Better measurement of the direct and indirect costs and benefits of resilience

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Contents

Executive summary

Resilience is defined as the ability of systems to proactively resist, absorb, recover from, or adapt to disruption within a timeframe which is tolerable from a social, economic, cultural and environmental perspective. Resilience has been increasingly emphasised and incorporated into New Zealand Government frameworks. Waka Kotahi NZ Transport Agency has developed and/or provided a range of tools, frameworks and materials to help transport professionals assess and plan for resilience.

However, there is little in the way of technical guidance contained within the *Economic Evaluation Manual* (EEM) to support the analysis of resilience for investment appraisal. This research report attempts to fill this gap. It aims to identify and develop techniques and methods that can be used to value and monetise the costs and benefits of resilience in transport infrastructure, described in a way that can be incorporated into the EEM.

A review was undertaken of relevant guidelines, literature and analysis in New Zealand and elsewhere. Most useful are materials that have been developed to assess road closures due to flood in Australia; however, most technical guidelines in land transport (or other sectors) pay little attention to resilience. There are also some technical studies that have explored aspects of resilience and disruptions. An increasing focus of the literature is the broader economic impacts of disasters using economic impact models.

Building on these materials, this report describes a suite of techniques and methods to use to incorporate resilience into transport investment appraisals. The costs to improve resilience relate to the additional infrastructure (capital and maintenance) costs and may be estimated as with any infrastructure investment. Accordingly, the focus of this work is on techniques and methods related to the benefits of resilience.

The resilience benefits are estimated as the avoided costs of disruption. These can be valued using an expected cost approach that accounts for the likelihood and severity of disruptions. In some cases, this may be simply done based on historical data on the average time of disruption. For some situations and some costs, it may be necessary to explicitly estimate the costs for different levels of severity of disruptions.

There are a range of disruptions costs, which can be broadly categorised as:

- user costs – costs associated with a change in use due to a loss of functioning of the transport infrastructure
- other direct costs – costs to non-users directly affected by the disruption, including the additional costs of repair
- indirect costs – costs of disruption not directly associated with use.

For disruptions with low to medium impact, much of the focus will be on the direct costs to road users. These depend significantly on the presence of alternative (diverting) routes and the change in road-user behaviour. Where alternative routes are available, the costs of disruption associated with road users can be estimated using estimates of the frequency and incremental costs of:

- diverting (primarily related to additional travel time and additional operating costs)
- waiting, which includes the additional travel-time cost of waiting en route, and the costs of displacement, which refers to postponement of trips
- cancelling trips, the cost of which may be estimated based on costs of diversion.

The costs to consider, the methods and the depth of analysis needed will vary depending on the situation. The simplest situations will involve short disruptions that result in road users taking diverting routes. More complex situations arise when there is a risk of severe disruptions with long-term effects and/or impact on critical infrastructure. In such cases, other methods may be required to complement or replace some of the standard techniques.

Disruptions have a number of features that pose challenges for investment appraisal. First, while uncertainty is a feature of all investment appraisal, it is particularly so for analysis of high-impact, low-frequency events. For this reason, it is important that the uncertainty associated with resilience analysis be recognised in sensitivity analysis. Second, disruptions involve significant sudden impacts to transport networks and consequently to behaviour. Care is required in estimating how road users react to change. People and businesses can adapt over time to disruption to reduce the costs they incur. This modification of behaviour should be a consideration in evaluating behaviour. Third, in some situations, such as where there are no practical alternative routes, it is difficult to apply standard travel-cost methods. In such situations, other methods may be required.

A number of the techniques and methods are illustrated using the Manawatū Gorge Road as a case study.

We have identified the following areas for further research and development.

- **Displacement costs**
  These are the costs to road users associated with deferring travel (ie, not waiting en route) in response to a disruption. We expect the cost-per-hour of displacement to be significantly less than that of waiting; however, there is little public research that can be used relating to private vehicle use.
- **Integration of economic impact models into investment appraisal**
  Economic impact models are potentially useful for analysing how the costs of disruption change over time and the indirect economic effects that are difficult to analyse when alternative routes are not practical. Waka Kotahi has invested in the locally developed Measuring the Economics of Resilient Infrastructure Tool (MERIT) for such purposes; however, more work is required to ensure that the outputs can be integrated into investment appraisal analysis.
- **Distributional impacts**
  Under standard investment appraisal, only the net economic impacts are evaluated; however, sudden and severe disruptions can have significant distributional consequences with significant societal impacts, including business closures and employment losses.
- **Behavioural responses to disruption**
  The costs of disruption depend significantly on how transport users respond to a disruption and how their behaviour changes with the length of the disruption. Conducting surveys of transport users is a potentially useful method, particularly on routes where there has been a history of disruption. Further research on the process of undertaking such surveys and how they may be used would be beneficial.

Abstract

The primary objective of the research is to identify and develop critical techniques and methods that can be used to value and monetise the costs and benefits of resilience in transport infrastructure, described in a way that can be incorporated into the *Economic Evaluation Manual*.

The project was conducted in 2019–20. The costs of resilience relate to the costs of infrastructure. The benefits of resilience are estimated as the avoided costs of disruption. There are a variety of disruption costs, including costs to users of the infrastructure, other direct costs and potentially indirect costs associated with non-users. These can be valued using an expected cost approach that accounts for the likelihood and severity of disruptions. In some cases, this may be simply done based on historical data on the average time of disruption; however, for some situations and some costs it may be necessary to explicitly estimate the costs for different levels of severity of disruptions.

1 Introduction

1.1 Purpose

Waka Kotahi NZ Transport Agency engaged Sapere to undertake research to identify and develop critical techniques and methods that can be used to value and monetise the costs and benefits of resilience in transport infrastructure, described in a way that can be incorporated into the *Economic Evaluation Manual* (EEM) (New Zealand Transport Agency, 2018b).

This research paper aims to contribute to Waka Kotahi by:

- developing and testing methodologies to better measure the direct and indirect costs and benefits of resilience
- identifying key factors, variables and matters that should be considered in the (ex-ante) cost–benefit analysis (CBA)
- providing guidance on how these key factors, variables and matters can be obtained, valued and monetised.

The paper describes a framework and methodology that aims to provide a robust quantification of the costs and benefits of resilience that can be incorporated into the EEM. These improved methods will help ensure resilience benefits are captured alongside other benefits and result in better and more well-informed decision-making.

1.2 Project background

This research paper builds on the work carried out in NZ Transport Agency research report 614, *Establishing the Value of Resilience* (Money et al., 2017). The paper focused on the development of a consistent approach to determining transport resilience but did not explicitly develop techniques and methods that could be used to quantify resilience.

The EEM is published by Waka Kotahi. It provides the technical guidance and procedures for undertaking social CBA of transport investments in accordance with the Waka Kotahi Investment Assessment Framework. The current methodologies used to value resilience in the EEM are under-developed, and there appears to be a lack of understanding of the value of resilience and how to incorporate it into the appraisal of transport investment projects.

The selection and design of transport investments to be evaluated is guided by other Waka Kotahi materials. These include the *Highway Structures Design Guide*[1] and the companion *Bridge Manual*,[2] which provide general and specific design criteria for highway structures and bridges in New Zealand, including guidelines and/or requirements regarding risk evaluation, flooding and seismic risk.[3]

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1 https://www.nzta.govt.nz/resources/highway-structures-design-guide/

2 https://www.nzta.govt.nz/resources/bridge-manual/

3 Similar guidance is provided in other jurisdictions. The Queensland Government Department of Infrastructure, Local Government and Planning's (2016) *Natural Hazards, Risk and Resilience* specifies minimum flood levels for community infrastructure.

Investment activities are also guided by the Waka Kotahi 'Planning & Investment Knowledge Base', which includes 'threshold levels for investment activities to address resilience'.[4] The threshold levels are based on the expected duration and frequency of the road closure, the road's classification (One Network Road Classification) and whether any alternative routes exist. The thresholds can be used to determine when it is appropriate to propose investment activities to overcome resilience problems. For example, a 'National' road with a viable alternative route has a threshold (ie, acceptable) of road-closures lasting 5–12 hours for two road closures per year.

The EEM (section 10.8) notes that 'Network resilience can be the major driver for resilience for regional roads and may be a secondary outcome of an investment in other activity classes'.

1.2.1 Policy context

Resilience has been increasingly emphasised and incorporated in recent New Zealand Government frameworks.

Of greatest relevance is the New Zealand Government's (2018) *Government Policy Statement on Land Transport 2018/19 – 2027/28,* which includes an 'Access Objective: A land transport system that is resilient' (p. 18) and notes that:

> *When access to the transport system is disrupted, it has flow-on effects both on direct users of the network and those who receive goods and services via the transport system.*
>
> *Often, taking a whole-of-system approach will create the best outcome … This involves considering all parts of the transport system and non-transport systems relevant to resilience…*
>
> *Climate change and low frequency-high impact events (such as earthquakes) are the key long-term issues that have significant implications for the resilience of the land transport system.*

The New Zealand Treasury has developed the Living Standards Framework (LSF) with an overall objective to maximise intergenerational wellbeing. The core elements of the LSF are:

- 12 domains of current wellbeing, selected by the Treasury based on research about what is important for people and their wellbeing
- four capitals (natural, human, social, and financial and physical) that combine to generate current and future wellbeing
- risk and resilience.

The risk and resilience aspect of the LSF is of particular relevance to this report.[5] The evaluation of resilience costs and benefits may also contribute to the domains of wellbeing.

