	Region		Availability of back up equipment and replacement inventories available to respond to an event	Existence of plan/requirements for back up equipment relevant to different hazards and critical assets. Availability/readiness of back up equipment for deployment	4 – Requirements are well specified for different assets. Equipment is available and ready 3 – Requirements are well specified, however, not enacted 2 – Ad hoc approach 1 – No plan/requirements	2.0				

Procedural	Diversion and communication plans	Region		Diversion plans to alternate routes	Existence of robust, tested plans to establish diversions to alternate routes when failure of critical link occurs	4 – Plans are well specified for different assets. Systems are available, tested and ready 3 – Plans are well specified, however, not enacted 2 – Ad hoc approach 1 – No plan/requirements	2.0	2.0	33.33%	66.66	

REDUNDANCY continued							Weighted redundancy score	2.0			
Category 1	**Category 2**	**Filter: asset or regional (network) assessment**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Inter-dependencies	Supplier utility redundancy	Region		Awareness of redundancy issues (vulnerabilities) in supplier utilities. Do suppliers have sufficient system redundancy, resources, backup, materials, fuel etc to provide sufficient redundancy	Supplier staff and Transport Agency staff aware of redundancy issues within suppliers utilities (power, telecom, other)	4 – Good awareness and have been followed up 3 – Some awareness 2 – Minor awareness 1 – No awareness	2.0	2.0	33.33%	66.66	
	Supplier utility procedures	Region		Suppliers have implemented procedures to measure/improve redundancy	Evidence that suppliers have implemented procedures and improvements and that these are effective	4 – Suppliers have developed and implemented procedures and there is strong dialogue 3 – Initial dialogue and plans are being prepared 2 – Initial dialogue 1 – No action or evidence	2.0				

SAFE-TO-FAIL							Weighted safe-to-fail score	2.0			
Category 1	**Category 2**		**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Structural	Design	Region		Have safe-to-fail design approaches been considered in conjunction with robustness and redundancy design approaches (where considered relevant) for existing assets?	Evidence that safe-to-fail is considered across critical asset/route designs in the region and when planning for asset renewal and upgrades to improve resilience	4 – Design documentation shows consideration or incorporation of safe-to-fail approaches for >80% of critical assets where relevant. 3 – Design documentation shows consideration or incorporation of safe-to-fail approaches for >50%, <80% of critical assets where relevant 2 – No design documentation, however anecdotally safe-to-fail approaches will operate for >50%, <80% of critical assets wehre relevant. 1 – Safe-to-fail not considered at any stage	2.0	2.0	50.00%	100	
Procedural	Design	Region		Are safe-to-fail design approaches specified in design guidelines?	Evidence that safe-to-fail approaches are included within asset design codes and guidelines	4 – Design codes and guidelines consider safe-to-fail approaches explicitly for all assets 3 – Design codes and guidelines consider safe-to-fail approaches implicitly 2 – Safe-to-fail approach not included, but plans are to incorporate in near future 1 – Safe-to-fail not considered at any stage	2.0	2.0	50.00%	100	

Table B.2 Organisational resilience

All hazard assessment
Based on the principles of change resistance, networks, leadership and culture
Only score those elements that are relevant or of interest
Measure can apply to both asset or network/region
At least one rating is required for each category
User to complete columns highlighted in blue only

Score	4.0 = Very high (3.51 – 4)	3.0 = High (2.51 – 3.50)	2.0 = Moderate (1.51 – 2.50)	1.0 = (0 – 1.50)

CHANGE READINESS						Weighted change readiness score			2.7	
Category	Measure	Item#	Item measured	Measurement	Measurement scale	Individual score	Category average	Weighting (%)	Weighted score	Note/justification
Communication and warning	Early warnings		Existence and effectiveness of early warning systems, where applicable (ie where technology allows). Means to warn travellers of problems and let them know transportation options	Length and reliability of warning – ability to take practical action (note a score of 4 will be essentially impossible, given unpredictability of some hazards).	4 – Warning systems exist for all known hazards and will allow time for reaction 3 – Some hazards excluded (eg earthquakes) and warning time may not be adequate. 2 – Ad hoc warning systems 1 – No warnings	2.0	1.5	9.10%	13.7	
				Reach of warning – will 100% of population receive it?	4 – 100% reached 3 – >75% reached 2 – > 40-75% reached 1 – <40% reached (or no warnings – see above)	1.0				
	Communication systems		Identify probable affected people, communication options and needs and devise a plan ahead of time. Ensure multiple/overlapping communication channel options so that information can keep flowing despite power or other communication failures.	Existence and reliability of multiple, independent communication for transportation staff and managers (under extreme conditions)	4 – Systems exist and have back up and have been tested 3 – Systems exist but have gaps and funding is not adequate 2 - Large gaps in system, untested 1 – No system	2.0				
				Existence and reliability of multiple, independent communication for transportation users (under extreme conditions)	4 – Systems exist and have back up and have been tested 3 – Systems exist but have gaps and funding is not adequate 2 - Large gaps in system, untested 1 – No system	1.0				
Information and technology	Sensors		Use of remote sensors/GIS hazard maps/crowd-sourced information to provide current information on asset state, hazards and impacts.	Defined methodology and information gathering mechanisms (crowd sourced) to input to an existing information platform.	4 - Documented methodology and established information platform 3 - Partial documentation and platform development 2 - Not documented but some knowledge of potential process 1 - No knowledge of or development of methodology or platform	2.0	2.0	9.10%	18.2	
	Backup		Ensure critical information (eg on structures, hazards, stores, contacts) is routinely backed-up	Documented procedure and evidence of back-up	4 - Back-ups taking place 3 - Documented procedure, occasional back- up 2 - Documented procedure, no back-ups 1 - No procedure, no back-ups	3.0				
	Up-to-date information		Ensure critical information (eg on structures, hazards, stores, contacts) is current and up to date	Routine review of critical information and systematic procedure for updating	4 - Up to date critical information readily available 3 - Ad hoc review, systematic procedure available 2 - Ad hoc review, no systematic procedure 1 - Critical information not up to date	1.0				

CHANGE READINESS continued							Weighted change readiness score	2.7		
Category	**Measure**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Insurance	Coverage		Ensuring appropriate insurance covers are in place prior to an event occurring. Make sure the risks are properly dimensioned.	Annual review of insurance covers aligned with identification of emerging threats	4 - Insurance in place, reviewed annually, risks suitably dimensioned 3 - Ad hoc review of insurance, draft process for addressing emerging threats/ hazards 2 - Ad hoc review of insurance, no process for addressing emerging threats/ hazards 1 - Insurance not in place and risks not dimensioned appropriately	3.0	3.0	9.10%	27.3	
	Information		Understand information requirements of insurers and ensure appropriate information will be available when required	Documented requirements of insurers with procedures and responsibility for updating information in place	4 - Requirements documented and available 3 - Requirements documented, no process in place for making available 2 - Requirements understood (not documented), no procedure or responsibility in place 1 - Requirements not understood, no procedure or responsibility in place	3.0				

Internal resources	Roles and responsibilities		Identification of key people at national, regional and local levels – including other network providers and the public and private sectors. Define roles/responsibilities ahead of events, including defining the 'lead' organisation for particular types of events	Presence of organisational structure and role definitions to achieve the required coordination, signed off by all participants, and operating effectively on the ground	4 - Implemented and operating 3 – Participants reviewing structure and definitions for sign off 2 – Structure and role definitions available, no participants identified 1 – No structure or role definitions available, no participants identified	2.0	2.3	9.1%	21.2	
			Succession planning and knowledge sharing to ensure continuity and skill level maintained for emergency and resilience planning	Process for identifying and developing internal people to fill key business leadership and strategic positions as they become available including mechanisms for coaching and knowledge transfer	4 – Key positions identified and individuals sharing knowledge and experience with successors 3 – Informal process of identifying positions and individuals with no formal mechanisms for knowledge sharing 2 – Ad hoc process 1 – No formal or informal succession planning or knowledge sharing	2.0				
	Internal coordination		Single point of coordination of all relevant pre-event activities, with clarity of roles and accountability	Presence of organisational structure and role definitions to achieve the required coordination, documented and signed off by all participants, and operating effectively on the ground	4 – Implemented and operating 3 – Participants reviewing structure and definitions for sign off 2 – Structure and role definitions being drafted for participant review 1 – No structure or role definitions available, no participants identified	2.0				
			Single point of coordination of all relevant event response activities, with clarity of roles and accountability	Presence of organisational structure and role definitions to achieve the required coordination, signed off by all participants and operating effectively on the ground	4 – Implemented and operating 3 – Participants reviewing structure and definitions for sign off 2 – Structure and role definitions being drafted for participant review 1 – No structure or role definitions available, no participants identified	4.0				
	Hazard-specific resources/ skills		Skills/tools/resources/training to deal with a complete range of hazards that may occur	Evidence that staff have skills/tools/resources/training to deal with a complete range of hazards that may occur	4 – Skills and tools exist for all hazards and are maintained/updated 3 – Skills and tools exist but not updated 2 – Only some hazards prepared for 1 – No preparedness	2.0				
	Remote response ability		Ability to respond to hazards in remote areas	Ability to respond to hazards in remote areas, or existence of decentralised response options	4 – Remote areas considered and response options in place 3 – Remote areas considered, however no action taken 2 – Ad hoc approach 1 – No preparedness	2.0				

CHANGE READINESS continued									Weighted change readiness score	2.7
Category	**Measure**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Internal resources (continued)	Staffing/ responder needs		Definition of staffing needs, availability. Availability of sufficient numbers of staff to respond in an event, to man planned shifts – allowing for inability to get to work, looking after families etc. Ensure these and other gaps have been addressed in planning	Staffing/responder needs are defined for range of hazard scenarios – allowing for inability to get to work, looking after families etc	4 – Needs defined, keyed to scenarios 3 – Some needs defined and keyed to scenarios but with gaps in definitions 2 – Needs are being drafted and scenarios being determined 1 – No needs defined (or no plan – see above)	2.0				
				Estimated shortfall in staff/responders per defined needs – potentially from multiple sources. MOUs exist for alternative sources, especially from private sector	4 – Staffing and responders known to be available in line with defined needs 3 – Some shortfalls 2 – Major shortfalls 1 – No definition – see above	2.0				
	Cross discipline training		Cross-train staff to perform critical management response/repair services	Training programme curriculum includes multi-discipline critical management and response/repair services; and if required training for specific staff	4 – Training programme implemented and staff able to perform cross discipline services 3 – Training programme available but gaps in curriculum 2 – Training not yet implemented but being drafted 1 – No training available	3.0				

Planning strategies	Risk assessment and scenario planning		Robust risk identification and risk assessment practices including scenario planning for unforeseen risks (including cascade failure, concurrent failure etc)	Existence of robust risk identification and risk assessment practices including scenario planning for unforeseen risks (including cascade failure, concurrent failure etc)	4 – Practices exist and are regularly followed, reviewed and updated 3 – Practices exist, however inconsistent 2 – Ad hoc approach is undertaken 1 – No plans	2.0	2.1	9.10%	19.3	
	Emergency management plans		Existence of emergency response plans	Existence of plans formulated to address hazard scenarios, shared and signed off by all relevant parties (including community organisations) and covering: - command and control – coordination with other agencies and cities, roles, responsibilities - evacuations (including hospitals, jails) - communication systems - critical asset management (including system of systems interactions) - first response - law and order/response - public information - incorporation of citizen organisations	4 – Complete plans exist, keyed to scenarios 3 – Plans exist but with some significant gaps 2 – Ad hoc plans being drafted 1 – No plans	2.0				
	Joint planning		Understand the emergency plans of others and the impact of their requirements on our network. Do Transport Agency LOS meet their critical needs? Consider cost-sharing possibilities	Review emergency plans for other agencies and sectors, identify required actions and incorporate into plans as required. Cost-sharing agreements in place for significant requirements by others	4 – Cross-sector and agency emergency plans linked and Transport Agency requirements documented, cost-sharing agreements 3 – Emergency plans linked, gaps in Transport Agency requirements, no cost-sharing agreements 2 – Cross-sector and agency emergency plans selected for review 1 – Emergency plans not linked, Transport Agency requirements unknown	3.0				

CHANGE READINESS continued						Weighted change readiness score	2.7			
Category	Measure	Item#	Item measured	Measurement	Measurement scale	Individual score	Category average	Weighting (%)	Weighted score	Note/justification
Planning strategies (continued)	Land use planning		Site specific risk assessment undertaken with regard to location of proposed infrastructure – to mitigate against potential hazards Consider where land use/regulation may help mitigate events, eg green belts to reduce the impact of floods, tsunamis/costal storms, berms, wetlands, flood walls, buffer zones and levees	Existence of land use planning approaches directed to address resilience and longer term sustainability issues	4 – Requirements are well specified and processes in place 3 – Some consideration is made 2 - Ad hoc approach 1 – No plan/requirements/processes	2.0				
	Identification of priority routes/ structures to manage first		Identify ahead of time probably priority routes/structures for response, rehabilitation and protection form further disaster. Include identification of priority lifelines sites and community facilities.	Contingency plan in place for alternative routes/structures require for response, rehabilitation and protection from further disaster	4 – Complete plan exists, keyed to scenarios 3 – Plan exists but with some significant gaps 2 – Ad hoc plan being drafted 1 – No plan	3.0				
	Debris management		Identify ahead of time probably nature of waste, storage sites, routes to storage sites, possible needs for consents/waivers	Waste management plan developed for wastes keyed to event scenarios and agreement with district/regional council regarding consents and/or waivers	4 – Complete plan exists, keyed to scenarios 3 – Plan exists but with some significant gaps 2 – Ad hoc plan 1 – No plan	2.0				
			Consider the possibility of hazardous waste and the need to separate different types of waste	Defined procedure (including PPE handling requirements) and disposal/collection locations for management of hazardous waste; understand Hazardous Substances and New Organisms (HSNO) Act 1996 requirements for permits and controls of potential hazardous materials/substances	4 – Procedure in place and addresses all items (see measurement) 3 – Procedure exists with gaps 2 – Procedure being drafted 1 – No procedure	1.0				
			Consider recycling, environmental responsibilities and options	Waste management plan details recycling options and environmental responsibilities specifically around resource use	4 – Recycling options understood and in waste management plan 3 – Gaps in recycling options and in defined environmental responsibility 2 – Options being identified and responsibility being drafter 1 – No waste management plan	2.0				