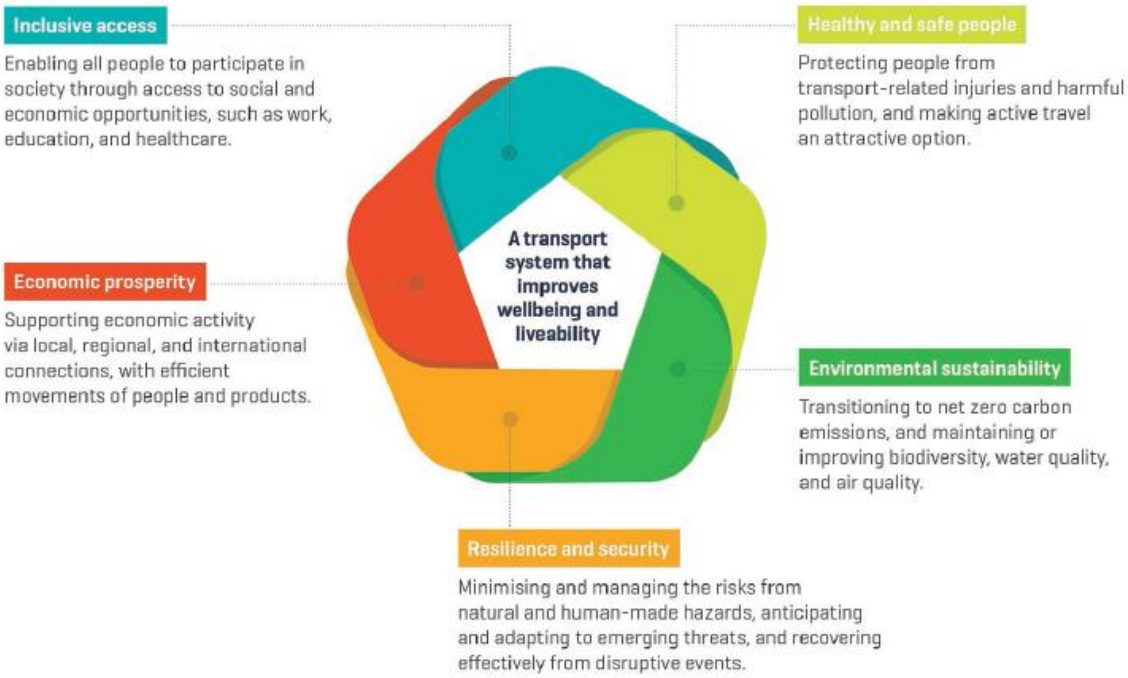
[4] https://www.nzta.govt.nz/planning-and-investment/planning-and-investment-knowledge-base/assessment-of-activities-by-activity-class/assessment-of-local-road-regional-and-state-highway-improvement-activities/

[5] As part of their work on the LSF, the Treasury released a discussion paper that examines how four overarching trends, relating to environmental, societal, economic and technological factors, would influence the risk landscapes for the four capitals in the LSF (Frieling and Warren, 2018).

The Ministry of Transport (2018) released the Transport Outcomes Framework, which 'defines a set of outcomes for New Zealand's transport system and explains how government should work toward these outcomes through a guiding principle of mode neutrality' (p. 2).[6]

According to the framework, the purpose of the transport system is 'to improve people's wellbeing, and the liveability of places' by contributing to five key outcomes, summarised in Figure 1.1 below. One of the key outcomes is 'Resilience and Security'. It also establishes a key principle of mode neutrality: 'To meet the outcomes, all transport planning, regulating, and investing needs to be done in a mode neutral way' (Ministry of Transport, 2018, p. 3).

Figure 1.1 Transport Outcomes Framework



Source: Ministry of Transport (2018, p. 3)

1.2.2 The position of Waka Kotahi on resilience

The position of Waka Kotahi is that 'the resilience of the land transport system is increased by managing risks and long-term resilience challenges and helping communities quickly recover from disruptions' (Waka Kotahi, 2020, para. 1).

To operationalise this position statement, Waka Kotahi developed a Resilience Framework[7] that describes its strategic approach to prioritise, guide and coordinate its ongoing activity and strategic work programme to improve resilience.

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6 The mode neutrality principle involves two important aspects: 1) Making sure all modes and options are considered and evaluated to find the best system solution. 2) Making users and decision-makers more aware of the benefits and costs of transport choices to incentivise robust decision-making and smart travel choices.

7 https://nzta.govt.nz/assets/Highways-Information-Portal/Technical-disciplines/Resilience/Resilience-response-framework/transport-resilience-framework.pdf

Further information on Waka Kotahi guidance and tools for planning for resilience is captured in section 2.2.1 of this report.

1.3 Methodology

The study was conducted in late 2019 and early 2020. The process of the review involved:

- establishing a Steering Group
- undertaking a literature review on approaches, methods and guidance to capture the costs and benefits of resilience in transport investment appraisal
- assessing existing approaches and methods that could be incorporated into the EEM
- developing a framework, method and guidance for quantifying resilience
- testing the framework with a case study involving the Manawatū Gorge
- identifying additional areas for research.

1.4 Report contents

The research report is structured as follows.

- Section 2 provides an overview of our literature review on resilience, including New Zealand and international approaches to resilience.
- Section 3 discusses the proposed framework for quantifying the costs and benefits of resilience and the key issues to consider.
- Section 4 applies the framework and methods to a case study on the route through Manawatū Gorge.
- Section 5 concludes and discusses areas for further research.

2 Literature review

2.1 Overview and context

Resilience of infrastructure is a broad topic and one that is receiving an increasing amount of attention, particularly due to concerns over the impact of earthquakes and climate change.

The focus of this report is on one aspect of resilience – guidelines for the costs and benefits of resilience with regard to transport infrastructure. Nevertheless, it is useful for context to briefly review some relevant aspects from the broader literature. Accordingly, this literature review:

- begins with a subsection that covers the concepts of resilience and key definitions
- examines existing guidelines, tools and analyses in New Zealand and other jurisdictions
- reviews existing analyses on the costs and benefits of resilience
- examines how the costs and benefits of resilience are evaluated in a standard CBA framework
- considers the extensions and issues when appraising resilience.

This literature review builds on existing work within Waka Kotahi, including prior research reports about resilience (see Table 2.1 below) and the EEM itself, which briefly refers to resilience.

The literature review was developed using the following interrelated steps:

- reviewing guidelines used elsewhere, including Australia, the United Kingdom (UK) and the United States (US)
- searching for, and reviewing, relevant academic and other public materials[8]
- interviewing, and/or corresponding with, stakeholders and parties with relevant expertise in New Zealand and other jurisdictions.

A substantial number of papers were reviewed. In the interests of readability and brevity, this chapter only captures a summary of the literature. Further references to the relevant literature are incorporated into later chapters.

Table 2.1 Key prior Waka Kotahi research reports on resilience

Reference	Title and description
Seville and Metcalfe (2005) Report 276	*Developing a Hazard Risk Assessment Framework for the New Zealand State Highway Network* provides detailed information on the: • cause of each hazard type (seismic, volcanic, landslides, flooding, snow and ice, tsunamis, wildfire) • key research carried out • consequences of each hazard (social, environmental and economic) • vulnerability of the state highway network to each hazard.

[8] Key search terms included combinations of terms related to economic appraisal (eg, 'cost benefit', 'benefit cost', 'economic analysis', 'appraisal'), resilience-related terms (eg, 'resilience', 'disruption', 'reliability', 'disaster', 'flood', 'earthquake') and terms related to specific topics (eg, 'Real Options'). In total, in excess of 100 documents were reviewed, around two-thirds of which are included in the Bibliography.

Brabhaharan et al. (2006) Report 296	*Natural Hazard Road Risk Management Part lll: Performance Criteria* examined the performance criteria for road networks in terms of resilience to natural hazard risk and developed a framework for setting performance measures. The report recommended resilience performance measures in terms of damage to the road, availability (how functional the road is after an event) and outage (the expected duration of issues). The research includes a survey of stakeholder organisations' views on acceptable frequency of issues.
Gordon and Matheson (2008a, 2008b) Report 355	*Engineering Lifelines and Transport – Should New Zealand Be Doing It Better?* Lifelines are essential 'utility' services that support the life of the community, such as water, wastewater, stormwater, power, gas, telecommunications and transportation networks. This project examined New Zealand engineering lifelines activity, its level of integration in road controlling authority management practices, and its relationship to the resilience of roading networks to natural hazards. The scope included a review of the risks to land transport infrastructure and the available tools and technology that could enhance lifelines practice.
Hughes and Healy (2014) Report 546	*Measuring the Resilience of Transport Infrastructure* explores the theory of resilience and proposes a qualitative measurement framework that broadly covers both technical and organisational dimensions of resilience.
Chow and Chen (2017) Report 631	*Benefits and Costs of Different Road Expenditure Activities* examines how benefit and cost appraisals for road operations, maintenance and renewal, and minor work improvements could be undertaken in a manner comparable with the appraisal framework for capital investments. The study focuses on improvements to resilience, safety and efficiency outcomes. Resilience benefits are quantified based on the reduced chance of a road closure, resulting in fewer detours for drivers and avoided restoration costs for road authorities. The approach is demonstrated using a set of hypothetical examples.
Money et al. (2017) Report 614	*Establishing the Value of Resilience.* The study produced a taxonomy of resilience terminology, including a resilience definition and resilience measures (relating to robustness, redundancy, recovery and leadership and governance), and developed a qualitative decision support tool to weigh up different controls to improve resilience.
Brabhaharan et al. (2018) Report 613	*Seismic Design and Performance of High Cut Slopes* developed guidelines for the seismic design of high cut slopes along transportation routes in New Zealand. The guidelines provide for assessment of a resilience importance category based on the importance level of the route and the resilience expectations for the route.