Clear recovery priorities	Roles and responsibilitie s		Where relevant identify and roster (for readiness) emergency team members	Emergency roles defined and assigned to specific team members; roster maintained and response tested through training drills	4 – Team members perform emergency roles well in training drills 3 – Emergency roles defined, team member negotiation in progress 2 – Ad hoc definition of emergency roles and team members 1 – No roster for emergency team members	3.0	2.5	9.10%	22.8	
	Prioritisation		Develop ways to prioritise the allocation of transportation system resources, eg systems to allow emergency services, public services, freight vehicles priority over general traffic during emergencies. Contingency plans to allocate fuel and resources	Prioritisation and resource allocation system established and tested for efficiency	4 – Efficient process for allocation and prioritisation of system resources 3 – Partial development of process, not tested 2 - Process identified for development 1 – No process for allocation and prioritisation of system resources	2.0				
	Equipment and other needs		Definition of equipment and supply needs, availability and training to use it	Equipment needs are defined for range of hazard scenarios	4 – Needs defined, keyed to scenarios 3 – Some needs defined and keyed to scenarios but with gaps in definition 2 – Needs are being drafted and scenarios determined 1 – No needs defined (or no plan – see above)	2.0				
				Estimated shortfall in available equipment per defined needs – potentially from multiple sources. MOUs exist for alternative sources, especially from private sector	4 – Equipment known to be available in line with defined needs 3 – Some shortfalls 2 – Major shortfalls 1 – No definition – see above	3.0				

CHANGE READINESS continued								Weighted change readiness score	2.7	
Category	**Measure**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Proactive posture	Advance agreements		Where relevant consider advance agreements for access (eg to private property or property owned by other public entities) construction, engineering, consulting, surveying, materials and equipment supply, telecommunications and broadcasting	Assess post event needs and put in place pre-event agreements for property access, supply of materials and specialist services (eg consulting, surveying)	4 – Comprehensive assessment of post event needs and agreements in place 3 – Some needs known and some agreements in place 2 – Some needs known, no agreements 1 – Needs unknown, no agreements	2.0	2.0	9.10%	18.2	
	Training drills		For enduring risks or low probability/high impact events affecting surrounding communities, consider linking disaster risk awareness to local community events in order to maintain an attitude of awareness and preparedness	Disaster risk awareness training implemented during community events for enduring or low probability high impact events	4 – Regular awareness training taking place keyed to scenarios 3 – Ad hoc awareness training, not keyed to scenarios 2 – Development of awareness training and scenarios – not implemented 1 – No training	2.0				

Drills and response exercises	Training/drills		Availability, take-up and effectiveness of training	Training offered and available to all identified and relevant staff	4 – Training 'curriculum' derived from known or anticipated needs available to all 3 – Ad hoc training classes address some issues for some areas of the city 2 – Ad hoc training classes with little relevance 1 – No training	3.0	3.2	9.10%	28.8	
				% of relevant staff trained in last year	4 – 80% or more trained in all subjects 3 – 40% or more 2 – 10% or more 1 – No training	4.0				
				Reinforcement of effectiveness training	4 – Refreshes and emergency drills city-wide 3 – Refreshers and emergency drills in some areas 2 – Ad hoc refreshers and emergency drills in minimal areas 1 – No validation	3.0				
			Post event planning – pre-event	Post event recovery plan exists detailing: - Interim arrangements for damaged facilities anticipated from hazard scenarios - Triage policies - Counselling and personal support arrangements - Community support arrangements - Economic 're-boot' arrangements – interim tax relief, incentives etc	4 – Plan exists and has contingency funding, plan addresses community needs 3 – Plan exists but has gaps and funding is not adequate 2 – Plan being drafted and funding options explored 1 – No plan	3.0				
			Practices and drills	Testing of plans annually, by reference to non-emergency events and through specific exercises including the public	4 – Annual suite of exercises with significant public engagement 3 – Less than annual exercises, some public engagement 2 – Plans in place, exercises yet to be implemented 1 – No exercises (or no plans – see above)	3.0				
			Develop and test a traffic management plan	Traffic management plan (TMP) for different event scenarios developed and tested through practice drills	4 – TMP tested and available 3 – TMP drafted, not tested 2 – TMP being drafted, significant gaps 1 – No TMP	3.0				

CHANGE READINESS continued								Weighted change readiness score	2.7	
Category	**Measure**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
	Capex availability		Capital funds (from multiple sources as applicable) are available for long-run engineering and other works required to build resilience	Presence of a prioritised, funded capital plan and priorities	4 – Plan exists and is 100% funded 3 – Plan exists but only 50% funded 2 – Ad hoc plan exists and partially funded 1 – No plan	2.0				
	Opex funding for resilience initiatives		Revenue funds (from multiple sources as applicable) are available and ring-fenced to meet all operating expenses and incentive payments required to build resilience	Presence of separately delineated budget line item and commitment to protect this in future years	4 – Budget exists and is 100% adequate for tasks at hand 3 – Budget exists but covers 50% of known tasks 2 – Budget exists 25% of known tasks 1 – No budget	2.0				
	Capex priorities		Priorities for investment $$ in resilience are clear and defensible, based on a view of most beneficial impact	Presence of a reasoned set of priorities in the capital plan based on resilience impact achieved	4 – Priorities exist and are argued coherently 3 – Priorities exist but rationale is generally unclear (or at least not explicit) 2 – Priorities and rationale under development 1 – No prioritisation – spending, if any, is haphazard	1.0				
Funding	Integration with resilience		Interaction between other initiatives and resilience	Every spending initiative is systematically reviewed for its potential to improve resilience	4 – Systematic review 3 – Ad hoc – often quoted 2 – Ad hoc – seldom quoted 1 – Not really mentioned	1.0	1.7	9.10%	15.2	
	Contingency funding		Contingency fund for post disaster recovery available, sufficient and able to be released quickly	Existence of a fund capable of dealing with estimated impacts from a 'most probable' scenario – and able to be released quickly	4 – contingency from 'most probable' scenario is estimated and 100% funded 3 – Fund exists but only at 50A% of estimated need (may be commitments from other agencies to supply the rest) 2 – Fund exists but only at 25% of estimated need (may be commitments from other agencies to supply the rest) 1 – No fund	3.0				
	Modelling		Model financial effects of events using different scenarios to ensure a broad range of options are considered and where relevant, prepared for (including considering the financial impact of multiple events occurring at the same time or close together; and the possibility of exhausting emergency funds)	Evidence of financial modelling having been undertaken, scope agreed and dissemination of results to relevant stakeholders	4 – Modelling undertaken and published 3 – Modelling undertaken 2 – Modelling scoped, not undertaken 1 – No modelling	1.0				