2.1.1 Defining resilience

In their report for Waka Kotahi titled *Establishing the Value of Resilience*, Money et al. (2017) reviewed over 100 definitions of resilience. From this, they arrived at the following definition, which has since been adopted into the EEM (section A10.8).[9]

> *Resilience is the ability of systems (including infrastructure, government, business and communities) to proactively resist, absorb, recover from, or adapt to, disruption within a timeframe which is tolerable from a social, economic, cultural and environmental perspective.*

This definition highlights that the benefits of resilient infrastructure are derived from the ability of infrastructure to minimise the cost of disruption. Resilience is similar to but broader than robustness, which they define as the ability of systems to withstand disruption and continue to provide an acceptable level of service. Money et al. (2017, p. 7) identified robustness as one measure of resilience alongside:

- *Redundancy: Provision of functionally similar outcomes, to an acceptable standard, during lost or degraded levels of service.*

[9] The EEM (p. 5-416) notes: 'The definition of resilience is fast evolving and may be subject to review.'

- *Recovery: The ability to restore an acceptable level of service after disruption.*
- *Leadership and governance: The ability to develop an organisational mind-set/culture of enthusiasm for responding to challenges (for example through the development of an agile and flexible asset monitoring and management programme).*

Resilience can be improved in multiple ways. This is reflected in the Waka Kotahi Resilience Framework (New Zealand Transport Agency, 2018a), which established objectives related to reduction of risk, readiness, response and recovery.[10] As discussed below, the multi-objective approach has some implications for road-infrastructure investment as the benefits associated with resilient transport infrastructure depend in part on the extent to which resilience is being met by other means. For example, the resilience of a road network may be improved by increasing the resilience of a particular road or through expanding the capacity of alternative routes. Similarly, the case for increasing resilience may also be reduced through investment in improving the speed of disaster response should a disruptive event occur.

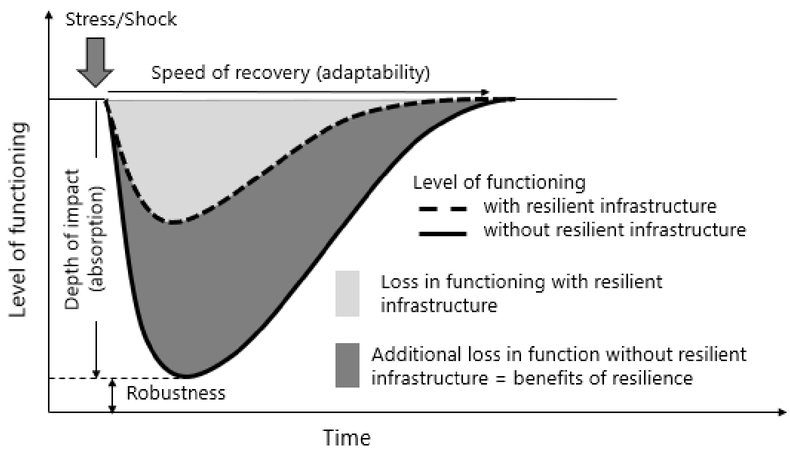
The LSF summarises resilience as having two dimensions:

- an **absorption capacity dimension**, which comprises resistance to a stress or shock event and buffers that can reduce the depth of impact
- an **adaptability dimension**, which focuses on elements of adaptability and innovation that maximise the speed of recovery.

These dimensions are illustrated in Figure 2.1, which shows the level of functioning of an asset in response to a disruption (stress/shock). The more robust the system (greater absorption capacity), the lower the depth of the fall. The speed of recovery in the level of functioning depends on the adaptability. The cost of the disruption is reflected in the dip in the level of functioning (both the shaded grey areas).

More-resilient infrastructure can improve the robustness of the system, reducing both the depth of loss of functioning and the recovery period (the dark grey area). The benefits of resilience are derived from these reductions in the loss of functioning both in terms of depth and time.

Figure 2.1 Two dimensions of resilience: absorption and adaptability



Source: Adapted from Frieling and Warren (2018) and McDaniels et al. (2008)

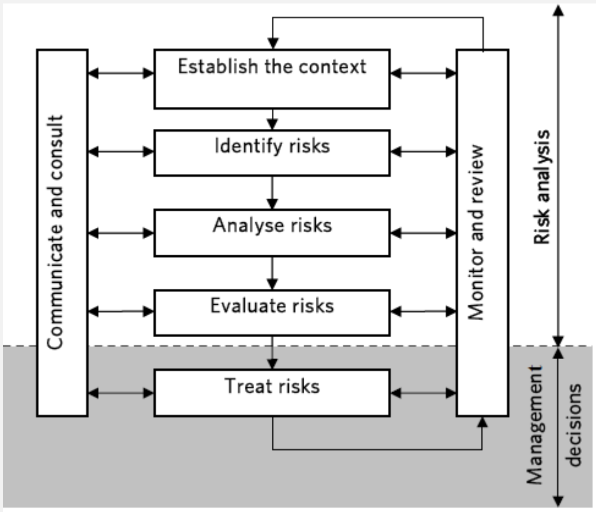
[10] The framework states that by working towards these objectives, communities will be 'less exposed to, and better prepared to deal with, the economic, physical, social, cultural and environmental impacts of risks and shocks from natural hazards and other disruptive events' (New Zealand Transport Agency, 2018a, p. 2).

2.1.2 Risk assessment in the context of resilience

Prior to a CBA being undertaken, it is necessary to identify the options for consideration. This involves a risk assessment, which is the process of risk identification, analysis, and evaluation for a series of options.[11] The EEM incorporates some, but limited, guidance on risk assessment and management (see Box 2.1 below).

Box 2.1 The risk assessment process

Appendix A13 of the EEM covers 'risk analysis', which follows the principles set out in the Australian/New Zealand Standard AS/NZS 4360 on risk management and analysis (steps illustrated in the diagram below). There is limited reference to analysis of risks of disruptions; however, section A13.12 'Example of risk analysis' provides an example involving analysis of replacing a bridge that is susceptible to an earthquake.



Source: New Zealand Transport Agency (2018b, Appendix A13.4)

A risk assessment is required to identify options, which may then be evaluated using a formal CBA. Options that mitigate or treat risks more than others may be shortlisted for further evaluation. Risk assessment is also necessary to assess the likelihood and significance of events, which are key inputs into the quantification of the costs of disruption.

Evaluating the benefits of resilience follows a similar process to risk assessment. Prior to a CBA being undertaken, resilient options must first be analysed for their potential to mitigate risk. We provide a simple example in the context of resilience:

- **Establish the context** – There is a one-lane bridge that connects a small town with few alternatives in a high-flood area.
- **Identify risks** – The bridge is not built to withstand a large flood, which would result in alternative routes being taken, which imposes additional cost.
- **Analyse risks** – There is a small possibility the bridge may withstand a 1-in-10-year flood but be flooded in other instances.

[11] Refer PIARC Technical Committee (2019, section 6.2). They note that, according to ISO Guide 73, risk evaluation is the process of comparing the risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable.

- **Evaluate risks** – Options to minimise risk/maximise resilience may be to upgrade the existing bridge, build a new bridge, or do nothing until a flood event occurs.
- **Treat risks** – Based on the evaluation, choose a preferred option to treat risk/maximise resilience.

There is a much broader and deeper international literature on risk assessment and management with regard to infrastructure (land transport and otherwise) that has grown significantly with increased interest in climate change adaptation.

2.1.3 Hazards – sources of disruption

Understanding the potential sources of disruption ('hazards') is important for measuring the resilience of transport infrastructure. The EEM refers broadly to hazards and provides limited guidance as to the type of hazards to consider.

There is a broad range of potentially relevant hazards. Hughes and Healy (2014) categorised 'hazards' into:

- three types: natural, technological, social/political
- whether they are 'stress' events, which are long-term and gradual change processes, or 'shock' events, which are short-term and sudden change processes.

A summary of hazard events, as identified by Hughes and Healy (2014), is provided in Table 2.2 below. The authors note that shock events are, by definition, largely unpredictable and consequently more difficult and costly to plan for. A challenge with any risk analysis is that hazards are unknown.[12] For example, the COVID-19 pandemic has had significant and far-reaching impacts on transport use (road and other); however, such a hazard was not identified in the literature reviewed.

Table 2.2 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.

Source: Hughes and Healy (2014)

[12] Hughes and Healy (2014, p. 24) state:

> *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.*

Hughes and Healy note that the EEM currently has a framework for measuring transport congestion, which they identify as a stress hazard. In the context of New Zealand transport infrastructure, other relevant work has been undertaken to identify and quantify hazards to the transport system (see Table 2.1).

2.2 Existing guidelines and tools

This section reviews the guidelines, tools and analysis that are available in New Zealand and elsewhere that may be useful in developing technical guidelines for evaluating the costs and benefits of resilience.[13]

There is a plethora of public documents that provide guidance on conducting social CBA that are of potential relevance to this project. Existing relevant guidelines and tools include:

- the EEM and other general guidelines in New Zealand
- general and transport-specific guidelines in other jurisdictions
- guidelines and materials focused on resilience-specific topics, including economic evaluation, and also related topics such as climate change adaptation and risk assessment.

2.2.1 The extent to which 'resilience' is incorporated into guidelines

Most guidelines on economic appraisal provide little mention of resilience. For example, resilience is not discussed in the World Bank's *Cost-Benefit Analysis in World Bank Projects* (Independent Evaluation Group, 2010).

The lack of attention paid to resilience may implicitly reflect the view[14] that any comprehensive CBA should consider the costs and benefits of resilience. If resilience is implicitly considered, what are reasons for its explicit inclusion? Possible rationales include:[15]

- It may be overlooked because resilience is a 'relatively new' concern in economic appraisal. It should be included now to reflect changing priorities.
- People are often compliance-focused, therefore explicit reference is important to ensure consideration of resilience.
- Resilience is a diverse topic, which may not be well understood. Projects such as ours help to add to the body of knowledge.
- There is value in obtaining common and consistent application of methods to enable comparison of projects.

2.2.2 Resilience in other sectors

Issues of resilience are not unique to land transport. Resilience is a consideration in other infrastructure analysis, including ports (air and water), utilities (electricity, gas, water), buildings and other (including flood banks).[16]

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[13] As noted in section 1.2, the selection and design of transport investments is also guided by other materials, including design guidelines and threshold levels for investment activities to address resilience.

[14] Noted by Deloitte Access Economics (2016, p. 32).

[15] This list is derived from a number of sources, including Deloitte Access Economics (2016) and interviews.

[16] As is the case for transport, the consideration for resilience may be in large part determined by other criteria and guidelines. For example, a common risk management principle with regard to safety is that risks should be minimised to be as low as reasonably practicable.

Public CBAs – particularly where resilience is a core component – are rare. An exception is that some CBAs undertaken of hazard (primarily flood) mitigation measures by some New Zealand councils are in the public domain.[17] In such cases the benefits of hazard reduction/resilience are the primary focus, and our assessment is that they would consider similar issues to the resilience issues to be considered in a CBA for land transport infrastructure.

There are also guideline documents that have been developed for other sectors. A recent useful example is a handbook by the National Academies of Sciences, Engineering, and Medicine (2019) titled *Climate Resilience and Benefit Cost Analysis: A Handbook for Airports*.

Finally, there have been some meta-analysis studies that have attempted to evaluate the benefits of disaster risk reduction. Such studies have tended to suggest sizable returns to disaster risk reduction (Mechler, 2016, p. 2123).[18]

2.2.3 New Zealand guidelines and tools

2.2.3.1 Guidelines

In New Zealand the key relevant guides are:

- the EEM, which offers transport-specific technical guidance and procedures for undertaking social CBA for transport investment
- guidance material provided by the Treasury, including a website for matters related to CBA and a guide to CBA (New Zealand Treasury, 2015).

Section 10.8 of the EEM discusses 'Resilience and Security of Access'. It specifies a risk-based evaluation is to be used when assessing investments with the purpose of increasing network resilience. It notes that 'the benefits are usually calculated by considering the additional transport costs imposed by any disruption, and the extent to which these may be reduced by investment in either infrastructure or network management'. It states that quantifiable risks of disruption are to be included in the evaluation[19] and provides some guidance in how to assess and analyse risk. The EEM (section 10.4) also includes a general discussion on 'Risk and uncertainty'.

2.2.3.2 Tools and information

Waka Kotahi currently provides a suite of resilience planning tools and information that can be used in a business case context to help develop interventions and agreed responses to improve the resilience of networks. A summary of key resilience-related planning tools provided on the Waka Kotahi website is provided in Table 2.3 below. For economic assessment, Waka Kotahi provides reference to the Measuring the Economics of Resilient Infrastructure Tool (MERIT), which can estimate the economic consequences associated with disruption events to support infrastructure planning and decision-making (see Box 2.2 below). There are other public tools that may be used in conducting a CBA or estimation of losses due to hazardous events. These include the Treasury's CBAx tool.

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[17] An example is work by Castalia (2016) for Otago Regional Council.

[18] The Mechler (2016) study was based on a review of 40 studies from a range of countries and sectors.

[19] Specifically, it states:

> *Where there is a quantifiable risk of disruption to traffic, damage to vehicles, the roadway or structures, or injuries to road users from natural or human-made events, and the activity reduces or eliminates the impacts compared with the do-minimum, then the benefits of the reduced or eliminated impacts must be included in the activity evaluation.* (p. 4-71)

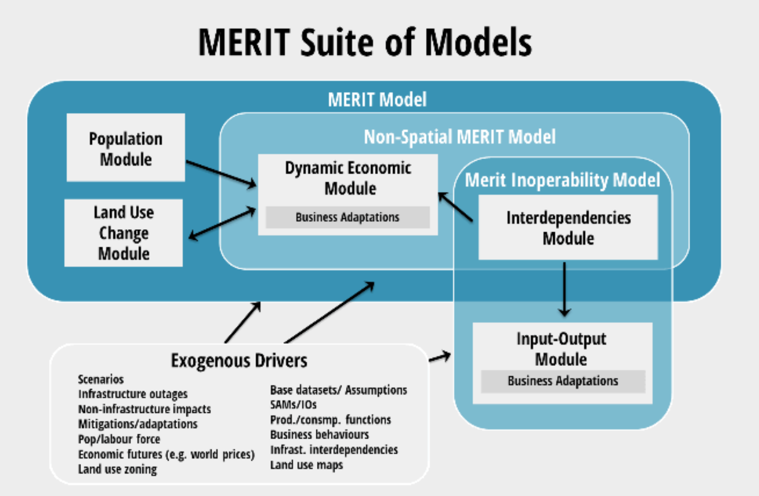
Table 2.3 Waka Kotahi resilience planning tools

Purpose/Tool	Detail
Resilience Response Framework	A framework to assist in determining an appropriate strategic response for an identified resilience problem.
For considering resilience in the strategic business case	
Hazard exposure scan	The maps section of the Waka Kotahi website provides an assessment of key natural hazards focusing on low-frequency, high-impact events (such as earthquakes) that may impact the availability of the network, and includes an assessment of the extent and duration of the outage.
Identify detour routes	Interactive detour maps that identify agreed alternate routes, comparative distance and travel times, which vehicle types each route is suitable for, and other key pieces of information.
One Network Road Classification assessment	A tool for documenting an assessment against the One Network Road Classification. This assessment aims to help determine the scale of the problem and to assist in assessing the strategic fit of a project.
Resilience risk priority	The resilience prioritisation tool provides an aggregated or detailed level of resilience hotspots of state highway segments across the network. The purpose of the tool is to help prioritise where to focus attention in improving the resilience of the state highway network.
For considering resilience in the programme business case	
Low-probability, high-impact event assessment methodology	A methodology for the regional-level assessment of the resilience exposure of the state highway network for low-frequency, high-impact natural hazards. The results of these assessments will inform the development of programme business cases.
Traffic Road Event Information System database	The database contains information on all road events from planned roadworks, unplanned incidents and even parades or sports events.
Economic assessment	MERIT (see Box 2.2 below for details).
Social assessment	The MapHUB Resilience map shows the potential social impacts for communities of particular network outages.

Source: www.nzta.govt.nz/roads-and-rail/highways-information-portal/technical-disciplines/resilience-nzta-focus-on-resilience/resilience-planning-tools/

Box 2.2 MERIT (Measuring the Economics of Resilient Infrastructure)

MERIT is a suite of 'integrated spatial decision support systems' that estimate the economic consequences associated with disruption events.



Disruptions are evaluated through time (ie, it covers both the event and the subsequent response, recovery and rebuild phases), across space (ie, by detailed spatial location, region and nation as a whole) and for multiple stakeholders (ie, households and industries).

Uniquely, the MERIT suite captures household and business behavioural adaptation that may occur following an event. MERIT can add value to investment planning by assessing the socio-economic implications of any set of resilience investment options.

Each module can be run together and separately as required. At its most complex, it has multiple features.

- It is fully spatial – that is, it tracks land use and demographic change at 50 m × 50 m resolution, enabling it to be used for evacuation planning, relocation (post-event), and assessing disruption of future urban forms.
- It has an integrated transport model (a standard 4-step transport model, compatible with the Auckland Region Transport Model, Wellington Strategic Transport Model and Waikato Regional Transport Model).
- These models all run simultaneously – that is, tracking changes in land use, transport dynamics and economy. This includes all critical feedbacks between these models – that is, changes in transport infrastructure will change land use, which changes the economy etc.

At its least complex, it has an interoperability model that focuses on short-duration disruptions. This was developed to look at disruption in electricity and telecommunication networks.

It has an integrated interdependencies module that captures the relationships between different horizontal infrastructures. This enables it to track the consequences of failure in one infrastructure type on other infrastructure types, and these on others etc.

Source: https://www.merit.org.nz/merit/, personal correspondence

2.2.4 Australian guidelines

In Australia, the most relevant set of guidelines is the Australian Transport Assessment & Planning (ATAP) guidelines produced by the Transport and Infrastructure Council (TIC), which aim to 'outline best practice for transport planning and assessment in Australia'.[20] The ATAP guidelines have replaced the previous National Guidelines for Transport System Management. Of particular relevance for resilience, ATAP guidelines were recently released for 'Flood resilience initiatives' (TIC, 2019).

The ATAP guidelines have some relevance for New Zealand as there is New Zealand representation on the ATAP Steering Committee and there appears to be recognition that there are benefits to Australia and New Zealand sharing common approaches where possible.

[20] www.atap.gov.au/

Some Australian states also maintain technical transport-specific guides; however, these are increasingly referring to the ATAP guidelines. The most relevant are:

- ***Transport for NSW Cost-Benefit Analysis Guide*** **(formally *Principles and Guidelines: Economic Appraisal of Transport Investments and Initiatives*)**
  This NSW guide notes that the 'ATAP Guidelines have been referred to for best-practice throughout this document. ATAP aims to be nationally consistent, however some recommendations may not be appropriate in the NSW context' (Transport for NSW, 2019, p. 15).
- ***Transport and Main Roads Cost-Benefit Analysis Manual – Road Projects***
  Produced by the Queensland Government Department of Transport and Main Roads (Qld DTMR, 2011), this manual is described as a comprehensive practical reference tool for practitioners. The Queensland guidelines are notable in that they include explicit guidance on resilience relating to flood disruptions and road closures. The Qld DTMR CBA manual accompanies an Excel model that is available to Qld DTMR staff and others approved by the Qld DTMR.

In Australia, there are a range of other guidelines that cover CBA for infrastructure. Of relevance, these include:

- state-based general CBA guidance (similar in scope to the Treasury's CBA guidelines)
- other sector-specific guidelines; for example, NSW Health (2018) has developed *a Guide to Cost-Benefit Analysis of Health Capital Projects*
- non-technical guidelines; for example, VicRoads (2015) *Climate Change Risk Assessment* summarises work undertaken to assess the risks to VicRoads infrastructure associated with climate change.

Most guidelines provide limited discussion of resilience. An exception is that the NSW Treasury (2019) has released draft *Guidelines for Resilience in Infrastructure Planning Policy: Natural Hazards*. The draft paper provides mainly high-level guidance and has limited relevance for this project.