	Internal		Continuously expand understanding of emerging threats, 'black swan' events and adjust to the new threat environment	Established process (workshops) for identifying threats with minuted and documented actions for transport sector and across sectors	4 – Process implemented and outcomes documented 3 – Process implemented, no outcomes documented 2 – Process drafted, no outcomes 1 – No process	1.0				
	Sensing		New system stresses are efficiently and rapidly incorporated into current understanding – including new stressors, near misses etc. Ability to translate this to foresight and prediction of new hazards.	Existence of processes for encouraging, recording, reporting, communication new stressors and hazards	4 – Processes in place and well enacted and embedded in culture 3 – Processes new and non-enacted 2 – Ad hoc 1 – No process	1.0				
Situation awareness (sensing, anticipation, adaptation)			Staff are encouraged and rewarded for identifying warning signs, weak links or new hazard types	Existence of processes to reward staff for identifying new hazards, weak links and warning signs	4 – Processes in place and well enacted and embedded in culture 3 – Processes new and non-enacted 2 – Ad hoc 1 – No process	2.0	1.5	9.10%	13.7	
	Evaluation		Maintain ongoing transportation system evaluation to provide early detection of possible problems	Systematic and scheduled evaluation process implemented with problems identified and rectified	4 – Comprehensive evaluation process with mechanism for fixing problems 3 – Evaluation process, no mechanism for fixing problems 2 – Ad hoc evaluation, no mechanism for fixing problems 1 – No evaluation process	2.0				

CHANGE READINESS continued						Weighted change readiness score	2.7			
Category	**Measure**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Learning	External		Exposure of public to education and awareness materials/messaging	Coordinated PR and education campaign exists with structured messaging, channels, etc	4 – Systematic, structured campaign exists 3 – Some structure, not systematic 2 – Infrequent ad hoc campaign 1 – No campaign	2.0	2.5	9.10%	22.8	
				Validation of effectiveness via market research follow up	4 – Validation via comprehensive survey at completion of campaign 3 – Occasional structured validation not campaign specific 2 – Unstructured ad hoc validation 1 – No validation	2.0				
	Internal		Exposure of staff to education and awareness materials/messaging	Coordinated PR and education campaign exists with structured messaging, channels etc	4 – Systematic, structured campaign exists 3 – Some structure, not systematic 2 – Infrequent ad hoc campaign 1 – No campaign	3.0				
				Assessment/validation of effectiveness via market research follow-up with staff	4 – Validation via comprehensive survey at completion of campaign 3 – Occasional structured validation not campaign specific 2 – Unstructured ad hoc validation 1 – No validation	3.0				

Breaking silos	Internal relationships		Establishing face-to-face relationships during normal times to facilitate interactions during times of crisis	Established programme for face-to-face networking and interdepartmental working groups	4 – People know department roles and key individuals 3 – Networking programme established, no interdepartmental working groups 2 – Networking programme drafted, no interdepartmental working groups 1 – No opportunity for face-to-face networking nor interdepartmental working groups	3.0	3.0	33.33%	100.0	

Leveraging knowledge (internal and external)	Information sharing		Where there are critical dependencies and/or interdependencies in an event affecting multiple utilities/networks, consider the availability and accessibility of critical structural/design information for emergency management purposes, particularly where multiple entities will need access to the multi-sector information, ie a current cross-sector critical infrastructure register containing structural information important in a crisis/event	Information sharing taking place across sectors. Cross-sector critical infrastructure register containing structural information important in a crisis/event is up to date	4 – Up-to-date register exists and information is being shared 3 – Information sharing taking place, register is not up to date 2 – Some information sharing taking place, no register 1 – No information sharing	2.0	1.5	33.33%	50.0	
			Agree information sharing protocols with partners	Protocol documented and publicised	4 – Protocol documented and publicised 3 – Protocol documented, not publicised 2 – Partial protocol development, not publicised 1 – No protocol, not publicised	2.0				
			Agree information sharing protocols for public	Protocol documented and publicised	4 – Protocol documented and publicised 3 – Protocol documented, not publicised 2 – Partial protocol development, not publicised 1 – No protocol, not publicised	1.0				
	Inter-agency compatibility		Inter -operability of multiple systems – communications, fire hose diameters, emergency management systems, etc	Lack of unresolved incompatibility on major shared physical communications or IT systems	4 – Explicit efforts to ensure compatibility and no known incompatibilities 3 – At least one major incompatibility 2 – Multiple incompatibilities, no attempt to rectify 1 – No attempt to harmonise with one of more key agencies or adjacent governments	1.0				