2.2.5 Other international guidelines

There are some international guidelines of interest. These include the guidance from PIARC (the World Road Association) of which New Zealand and Australia are full country members.[21] PIARC provides a range of technical guides on creating and transferring knowledge in the road transport sector.

There have also been a range of non-technical guidance materials generally focused on adaptation to climate change and risk analysis more generally. Most of these are focused on supporting risk-assessment process. PIARC released a series of reports in 2019 relating to climate change adaptation.

We list specific UK and US guidelines below. Other useful international documents include materials from:[22]

- the European Union – including the *Guide to Cost-Benefit Analysis of Investment Projects* (European Commission, 2014)

[21] PIARC was established as a non-profit association in 1909 as the Permanent International Association of Road Congresses. It was known as the World Road Association until a renaming in late 2019. Its core members are road agencies in over 120 countries (see www.piarc.org).

[22] Many other guidance materials that considered resilience in infrastructure were examined but have not been listed as we assessed them as having limited relevance to this study.

- the World Bank, which produces a range of guidance material particularly relating to infrastructure.[23]

2.2.5.1 United Kingdom

Relevant UK guidelines are:

- *The Green Book* (UK HM Treasury, 2018), which is the UK Government's 'central government guidance on appraisal and evaluation'
- materials developed by the UK Department for Transport (2014) on transport resilience
- non-technical guidelines such as the UK Cabinet Office (2011) *Keeping the Country Running: Natural Hazards and Infrastructure*.

In 2014 the UK Department for Transport conducted a review of the resilience of the transport network to extreme weather events and concluded that:

> - *The economic rationale for investing in transport resilience is currently poorly developed and needs to be strengthened.*
> - *Infrastructure operators in particular need to develop methodologies for estimating the economic and social costs of disruption, and for capturing the costs of rectifying damage caused by extreme weather, so these can be factored into spending decisions on resilience measures.*
> - *At present, spending on resilience is largely event led and reactive, in contrast to the social cost benefit analysis approach, including travel time savings, which drives most transport investment decision making.* (UK Department for Transport, 2014, p. 10)

In 2015, the UK HM Treasury (2015) released supplementary guidance to its *Green Book* on valuing infrastructure spend, including a section devoted to interdependence and resilience. The guidance is reasonably high-level and non-technical.

2.2.5.2 United States

Relevant US guidelines are provided by a range of individual state departments and federal agencies. Relevant materials include the following.

- The National Academies of Sciences, Engineering, and Medicine (2020) recently published *Guidelines to Incorporate the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change.*
- The Federal Transit Administration within the US Department of Transport developed the Hazard Mitigation Cost Effectiveness Tool, 'an Excel Workbook that computes some common financial measures used for decision-making, including annualized damages, the present value of these damages, present value of total project benefits, present value of total project costs, net present value of the project, and the benefit-cost ratio' (US Federal Transit Administration, 2017a, 2017b).
- The US Federal Emergency Management Agency provides 'Hazus' (www.fema.gov/hazus), a methodology for estimating potential losses from earthquakes, floods, hurricanes, and tsunamis.

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[23] These include *Cost-Benefit Analysis in World Bank Projects* (Independent Evaluation Group, 2010); *Building Urban Resilience: Principles, Tools, and Practice. Directions in Development: Environment and Sustainable Development* (Jha et al., 2013); and *Strengthening New Infrastructure Assets: A Cost-Benefit Analysis* (Hallegatte et al., 2019).

2.3 Approaches to valuing costs and benefits of resilience

In public guidelines and other papers, the analysis of the costs and benefits associated with resilience and the approach for quantifying them follows a reasonably straightforward and common approach.[24] Under this approach, costs (where considered) are primarily associated with the costs of infrastructure (investment and maintenance) used to achieve improved resilience.

The benefits of resilience relate to the avoided costs of disruption. These costs of disruption are estimated as expected values; that is, values weighted by their likelihood of occurrence. These are derived (using a risk-based approach) as a function of the probability of disruption (frequency) and the duration of disruption (impact). In the studies observed, these include direct costs to users associated with a loss of functioning and other direct costs, most notably the costs to repair. The methods to estimate direct user costs are broadly consistent and include the incremental costs to road users from diverting, waiting and cancelling trips.

Some literature has considered the possibility of indirect costs associated with the flow-on impacts to a regional economy. For example, in addition to directly impacting users of a bridge, a bridge closure will likely indirectly impact non-users such as organisations that do business with users of the bridge. However, such impacts are often not factored into analyses and guidelines.[25] Some literature recognises that costs of damage to roads, bridges and other transport infrastructure can include damage caused to interdependent infrastructure, such as energy and water network infrastructure.

There is a large literature that has examined the combined direct and indirect effects of disasters. To analyse the interactions within the economy associated with indirect effects, models with varying levels of sophistication have been used. Computable general equilibrium (CGE) and input–output (IO) models have often been used; however, these have limitations, including that they have limited flexibility in modelling the extent to how different sectors are affected and how they adjust over time to a disaster. This has led to the development of new techniques for modelling the impact of disasters. One extension is the inoperability IO model (IIM),[26] which allows for different levels of inoperability across different sectors.[27] The MERIT model was designed as a further advancement integrating the 'operability' function of IIM models with dynamic CGE modelling.[28]

2.4 Existing analyses on the costs and benefits of resilience

Some public bespoke analyses have examined the costs and/or benefits associated with resilience/disruption to transport infrastructure. These analyses include 'cost-studies' that examined the costs

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[24] This is the broad approach adopted by Dalziell and Nicholson (2001), Wang (2018), the Qld DTMR (2011) CBA manual and the ATAP flood resilience initiatives (TIC, 2019).

[25] Mechler (2016) reported that most studies focus on the financial (ie, monetary costs) and ignore indirect effects. The Qld DTMR (2011) CBA manual and the ATAP flood resilience initiatives (TIC, 2019) ignore these impacts.

[26] The 'inoperability' of an economy is defined as the change in output over its normal expected output (Ali & Santos, 2012).

[27] The IIM has been examined and/or applied in several studies, including Okuyama and Santos (2014), Jonkeren and Giannopoulos (2014) and Santos and Haimes (2004).

[28] MERIT recognises that businesses may behave differently after a disaster. It also includes factors that allow businesses to improve their operability, such as pre-event mitigation, post-event adaptation and resilience (Brown et al., 2015).

of disruption, and 'CBA studies' that undertook a CBA of selected investments. Some notable studies include the following.[29]

- Tonkin + Taylor and EY (2017) provided an options assessment and CBA to analyse floods that could affect the Franz Josef township.
- Dalziel and Nicholson (2001) analysed the costs of hazards that could close the Desert Road section of State Highway 1 in New Zealand.
- Wang (2018) discussed the key concepts and developed a hypothetical worked example of a new bridge providing resilience benefits.
- Wardman et al. (2014) summarised the results of several 'cost-studies' and other CBA studies.

There are less detailed examples publicly available. Deloitte Access Economics (2016) discussed related concepts and conducts a high-level analysis of a new bridge to address flood risk in Dubbo along with case studies related to electricity and communications infrastructure. Similarly, there are other high-level analyses of case studies contained within other guideline documents. We have also been party to some analyses shared with us on an in-confidence basis that include consideration of resilience.

The Wellington Lifelines Group has been leading the Wellington Lifelines Regional Resilience Project and recently released a business case (Wellington Lifelines Group, 2019) for a programme of (transport and other) infrastructure investments to improve Wellington's resilience to a major earthquake. The business case includes costing and overall economic impact analysis but does not include a CBA of individual projects.

There have been several studies that have attempted to quantify the indirect effects of disasters that have caused disruptions to transport. However, the relevance of much of the literature is limited. Some of the literature does not directly examine welfare impacts in a way that can be imported into a CBA, and most studies do not isolate the impacts of a transport outage from broader impacts.[30] Notable studies from New Zealand include the following.[31]

- Clydesdale (2000) used an IO model to estimate non-user costs for a hypothetical disruption to Kaikōura. The author looks at road closures specifically but only estimates gross losses and does not net off expenses that would otherwise not be incurred if production was not occurring.
- The Ministry of Transport (2013) assessed the transport impacts of a storm that closed a major rail line in Wellington for multiple days. These impacts included repair to the damage on the transport network, the loss in value of travel time and reduction in production outputs due to employees being absent from work.
- Imran et al. (2014) studied the impact of significant disruptions in the Manawatū-Wanganui Region, including widespread failures caused by flooding in 2004 and the lengthy closure of a significant inter-regional road connection (the Manawatū Gorge State Highway 3 road) due to a landslide in 2011–12. The analysis was largely qualitative in nature.

[29] There are also many studies that have conducted non-economic evaluations. For example, the Department of Internal Affairs (2019) examined a 2017 fuel supply disruption in Auckland, and Imran et al. (2014) examined the impact of disruptions related to Manawatū Gorge.

[30] Most studies value the impact of a disaster rather than the impact that can be attributed to lack of resilience in transport infrastructure.

[31] Additional case studies for New Zealand using the MERIT are listed at www.merit.org.nz/case-studies. Similar studies have been reported elsewhere.

- Taranaki Regional Council (2016) examined the economic impact of a flood in the Taranaki region. However, the study does not distinguish the losses due to road closures and losses due to damage to other inputs to production.
- Market Economics (2016) used MERIT to estimate the economic impact of a large 2011–12 slip in the Manawatū Gorge that closed State Highway 3. The results of this study are examined in section 4.2.3.
- Market Economics (2017) studied the economic impact of the 2016 Kaikōura earthquake. The paper assessed the economic impact from disruption to horizontal infrastructure (ie, roads and bridges, water pipes, sewer pipes and stormwater pipes, household and government consumption and industry sectors, including tourism). This assessment provides direct impacts such as changes in expenditure, business operability and employment, and flow-on impacts caused by these direct impacts (known as indirect impacts). These indirect impacts are estimated using the MERIT model.

Among the international studies, we found few that focused on transport. The most relevant empirical examples identified are as follows.

- The US Department of Homeland Security (2011) assessed the gross domestic product (GDP) effects of a hypothetical port closure. The closure caused loss of business to firms, and the economic impact cascaded through the supply chain outside of the port region.
- Pfurtscheller and Genovese (2019) studied the impacts of a 2013 landslide in Tyrol, Austria. However, the study considers only the regional effects of the landslide (see Box 2.3 below).

Box 2.3 The Felbertauern landslide of 2013

The authors studied a 2013 landslide in Tyrol, Austria, that destroyed 100 metres of road. disrupted traffic and had several impacts on the regional economy.

They identified two loss categories:

(1) additional costs of commercial transport

(2) decrease of tourist flows.

To calculate (1), well-established methodologies such as driving time and kilometres driven were used to calculate the costs of diversion (vehicle operating costs were excluded). It was assumed there was no production loss in other industries as there were alternatives routes that commercial trucks could use to deliver goods. The additional transport cost is a loss in producer surplus.

To calculate (2), the authors used estimates of declines in overnight stays to estimate loss of income, which they assume is similar to the loss in production (there are cost savings to be had from reduced expenses, but these were considered negligible).

We note that the study considers only the regional effect of a landslide. We would expect some tourists to go to other locations in the country, in which case the loss to one vendor would be a gain elsewhere, in part mitigating the overall loss to the economy.

Source: Pfurtscheller and Genovese (2018)

3 Framework and methodologies

3.1 Introduction

This chapter provides a framework and recommended approaches and methodologies for quantifying the costs and benefits of resilience in transport appraisal. The material provided in the chapter has been developed from reviewing relevant literature, engaging with the Steering Group, and reviewing case studies (of historical transport projects) to pilot and test the framework methodology.

The proposed guidance material was developed to be consistent with the existing EEM and its primary function of providing 'consistency, transparency and comparability between the economic efficiency of multiple activities'.

The material developed is in accordance with accepted CBA economic concepts and principles. The development of the material was also guided by the following principles.

- **Accuracy** – The materials should encourage accurate estimates and avoid double counting.
- **Usability** – The materials need to be sufficiently simple to encourage use.
- **Flexibility/adaptability** – The materials should be sufficiently flexible and adaptable to different situations.
- **Breadth of benefits** – Consideration will be given to the broad range of benefits of resilience.
- **Reflect uncertainty** – The guidance will reflect that the frequency of disruptive events is inherently uncertain. It should not promote a full sense of accuracy.
- **Consistency** – The material should be consistent with the EEM and, where appropriate, align with other relevant frameworks. Consistency includes use of a common language.
- **Comparability** – The material should promote the use of common techniques and parameters where possible.
- **Cost effective** – The effort expended on the evaluation should be proportional to the problem itself.

Where possible, the terminology and descriptions have been developed to align with the EEM and other related materials. These include the Transport Outcomes Framework and the ATAP guidelines; in particular, the flood resilience initiatives (TIC, 2019). Other government documents such as the 2018 Government Policy Statement on land transport provide a useful context for the review but do not directly influence the materials.

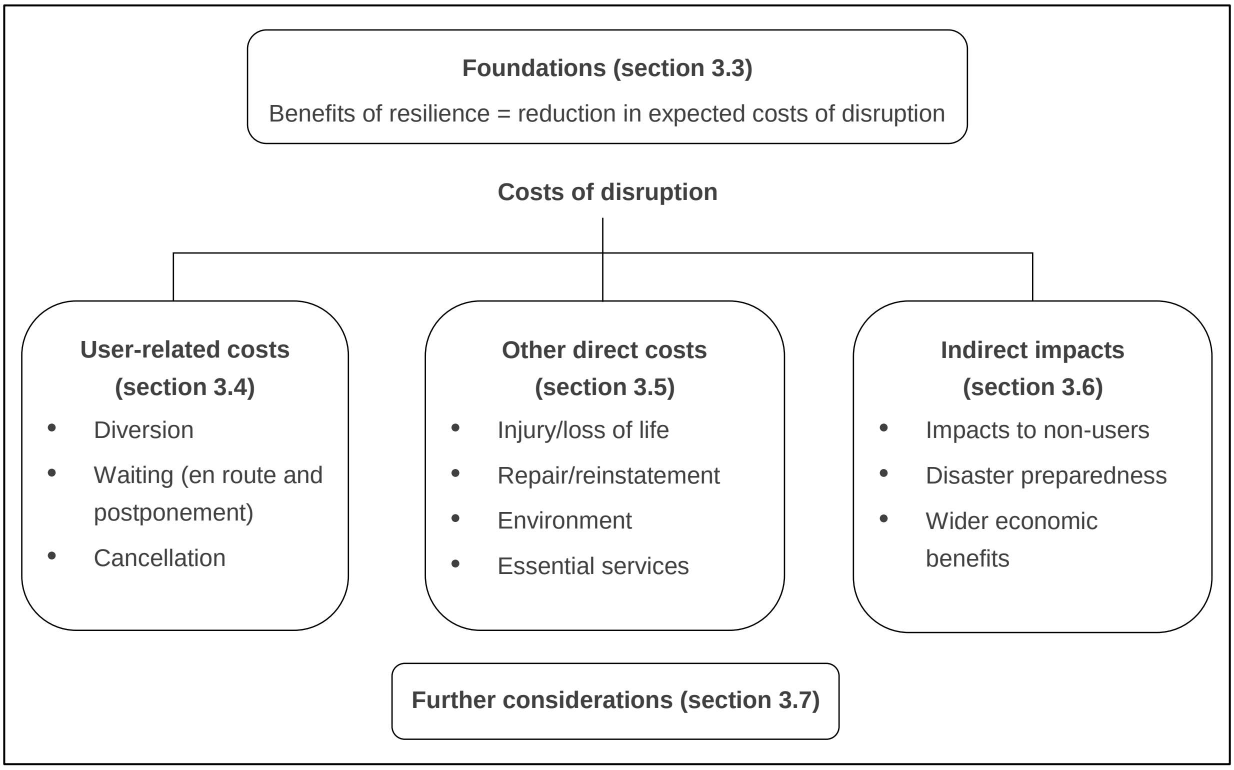
We expect the framework, approaches and methodologies to be mainly applied to projects affecting the road network, and often we refer to affected transport users as road users. However, the methods can be applied to non-road-user infrastructure projects (eg, light rail), and accordingly, in such cases the term 'road user' might be replaced with a more generic term of 'transport user'.

3.2 Chapter overview

As with all investment appraisal, the evaluation of resilience will involve comparing the costs and benefits of different options. The costs of achieving resilience are primarily associated with the additional costs of more-resilient infrastructure (investment and maintenance), and estimating the costs to improve resilience should be consistent with the estimation of costs of any other infrastructure investment. Accordingly, the focus of this work is on evaluating the benefits, which are substantially more complex.

An overview of the methods to evaluating the benefits of resilience in investment appraisal is illustrated in Figure 3.1 below.

Figure 3.1 Overview of methods for evaluating resilience



Resilience can be incorporated into transport appraisal by valuing benefits as the avoided costs of disruption. The costs of disruption can generally be valued using an expected-cost approach that accounts for the likelihood and severity of disruptions. In some cases, this may simply be done using average time of disruption. For some costs and situations, it will be necessary to explicitly estimate the costs for different levels of severity of disruptions. These foundational matters are discussed in section 3.3 below.

There are a range of costs, which are discussed in sections 3.4 to 3.6. Much of the focus of the technical guidance material is on the direct costs to users (section 3.4), which depend significantly on the presence of alternative (diverting) routes and the change in user behaviour. However, other costs, such as the impacts to related essential services, may be potentially more significant.

The costs to consider, the methods and the depth of analysis needed will vary depending on the situation. The simplest situations will involve short disruptions where there are alternative routes. In such cases, the analysis will largely involve estimation of changes in transport costs using (largely) standard transport cost methods.

More complex situations arise when the alternative options are limited, and the impacts extend to non-users. These and other indirect effects are considered in section 3.6. In such cases, other methods may be required to complement or replace some of the standard core techniques. Further considerations, including the adaptation of transport users to disruptions, the distribution of impacts, service expectations and use of surveys, the risk of multiple hazards, and other means of achieving resilience, are discussed in section 3.7. These more complex situations may involve bespoke analysis and/or the use of models that are designed to analyse the impacts of disasters.

3.3 Foundations

3.3.1 Introduction

Consistent with the definition of resilience, the benefits of resilience may be estimated as the expected avoided costs of disruption. These avoided costs may be estimated using a set of methods and techniques that are described in the following sections.

These methods and techniques largely build on those contained in the EEM. There are a number of features of disruptions that warrant special mention.

- First, an inherent feature of disruptions is uncertainty. While uncertainty is a feature of all appraisals, it is particularly prominent with respect to disruption, both in terms of the likelihood of a disruption and how users respond. This uncertainty needs to be acknowledged and considered in investment appraisal.
- Second, the behavioural response to disruptions is important and can change over time. In conducting evaluations, it is necessary to consider the extent to which travel use behaviour changes as users adapt to the disruption.
- Third, and potentially most importantly, severe disruptions can have transformational impacts, which may not lend themselves to standard techniques. For example, the most significant costs associated with a bridge collapse may be the impact on essential utilities associated with the bridge. These broader disruption impacts need to be identified. Accordingly, the nature and focus of the analysis and emphasis will vary with the features of the disruption being considered.