CHANGE READINESS continued						Weighted change readiness score	2.7			
Category	**Measure**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
	Advance financial arrangements across sectors		For failures affecting more than one network, and/or where working with others to return functionality is critical, ensuring cost-sharing agreements/options and mechanisms for expediting rapid release of funds are in place ahead of an event occurring	Presence of cost-sharing agreements and mechanisms for quick release of emergency funds	4 – Agreements finalised for all sectors 3 – Agreements finalised for some sectors only 2 – Agreements in process 1 – No agreements	3.0				
	Inter-agency compatibility		Emergency operations centre	Existence of emergency ops centre with participation from all agencies, automating standard operating procedures (SOPs) specifically designed to deal with hazard/event scenarios	4 – Ops centre exists and was designed to deal with 'most severe'; all agencies participate 3 – Ops centre exists but may have shortcomings or may not have SOPs 2 – Ops centre exists, lack of participation, no SOPs 1 – No ops centre	2.0				
	Business continuity/ awareness		Understand the broad range of interdependencies (ie other network providers/utilities, supply chain considerations, access to life-line infrastructure etc). Work with those most likely to be affected by an event to ensure they understand risks and probably LOS and factor them into their own business continuity planning	Cross-sector and cross-agency working group meets regularly to: - understand interdependencies and incorporate into their respective business continuity planning - analyse major incident impacts on ageing infrastructure and resulting cascade effects undertake complex hazard planning with cross-sector partners and develop joint plans as appropriate	4 – Working group established and meets regularly, outcomes achieved 3 – Working group established, but no progress 2 – Working group members identified, not met 1 – No working group	2.0				
Effective partnerships (external)	External coordination		Effective coordination with other tiers of government and relevant councils and other agencies	Presence of organisation structure and role definitions to achieve the required coordination, signed off by all participants and operating effectively on the ground	4 – Implemented and operating 3 – Participants reviewing structure and definitions for sign off 2 – Structure and role definitions being drafted for participant review 1 – No structure or role definitions available, no participants identified	1.0	2.1	33.33%	70.4	
			Effective coordination and co-option of the private sector	Identification of pre-and post-event role definitions to achieve the required coordination, signed off by all participants, and operating effectively on the ground	4 – Roles defined and contribution agreements in place 3 – Roles and contributions being negotiated 2 – Process underway for defining roles and contributions 1 – Roles and contributions unknown	2.0				
			Understand how both network/utility specific events and more general events (storms, earthquakes etc) affect co-located networks/utilities. Consider direct, indirect and downstream impacts	Cross-sector working group to identify effects on co-located network/utilities and direct, indirect and downstream impacts	4 – Working group has identified effects and impacts 3 – Working group has formed but no effects or impacts identified 2 – Working group members identified, not met 1 – No working group and neither effects nor impacts identified	2.0				
	Interagency compatibility and cooperation		Establish relationships, mutual aid arrangements and regulatory partnerships	Signed agreements in place outlining air arrangements and regulatory responsibilities	4 – Signed agreement 3 – Agreement drafted, relationships established 2 – Negotiations and relationship building underway 1 – No contact established	2.0				
			Understands interconnectedness with community and community facilities	Community leaders and facility operators identified and consultation underway (eg workshops) to represent interconnectedness with community and community facilities in planning and management processes	4 – Community and facilities interconnectedness represented in planning and 3 – Partial representation and tentative connections identified – not tested 2 – Community leaders and facility operators identified – not yet consulted 1 – Unknown connections or relationship management processes	3.0				
			Understand vulnerabilities across all aspects of supply chain networks	Working group of network provider, freight companies (and/or industry associations) and primary manufacturers (national and regional) and vulnerabilities identified	4 – Working group has identified vulnerabilities and meets regularly to review 3 – Working group identified and first meeting organised 2 – Working group members identified, no meetings 1 – No working group established	2.0				

LEADERSHIP AND CULTURE					Weighted leadership and culture score	2.8				
Category	**Measure**	**Item#**	**Item measured**	**Measurement**	**Measurement scale**	**Individual score**	**Category average**	**Weighting (%)**	**Weighted score**	**Note/justification**
Leadership	Roles and responsibilities		Assign specific resources to resilience planning and implement improvements when it makes sense to do so	Defined responsibilities and roles for resilience planning (including KPIs) with regular meetings and documented process for implementing improvements	4 – Resilience planning resourced and improvements implemented 3 – Partial resourcing of resilience planning, improvements not implemented 2 – Resilience planning being defined and responsibilities assigned 1 – No resourcing to resilience planning	3.0	3.0	25.00%	75.0	
	Leadership		Leaders think and act strategically and model resilience attributes. Ongoing promotion of a resilience culture within the organisation	Existence of ongoing management and leadership initiatives to model and encourage resilience culture	4 – Culture exists/embedded and is maintained 3 – Culture is developing 2 – Culture is absent, but plans in place to improve 1 – No resistance culture	3.0				
Staff engagement and involvement	Awareness		Staff are aware of and regularly involved in internal resilience discussion/training/exercises. Staff are aware of importance of vigilance and are aware of processes.	Level of engagement and awareness within staff.	4 – Staff highly involved and aware 3 – Staff moderately involved and aware 2 – Ad hoc 1 – No awareness	3.0	3.0	25.00%	75.0	
	Engagement		Staff are encouraged to challenge and develop themselves through their work and are rewarded for thinking outside of the box	Leadership, innovation, personal development are encouraged and actively promoted. Clear leadership from senior staff, and attributes are visible and understood	4 – Clear leadership at senior level, and company attribute visible, recognised and understood by over 80% of staff. 3 – Clear leadership and company attribute recognised by over 50% of staff 2 – Attributes are recognised by 2-% to 40% of staff 1 – Not part of company culture	3.0				
Decision-making authority	Crisis decision making		Procedures in place to assign authority to make quick decisions, reduce red tape – in relation to deployment of staff and resources as well as response decisions	Procedures and roles established to reduce red tape and allow quick decision making	4 – Procedures and roles agreed and in place for all elements 3 – Some procedures and roles agreed, not for all elements 2 – Ad hoc 1 – No procedures	3.0	3.0	25.00%	75.0	
	Advance agreements		Pre-event agreements help to mobilise required personnel, services and resources immediately after an event	Required personnel, services and resources identified and agreements in place for post-event response	4 – Agreements in place 3 – Some agreements, not for all services or resources 2 – Very few agreements 1 – No review of resilience benefits	3.0				
Innovation and creativity	Approach to projects		Extent to which any proposal/project in the Transport Agency is evaluated for resilience benefits	Explicit stage in policy and budget approval process where resilience benefits of any Transport Agency project/initiative are identified and counted towards the Registration of Interest for that proposal	4 – Documented and demonstrated review of resilience benefits in project development phase 3 – Documented review with inconsistent application 2 – Process not defined and may or may not be included in review 1 – No review of resilience benefits	2.0	2.0	25.00%	50.0	
	Processes to foster new resilience thinking		Existence of processes to foster new and innovative thinking about resilience and new approaches to building it across the network	Existence of processes and perceived level of application, adopted by staff	4 – Processes exist and consistently and regularly applied 3 – Processes exist but inconsistent application 2 – Process are ad hoc 1 – No processes	2				

Appendix C: Resilience, vulnerability and sustainability

C1 Resilience and sustainability

> *The sustainability of a system is a measure of its lifespan. Resilience is one measure of the potential sustainability of a system; so, resilience is to sustainability what, say, blood pressure is to health. Since resilience is a component of sustainability, the opportunity should exist to do both things simultaneously (*McRoberts 2010).

Much research has been undertaken regarding the linkages between sustainability and resilience, and in a variety of different contexts – such as green growth, urban design and land-use planning. Beatley (1998) suggests 'a sustainable community is a resilient one; it is a community that seeks to understand and live with the physical and environmental forces present at its location'. Saunders (2010) highlights the importance of sustainable urban design, land-use planning and building codes in delivering resilient communities.

Beatley goes on to state we have created unsustainable and non-resilient communities by:

- directly placing people and property in harm's way – by constructing in known hazard-prone areas (floodplains, coastal areas subject to storm surge, unstable land)
- indirectly placing people and property in harm's way – by damaging ecosystems and altering natural landscapes (draining wetlands, levelling sand dunes).

And Godschalk (1999) proposes: 'To sustainability's economic, environmental protection, and social criteria is added a fourth criterion – sustainable development must be resilient to the natural variability of the earth'.

Given the large and arguably incontrovertible weight of evidence pointing to humanity's influence on global warming and climate patterns, and our on-going modification and destruction of ecosystems and landscapes, it is clear that unsustainable practices have resulted in many communities being non-resilient and vulnerable.

Mitigation, by way of halting or reversing these unsustainable practices, is an obvious approach that is advocated by many, however for a variety of reasons have, to date, been unsuccessful.

Adaptation, therefore, has risen to prominence, which perhaps has at its core a belief that our unsustainable practices can continue, meaning communities will remain vulnerable; however; we can adapt and 'engineer' to build resilience nonetheless.

Grubinger (2012) argues there are in fact three responses:

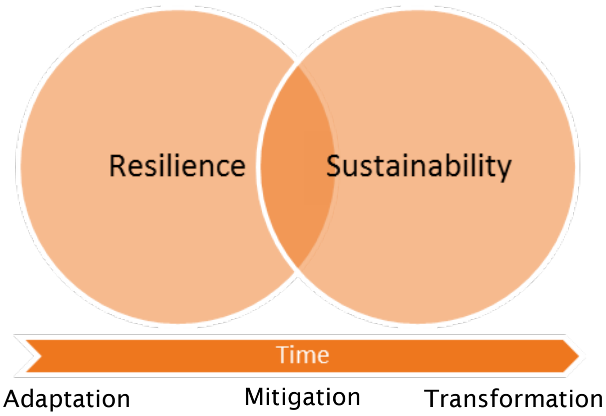
1 Over the short term (adaptation)

2 Medium term (mitigation, by way of reducing the extent of the problem)

3 Long term (transformation, ie solving the problem).

He goes on to relate each time scale to the concepts of sustainability and resilience through the diagram given in figure C.1.

Figure C.1 Resilience and sustainability



Source: Grubinger (2012)

C2 Resilience and vulnerability

Vulnerability has been defined as the measure of how susceptible a system or asset is to a hazard (caused by an event or gradual changes over time) and implies that sensitivity, exposure and adaptive capacity have been considered (Levina and Tirpak 2006; AECOM et al 2011). There is much in the literature regarding vulnerability and resilience and how the definitions relate to, or counter each other.

Vulnerability can be described as a deficit concept (Malone 2009) and so resilience and vulnerability could be considered as two ends of a spectrum (Levina and Tirpak 2006) with resilience being a positive measure. Folke et al (2002) termed vulnerability the 'flip-side' of resilience.

On the other hand, vulnerability can be viewed as a component of resilience (Maguire and Cartwright 2008), or indeed as suggested by Brabhaharan (2006), resilience a function of vulnerability (and other factors). Therefore it can be said that the infrastructure can be assessed as vulnerable but still have a level of resilience due to other influencing organisational, financial and social dimensions.

Gallopin (2007) undertook significant research into the linkages between resilience and vulnerability, and comments that 'a resilient system is less vulnerable than a non-resilient system, but the relation does not necessarily imply symmetry'. He also points out that depending on definitions used, there is considerable overlap in the concepts of resilience, vulnerability and adaptive capacity. He concluded that, 'vulnerability, resilience, and adaptive capacity are related in non-trivial ways. If care is not used, the field of human dimensions research can become epistemologically very messy'.

Despite the on-going academic debate around definitions, for this study we adopted a definition of vulnerability as follows, adapted from UNDRO (1980) and UNISDR (2004).

> *Vulnerability refers to the propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events.*

Vulnerability is often assessed in terms of exposure (the degree to which a system is exposed to a hazard), sensitivity (the nature and degree to which a system is affected by a hazard), and adaptive capacity (the ability of a system to adjust and moderate potential damages and cope with consequences).

It is noted that adaptive capacity affects a system's vulnerability through modulating both exposure and sensitivity to a hazard. That is, the higher the adaptive capacity of a system, the lower the influence of the exposure and sensitivity components, and as such, vulnerability is reduced (Engle 2011).

Appendix D: Criticality

D1 Critical infrastructure

In New Zealand, critical infrastructure is essential to the functioning of society and the economy. The management of critical infrastructure involves an understanding of lifeline infrastructure as defined by the Civil Defence and Emergency Management (CDEM) Act 2002, the principles and practices of asset management, including principles of risk management, and the interdependencies of critical infrastructure.

The fundamental first step in building resilience in infrastructure systems is to understand the criticality of the system itself and the various elements within a system, so efforts can be prioritised.

While no clearly defined or widely agreed definition exists in New Zealand for critical infrastructure, a number of frameworks exist that help determine criticality. The principle framework used in New Zealand is included within the *International infrastructure management manual* (NAMS 2011).

D1.1 Transportation context

The NZ Transport Agency has developed a state highway classification system which categorises national highways into five groups: national strategic high volume, national strategic, regional strategic, regional collector and regional distributor. Sections of highway are classified according to meeting a range of established criteria relating to: freight volume, annual average daily traffic flows, route to major centre of population, access to ports for freight, access to airports for passengers and importance for tourist traffic. It is noted that other land transport operators (eg rail) and local authorities will likely have their own systems for determining criticality.

Other criteria have also been suggested for evaluating criticality. URS (2005) summarised interviews with a range of key transport sector organisations and noted the following as factors which affect or determine the 'criticality' of transport assets (and which relate directly to the consequences or impacts of failure). Assets which were considered critical included those that:

- carry high volumes of traffic or freight (this would include most rail routes and major highways, port access)
- are vital to social/economic wellbeing
- have no other alternate route
- provide access to other critical infrastructure
- provide linkages between transport modes (eg the link span between road and rail as part of the inter-island ferry service)
- are control centres (such as the train control centre in Wellington)
- are sections of network that are critical to commercial imperatives for operators or users
- are critical to maintaining law and order, or national security.

The Victoria Transport Policy Institute (VTPI) (2010) provides additional thinking, from which the following can be added:

- provide for emergency response (police, fire, medical services, disaster relief)

- provide for operation of public services (utility repair and maintenance, waste collection etc)
- commercial and business travel
- high-value personal errands (basic shopping, medical)
- commuting (work and school).

Finally, the following criteria are also worth consideration, as they play an important part in understanding criticality from an organisational point of view:

- level of liability and financial exposure
- reputational risk and governance requirements.

The above criteria form a non-exhaustive list of factors affecting criticality for transport systems. The importance of criticality in developing a resilience assessment framework is discussed further in the body of the report.

D2 Lifelines infrastructure

In a New Zealand context, lifelines infrastructure has been defined as part of the CDEM Act 2002. This Act sets out which sectors are considered as critical lifeline infrastructure (utilities) and includes: transport, water, wastewater, stormwater, energy and telecommunications services. These organisations provide essential community functions and enable them to respond and provide for the wellbeing of their residents when hazards occur.