3.3.2 Incorporating the benefits of resilience

An investment appraisal will typically include consideration of options that have other benefits in addition to resilience. The other benefits should be estimated using the standard appraisal methods. In effect, the resilience benefits may be estimated as adjustments to the investment appraisal conducted for the non-disruptive state. Thus, if options are being considered with different levels of resilience, then the value of an option relative to base can be assessed as:

Value of Option relative to Base Case =

- net change in benefits in non-disruptive state *plus*
- net change in benefits of resilience

(Equation 3.1)

Where:

Net increase in benefits of resilience = Net reduction in expected costs of disruption

- expected costs of disruption under the Base Case *less*
- expected costs of disruption under the Option.

For example: Flooding causes annual costs of disruption of $1 million along a particular route. An alternative route is being considered that provides transport cost savings valued at $3 million per year. The new route is also subject to some flooding, but due to higher elevation, the annual cost of disruption is estimated to be $0.4 million. The annual benefits of the alternative route relative to the base case are then estimated as $3.6 million (ie, $3 million plus a $0.6 million reduction in disruption costs).

Where the disruption costs are expected to be material, an analysis should consider the options during normal and disrupted states. Of note, some disruptions (eg, flood or earthquake) may affect all options being considered, and some disruptions (eg, a rockslide) may be specific to each option.

In some cases, the impact of the investment will be solely to improve resilience (eg, rockfall preventative measure). In such cases, the benefits of the investment are simply to reduce the expected costs of disruption (including the associated damage).

It is preferable to explicitly value the disruption costs for each option. This helps to highlight the ongoing costs of disruption and facilitate consideration of interventions that may help to minimise these costs. Explicitly reporting disruption costs may also be important as the estimates of disruption costs will typically be subject to high uncertainty, due to the uncertainty associated with hazard events.

3.3.3 Accounting for risk and uncertainty

3.3.3.1 Overview

Although they are often used interchangeably the terms **risk** and **uncertainty** have different meanings. Risk refers to situations where possible outcomes are identified and are expected to occur with a probability that can be reasonably estimated. In contrast, uncertainty refers to situations where potential outcomes cannot be reasonably identified, or the probability cannot be measured. Many disruptive events, such as floods, may be categorised as risks due to the availability of information (including historical data and flood maps) that can be used to estimate the likelihood of the event. The disruption of the COVID-19 pandemic illustrates uncertainty – we note that a pandemic was not identified as a potential disruptive hazard in any of the literature we had reviewed, and we are not aware of any reasonable means to forecast the likelihood of future similar events.

Techniques to incorporate risk and uncertainty into investment appraisal are discussed below. A starting point is to conduct a risk analysis (see section 2.1.2 above, and section A13 of the EEM) so as to identify potential hazards (sources of disruption) and assess, where possible, their impact and likelihood. In identifying the sources of disruption, it is important to consider the broad range of transport-related hazards that may be significant. These may include, as categorised in Table 2.2, natural, technological and social/political hazards.[32]

The process of risk analysis is critical to the CBA of resilience. It is required to develop options for a CBA as well for quantifying the expected disruption costs associated with different options. While there are numerous guides, publications and tools that support the process of risk assessment, there are inherent difficulties with the process. Issues and challenges include:[33]

- the dependency on assumptions that are 'informed by imperfect historical records'
- the problem that uncertainties in a model compound

[32] Consideration should also be given to emerging and future sources of disruption. For example, power disruptions may become a source of transport disruption as the vehicle fleet becomes increasingly electrified.

[33] This list is from Crawford et al. (2018), who provide a recent and useful guide to risk modelling as a tool to support natural hazard risk management in New Zealand local government. While the paper is focused on the use by local government, it is nevertheless a useful resource.

- there is a continued immaturity of risk modelling and its data[34]
- the distribution of impact of some hazards may be fat-tailed, whereby some of the highest impact events are more likely than forecasted, based on existing probability distributions.

Furthermore, all risk analysis and risk management rely on judgements regarding both technical issues and preference issues, made either implicitly or explicitly.[35]

3.3.3.2 Accounting for risk

To account for risk, the costs of disruptions should generally be valued as expected values; that is, the average costs of disruption, weighted by their likelihood of occurrence.[36] This approach, which treats expected values as being equivalent to certain amounts, is common practice in conducting a social CBA and is consistent with the guidance of the EEM (section 2.10).

In effect, the approach of using expected values assumes that society is risk-neutral with regard to the distribution of outcomes. Although individuals are generally assumed to be risk-averse (ie, they prefer a certain value over the same expected value) the approach is generally considered reasonable when pooling risk over a collection of policies and/or over a large population.[37] In some situations, the outcomes may be so severe (eg, a large loss of life) or broad (eg, widespread societal disruption) that the assumption of risk-neutrality is inappropriate. In such cases, the expected value approach may undervalue the benefit of resilience. To address this concern, the severity of the outcomes should be highlighted in the analysis.

Calculating expected values may be unnecessary where the value of resilience can be estimated directly from surveys of affected stakeholders (in such cases the calculation has been internalised in the survey).

The approach to calculating expected values may vary by severity and frequency of disruption. For resilience to frequent disruptive events, there may be sufficient historical data to estimate the expected costs of disruption based on historical averages. For example, with regard to the frequently flooded roads, the costs of disruption may be estimated as a function of the annual average time that the road is closed.

$$Expected\ annual\ disruption\ costs\ =\ function\ (annual\ average\ time\ of\ closure) \quad \text{(Equation 3.2)}$$

In other situations, historical data may be insufficient to provide a guide. For example, a route may be expected to be vulnerable to a severe earthquake or flood, for which there is no historical precedence. In such cases it may be necessary to estimate expected disruption costs based on estimates of the likelihood and severity of disruptive events. As the severity (and therefore costs) is related to frequency, the expected

[34] Crawford et al. (2018, p. 616) note:

> *while work is ongoing to further develop risk models, they cannot yet compute multi-hazard events or cascading consequences, and cannot be used to their fullest extent due to unavailability of data and expense of developing it. Even though practitioners see the benefits in risk modelling, they're reluctant to invest in its development due to resource pressures (time, capability and money), as well as the limited assurance that decision-makers would appreciate its value.*

[35] As noted by Chang et al. (2014, p. 420).

[36] For many disruptions (eg, flood) the severity of the disruption (and thus its cost) will be related to the likelihood, with more severe and costly events having a lower frequency.

[37] The approach can be justified using the Arrow–Lind principle, which is that, under certain assumptions, the social cost of the risk moves to zero as the population tends to infinity, and therefore the government should behave as an expected-value decision maker (Arrow & Lind, 1978).

annual disruption cost may need to be estimated as a weighted average of events with different levels of severity as follows:

$$Expected\ annual\ disruption\ costs\ = \sum_i Annual\ probability\ disruption_i\ \times\ cost\ of\ disruption_i$$

(Equation 3.3)

Where the subscript *i* refers to disruptions of different severity (eg, a 1-in-200-year flood).

This approach is elaborated in section 3.4.1.2 below.

In some cases, it may be appropriate to combine both methods. Consider a route that has been subject to frequent flooding and includes a bridge that is expected to be damaged should a very severe flood occur (eg, a 1-in-100-year flood). Should the bridge be damaged, the period of closure may be significantly greater than historical averages due to the time to conduct the repair. In such a situation, the average historical costs would understate the expected cost. To address this issue, the expected annual disruption costs may be estimated as the sum of the costs estimated using historical averages plus an increment to reflect the additional expected annual disruption cost that would occur should the bridge be damaged, multiplied by the likelihood of that occurring.

3.3.3.3 Accounting for uncertainty

All investment appraisals involve forecasts and incorporate uncertainty. However, uncertainty is likely to be a more significant factor for projects for which resilience is a prominent consideration. This is particularly true for low-frequency, high-impact events, such as natural hazards. By their nature, disasters are low-probability events, and consequently there tends to be limited information to assess the probability and the potential impact.

The uncertainty in the analysis should be acknowledged and reflected in the appraisal. Consistent with the EEM, sensitivity analysis should be conducted (particularly with regard to high-impact events). Comprehensive risk assessments should be undertaken to consider the broad range of potential impacts.

Consideration should be given to the risk that the likelihood and impact of disruptions may differ significantly to that assumed. This may also be an issue when historical data is used – it is important to assess the risk that historical data is not representative.

Where new information is expected to become available in the future that may modify the optimal decision, a real-options approach may be appropriate. In the resilience context, this may be appropriate because information improves over time as the impact of climate change becomes clearer and/or as hazard-risk analysis and modelling improve.

In such cases, the optimal decision made in the present may provide flexibility to take different actions in the future as new information unfolds. For example, an evaluation may consider a relatively expensive option in the short term because it provides the flexibility for expansion in the future should demand expand more than predicted. This is considered in the EEM in ‘A10.9: Investment option values’.

Consideration should also be given to the effect of climate change, where appropriate.[38] Climate change is expected to affect the likelihood and intensity of a range of natural hazards that cause disruptions and,

[38] The need for, and challenges of, evaluating the impacts of climate change are reflected in the 2018 Government Policy Statement on land transport (New Zealand Government, 2018, pp. 18–19).

consequently, the value of mitigation that is incorporated into a CBA. Furthermore, rising sea levels (and associated risks with storm surge) may have a broad impact on the transport network.[39]

3.3.4 Types of disruption costs

The costs of disruption may be categorised as:

- **user costs** – costs to users associated with a loss of functioning of the transport infrastructure[40]
- **other direct costs** – other costs directly as a result of the disruption
- **indirect costs** – costs of disruption not directly associated with use of the infrastructure.

A summary of these is provided in Table 3.1 below. Not all costs will be material to an investment appraisal. As with other costs and benefits, the depth of analysis on disruption costs should be commensurate with their expected significance.