The CDEM Act requires lifeline utilities to:

- function to the fullest possible extent during and after an emergency
- have plans for such functioning (continuity) that can be made available to the Director of the Ministry of Civil Defence & Emergency Management
- participate in CDEM planning at national and regional levels where requested
- provide technical advice on CDEM issues where reasonably required.

Critical lifelines infrastructure has been identified in a number of New Zealand regions by the relevant regional lifelines group in coordination with lifeline utilities – using risk management approaches and ‘levels of criticality’. These groups focus on ‘enhancing the connectivity of lifeline utility organisations across agency and sector boundaries in order to improve infrastructure resilience’.

To achieve this, organisations within lifeline groups have identified infrastructure which is critical to the provision of services during events, and through this, infrastructure ‘hotspots’ and ‘pinchpoints’ have been identified. Hotspots are geographical locations where multiple utilities are co-located, where there is exposure to hazards, and where collaboration is likely required to mitigate risk. Pinchpoints are those locations within an infrastructure sector where there is a particular weakness or vulnerability.

Appendix E: Hazards, rare events and failure modes

The following sections discuss a) general types of hazards and how they relate to the transport system, b) 'rare' events and how these can be characterised and assessed and c) consideration of linear and non-linear failure modes.

E1 Hazards

In general, 'hazards' can be categorised into three types: natural, technological, or social/political in nature. In addition, these can be further broken down into 'stress' events, that are long-term and gradual change processes, and 'shock' events, that are short-term and sudden change processes. These shock events are by definition, largely unpredictable and more difficult and costly to plan for.

Stress events can either be hazards in their own right (eg gradual degradation of the condition of the assets over time due to changing climatic conditions such as sea level rise), or contributors to increased frequency and severity of 'shock' hazards. An example is increased rainfall intensity due to climate change, causing exacerbated flooding.

In the context of New Zealand transport infrastructure, some relevant work has been undertaken by Gordon and Matheson (2008) and Seville and Metcalfe (2005) to identify and quantify hazards to the transport system. Seville and Metcalfe (2005) provide detailed information about the cause of each hazard type, the key research carried out, and the consequences for and vulnerability of the state highway network to each hazard.

Gordon and Matheson (2008) built on this previous work and undertook a broad assessment of the relative probability, consequences and the level of risk exposure to a range of hazards on a regional basis across New Zealand. Numerical ratings were assigned to each type of hazard and its consequence, and these were combined to form an overall risk exposure rating.

Table E.1 summarises the range of transport-related hazards considered in these previous studies and includes others of relevance, categorised into shock and stress events for each general hazard type.

Table E.1 Summary of transport-related hazards

Hazard	Shock hazard	Stress hazard
Natural	Seismic events, volcanic events, landslides (and avalanches), flooding, snow and ice, tsunamis, wildfire, storms.	Climate change related hazards (sea level rise, waves, storm surge, increased temperature and rainfall, more intense storm events).
Technological	Failure or malfunction of key infrastructure such as computer or telecommunication systems, major accident, planned closure for maintenance	Congestion of transport networks. Scarcity of resources such as oil.
Social/political	Terrorist event, strike of staff, major accident or action resulting in road closure (eg public event), loss of public confidence in infrastructure safety	Growth, repair (human) resources unavailable over time.

Gordon and Matheson (2008) further define potential hazards to the transport network and their level of impact as shown as an example in table E.2. This table does not, however, illustrate interdependencies with other lifeline infrastructure and potential cascade failure. It is important that interdependencies and cascade failures are considered in hazard scenarios.

Table E.2 Infrequent hazard events, which would be unlikely to occur within a 100-year period, but typically with significant consequences

Hazard type	Description of hazard and effects	Impact on road transport
Flooding	• Very severe flooding in one or several river catchment systems and associated plains • Major stopbank failure(s) or overtopping adjacent to urban areas	• Severe disruption, typically in a single and/or neighbouring region(s) • Many bridges and approaches damaged with major washouts • Roads submerged for more than one week • Areas isolated and/or detours may be required for many weeks to months because of damage
Meteorological	• Extreme storm event involving wind and/or rain, very heavy snowfall	• Unsafe to drive road closures and disruption during the event of a week or more • Limited asset damage but more significant if is associated with landslides
Coastal	• Very high waves with wind and storm surge, possibly major cyclone • Long-term coastal changes may result from the event Large scale tsunami which inundates low lying land over an extensive part of the coastline	• Road inundation, washouts and bridge damage, with disruption effects lasting several weeks to months
Landslide	• Large earthquake generated avalanches and landslides in hill country • Earthquake after heavy rainfall	• Closure of alpine and hill country routes for weeks to months • Local but significant asset damage which can take many months to restore
Seismic	• Large magnitude earthquake within a region	• Total closure of some routes for weeks to months due to damage to structures • Very significant asset damage
Volcanic	• Large quantities of ashfall and debris	• Potential closure of large parts of the road network within a region. Very disruptive if activity is prolonged

Source: Gordon and Matheson (2008)

This detailed work undertaken by Gordon and Matheson (2008), Seville and Metcalfe (2005) and Gardiner et al (2008), as well as relevant lifelines studies all contribute to a relatively comprehensive picture of:

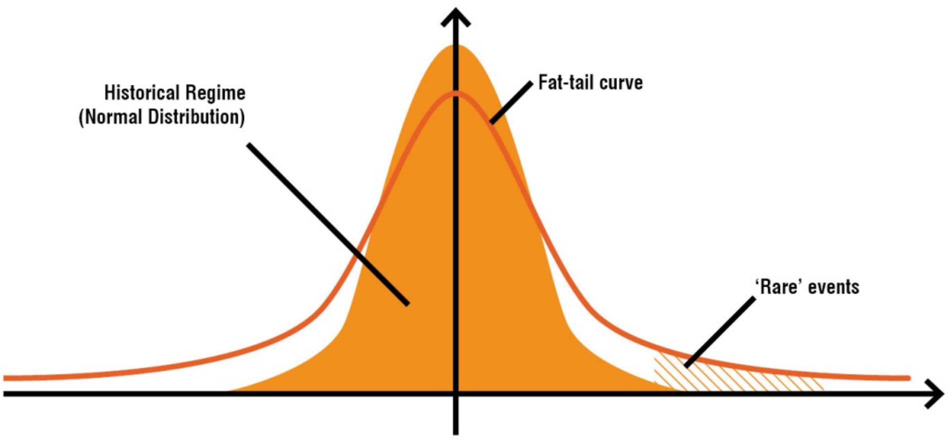
- types and mechanisms of different hazard events, including where and why they occur, and the probability of them occurring in the future
- methods to estimate the vulnerability of transport assets, or recommended sources of data to aid in such an assessment.

As such, it is recommended that these studies, along with the Transport Agency's own understanding of hazards on the roading network form the basis of the understanding of hazard likelihood and consequence when assessing risk and resilience.

E2 Rare events

There is a growing body of evidence that historical analysis of extreme events and their probability distributions fail to correctly predict extreme events. Historically, random extreme events have been assumed to follow a normal distribution with 95% of possible events falling within two standard deviations from the mean and 99.7% within three standard deviations. In fact, it is becoming apparent that events which may be at the extreme end of a normal distribution are occurring with much greater frequency than predicted (Mello 2005; Berger et al 2008). Not only is the frequency of these events often significantly underestimated, so is the damage they can cause. This is demonstrated via a 'fat-tail distribution' as shown in figure E.1.

Figure E.1 Fat-tail distribution of hazard events



Taleb (2008) named these rare events 'black swans', and developed three characteristics to describe them:

1 They lie outside the realm of regular expectations, because nothing in the past can convincingly point to their possibility.

2 They carry an extreme impact.

3 In spite of their outlier status, human nature causes people to concoct explanations for the occurrence after the fact, making it explainable and predictable.

Other terms that exist for these events include: 'unknown-unknown' events (Donald Rumsfeld), and 'high consequence, low likelihood' events. Research on how to assess and manage these events generally falls into one of two categories:

1 These events are inherently unknowable unless and until they happen, when they become obvious with hindsight. Therefore, they cannot be planned for using a standard risk assessment process (Hillson 2013).

2 These events are foreseeable and should be included in a risk assessment approach as high consequence, low likelihood, and as such, measures to mitigate/respond to the impacts can be developed.

In the context of critical infrastructure protection, an assessment of rare events is useful in directing the infrastructure utility to think the unthinkable, consider the combinations of events that might occur, consider what is happening elsewhere (horizon scanning), to be more creative in risk identification and identify events that might be known by others but a ‘black swan’ or an ‘unknown-unknown’ to the organisation conducting the resilience assessment.

These rare events could include a range of extreme stand-alone events (for example, cyber attack that takes over the traffic control systems or a hostage crisis causing closure of roads). They could also include a combination of multiple unrelated hazards (concurrence), failure within the infrastructure network itself, caused by a failure of an upstream dependency (cascade failure). These failure modes are discussed further below.

E3 Modes of failure

The transportation system can be described as a complex system, or ‘system of systems’. This is due to the range of interdependencies involved, and leads to a wide range of possible failure modes. Some of these may fall into the black swan category as discussed earlier.

It is not the intention of this paper to explore failure modes in detail; however, in general there are a number of main failure modes that should be considered when assessing the impact of hazard events. These include simple, linear failure, complex-linear failure and complex, non-linear failure (Hollnagel 2011).

Table E.3 Failure modes

Failure mode	Description	Potential (typical) response examples
Simple, linear failure	Simple, linear failure (or domino/cascade) can be categorised by failure of one asset triggering the failure of an interconnected and successive asset (ie interdependent). Cascading failures usually begin when one element of an infrastructure network fails and nearby infrastructure is required take up the slack for the failure. This causes an overload of the assets within the network and causes them to fail, prompting further assets to fail and causing a cascading effect to occur. Cascade failures can be considered within a risk assessment by considering it as an event in itself, or if reasonable and applicable, as the consequence of the infrastructure failing.	Failure can be mitigated by finding and eliminating possible causes. Resilience can be built by strengthening the asset or improving the organisation’s ability to respond.
Complex, linear	Failure results from a combination of failures and latent conditions – often hidden dependencies. These could be due to degradation or weakness of components (technical organisational, human). For example, a human error, results in omission of maintenance activities on stand-by pump within a pump station. The human failure combines with the failure of the main pump, and the stand-by pump – resulting in severe flooding.	Failure can be mitigated by strengthening barriers and defences. Resilience can be built by improving observation of indicators.
Complex, non-linear failure	Failure results from unexpected combinations (concurrence) of events or combinations (resonance) of normal performance variability. Important to understand dynamic nature of system performance than to model individual failures/human reliability. An example would be a train derailment into buildings, caused by a driver behind schedule who manually exceeds the maximum allowed velocity in order to meet performance targets.	Failure can be mitigated by monitoring and controlling performance variability, improving anticipation, responsiveness and adaptive capacity.

Appendix F: User guidance

This appendix contains further guidance on the implementation of the measurement framework to complement the body of this report. The framework is a spreadsheet tool with a series of questions across the various dimensions and principles developed. (Please note that the spreadsheet is presented in this report as three MS Word tables – see appendix B, tables B.1, B.2 and B.3.)

1 There are two separate spreadsheets: the first is for an 'all-hazards' assessment, and the second a 'specific-hazard' assessment. Refer to the body of the report for explanation of these terms.

2 Within each spreadsheet, there are three tabs:

   a Summary dashboard (table B.1): this tab reports the overall resilience scores and weightings, summarised from the three tabs below.

   b Technical assessment (table B.2): questions need to be answered in technical context, and a drop down filter can be used to undertake an assessment at either an asset or network/regional level.

   c Organisational assessment (table B.3): questions need to be answered in an organisational context. The same questions apply at an asset, or network/regional level.

3 Weightings: These can be applied at the category, principle or dimension level. The weightings are a percentage and must add to 100% across each group (there are check totals which indicate the sum totals). The weightings allow the user to preferentially place importance across (say) one principle over another. For example, one may determine that 'robustness' is more important than 'redundancy' or 'safe-to-fail' and as such, allocate a weighting of 40%:30%:30%. It is important to note that the weightings are subjective and will be based on the user preference. In all instances, the individual scores for each question can be viewed and interrogated to determine reasons behind a specific category, principle or dimension score.

   Weightings should be set evenly and only changed if there is clear agreement between people responsible for the evaluation that a certain category/principle/dimension is of more or less relevance. For example, in some cases a 'safe-to-fail' option for design may not be viewed as appropriate, and as such can be weighted down to account for this.

   The spreadsheet has cells to apply notes which should be used to record rationale etc.

   If the tool is used to compare different assessments across regions or assets, then care should be taken to ensure that a consistent approach is taken in applying weightings.

4 Number of questions to answer: It is recommended that as many questions are answered as possible by the user. The category scores are generated by averaging the series of questions within each category, so at least ONE question **must** be answered in order to generate a score. Not answering any questions within a category will lead to an error within the spreadsheet. Care has been taken to not provide questions which overlap with each other.

5 Subjectivity: The questions have been developed with explanations to provide as much clarity as possible, and to facilitate a clear choice when responding and assigning scores. This measurement framework is qualitative by nature, and there always will be subjectivity when assigning scores and weightings. To mitigate this, scores should be developed in a group setting and with appropriate breadth of knowledge and range of stakeholders.