Table 3.1 Types of disruption cost

Category	Section
Direct costs to users associated with a loss of function. Associated with:	3.4
Diversion through alternative routes	3.4.4
Waiting for disruption to clear, including waiting en route and postponement	3.4.5
Trips cancelled	3.4.6
Other related costs (accommodation costs, loss of perishables, use of alternative modes)	3.4.7
Other direct costs	3.5
Injury or loss of life (due to less-resilient infrastructure)	3.5.1
Repair/reinstatement and other costs	3.5.2
Environmental and other externalities (including congestion)	3.5.3
Impact on essential services (including utilities and emergency services)	3.5.4
Indirect costs	3.6
Disruption costs to non-users	3.6.1
Wider economic benefit impacts	3.6.2
Disaster preparedness (eg, inventories)	3.6.3

[39] There are some studies (eg, Nemry & Demirel, 2012; PIARC Technical Committee, 2019) that have attempted to analyse the impacts of climate change on transport infrastructure and networks. The findings of such studies highlight that climate change should be a relevant consideration in CBA of infrastructure investment; however, little guidance is provided.

[40] A question for any CBA is ‘Whose benefits and costs should be counted?’ (a concept known as ‘standing’). Typically costs and benefits to foreigners are excluded in CBA (eg, New Zealand Treasury, 2015, para. 301). In some transport appraisals involving resilience, the affected users may include a significant portion of foreign tourists. We recommend that for assessing the benefits of resilience, foreign tourists be treated no differently to locals because: a) a bad experience can impact negatively on New Zealand’s reputation as a tourist destination; and b) of the practical difficulty of separately analysing the impacts to foreign tourists.

3.3.5 The appropriate modelling approach

The appropriate approach will vary with the nature and impact of the disruptions that are being considered.

The benefits of resilience to minor recurrent disruptions, such as those caused by congestion and minor incidents, may be best estimated using the EEM methods to quantify reliability (see EEM sections A4 and A18). For less frequent and more severe disruptions (eg, due to floods and rockfalls), the methods described in this report may be applied.

The situations may vary greatly in complexity. The simplest situations are where the expected disruptions are short (less than a week), there is historical data (on the frequency and impact of disruption) and there are alternative routes available, which can be used as a basis for estimating the costs to users. In such cases, the expected costs of disruption will primarily relate to the change in users' transport costs, which can be calculated by applying techniques consistent with those contained in the EEM.

For a variety of reasons, the analysis may be more complex and may require different approaches, including bespoke analysis and/or use of disaster modelling. While we expect that in most cases the analysis will involve directly estimating changes in transport user costs using the travel-cost methods, alternative approaches such as the use of a survey to determine willingness-to-pay (WTP) may be applicable in some circumstances.

Table 3.2 provides some brief examples of appraisals with different modelling implications.

Table 3.2 Example situations and modelling implications

Situation	Implications for modelling
Recurrent disruptions (eg, congestion, public transport delays)	• Resilience benefits may be best estimated using improvements in reliability.
Medium-impact, medium-frequency events (eg, roads exposed to frequent floods)	• The most significant costs will likely relate to users, which can be estimated using standard techniques. • Data from prior events may be used to assess likelihood and event severity, user behaviour and costs of repair.
High-impact, low-frequency events (eg, earthquake, major flood)	• Historical data may be unavailable, and forecasts will be required on likelihood, severity and user behaviour. • Disruptions may last long enough to see significant adaptation (ie, changes in behaviour) by users.
Damage to unique transport asset (eg, key road link to a port)	• Costs of disruption may not be estimated based on use of alternative routes. Potential for significant production losses. Non-standard modelling required.
Damage to collocated essential infrastructure (eg, bridge that is a conduit for essential utilities)	• Loss of utilities may outweigh (perhaps significantly) the cost to road users. • Potential for significant economic impacts.
Multiple hazards affecting multiple elements of transport system	• May need to consider a range of disruptive scenarios. • Simulation modelling (eg, Monte Carlo analysis) potentially useful in analysing risks.

3.4 Direct costs to user from a loss of functioning

The direct costs to transport users stem from a loss of functioning of the transport infrastructure. A starting point for analysing the transport-user costs is to obtain (or estimate) data on usage and the likelihood of loss of functioning.

Consistent with the EEM, usage may be expressed in terms of annual average daily traffic (AADT). The direct costs to users will vary by type of vehicle and trip purpose. Where the traffic composition is not known, estimates contained in the EEM (Table A2.3 Traffic composition (%)) can be used.

3.4.1 Estimating the period of disruption

3.4.1.1 Using historical data to the period of disruption

The loss of functioning may potentially be estimated based on historical data on closure. For some causes of disruption (eg, floods and rockfalls), historical disruption data that can provide a basis for analysis will be available.

A hypothetical example of this data is shown in Table 3.3.

Table 3.3 Hypothetical base case disruption data

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Disruptions	1	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0
Hours closed	50	30	0	0	0	0	24	0	0	0	0	0	0	4	24	0	0	0	48	0

Source: Hypothetical data

The historical data can be used to calculate the average annual time of closure (AATOC).[41] The AATOC is the average number of hours a road (or other link) is closed per year and may be used as the basis for estimating the cost of closure. It can be simply calculated using historical data as the total hours the route has been closed divided by the number of years over which the disruption data has been evaluated. In our example above, this is calculated as:

$$AATOC = \frac{(50+30+24+4+24+48)}{20} = \frac{180}{20} = 9\ hours\ per\ year$$

(Equation 3.4)

3.4.1.2 Estimating AATOC when historical data is not available

For some disruptions, the necessary historical data will not be available or will be inadequate because the range of hazard events has not been experienced. For example, an earthquake or major flood may cause significant damage to infrastructure that has not previously been experienced. In such cases, the AATOC can be calculated based on estimates of how the disruption varies with events of different severity.

The severity of hazard events such as floods and earthquakes is generally categorised by the events' annual recurrence interval (ARI). The ARI, or 'return period', is the average, or expected, period of time between hazard events that exceed a given magnitude. The inverse of the ARI is approximately[42] the annual exceedance probability (AEP), which is the probability that the natural hazard event of at least that magnitude occurs in the year.[43] Thus, a flood with an ARI of 100 years has an AEP of 1%. Alternatively put, the probability of a flood with an ARI of 100 years or more occurring in a given year is 1%.

41 The calculation of AATOC and ADC is part of the Qld DTMR (2011) CBA manual and the ATAP guidelines for flood resilience initiatives (TIC, 2019).

42 The AEP can be more accurately estimated as $AEP = 1 - exp(-1/ARI)$.

43 The probability of occurrence of an event over a number of years can be estimated as follows.

$$Probability\ of\ exceedance\ over\ X\ years = 1 - (1 - AEP)^{X}.$$

An example of calculating the AATOC using this method with hypothetical data is illustrated in Table 3.4 and Figure 3.2 below. In the example, data has been collected on the estimated time of closure associated with different severity of events as measured by their ARI.

The procedure involves the following steps:[44]

1. Determine the minimum magnitude (as measured by event ARI) for which a disruption would cause closure. In the example provided this has been estimated as 2.5 years.
2. Calculate the AEP for each ARI (approximated as 1/ARI).
3. Estimate the duration of closure for higher ARI events.
4. Calculate the AATOC for each ARI range. This is estimated as the product of:
   a. the difference in AEP (eg, for the ARI range from 5 to 10 years the AEP difference is 0.1 = 0.2 – 0.1), and
   b. the average time of closure estimated from the boundaries of the range (eg, for the ARI range of 5 to 10 years, this is the average of 24 and 30 = 27 hours).
5. Calculate the total AATOC as the sum of the AATOCs for each ARI range.

Table 3.4 Hypothetical example of calculating total AATOC

Return period in years (ARI)	~AEP	Estimated time of closure
2.5	0.4	0
5	0.2	24
10	0.1	30
20	0.05	36
50	0.02	42
100	0.01	48
Max (10,000)	0.0001	60

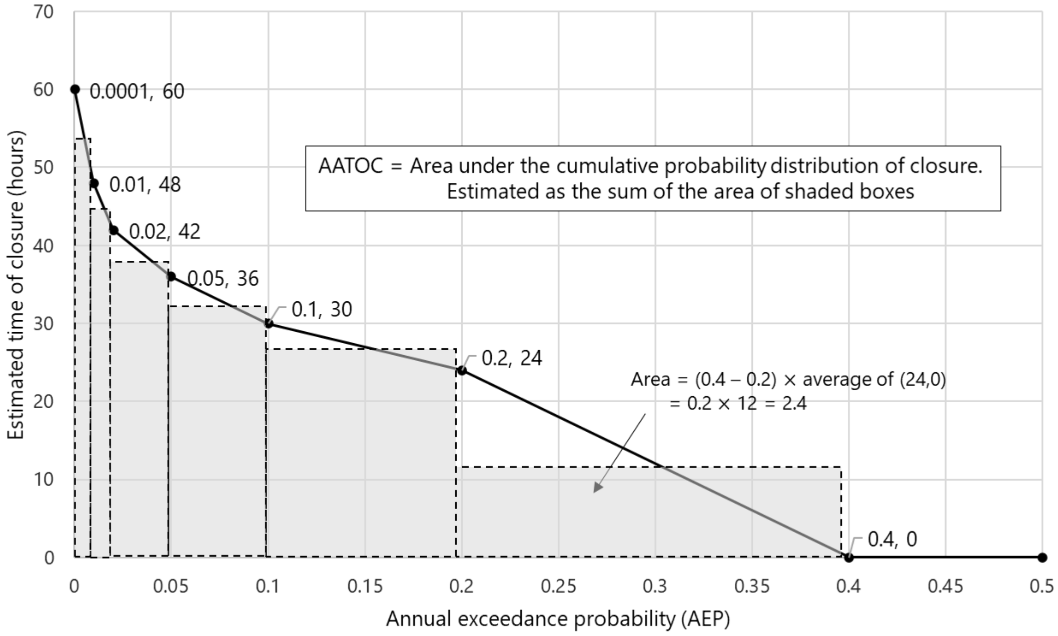
→

(a) AEP difference (ARI range)	(b) Avg. time of closure	AATOC = (a) × (b)
0.6 (up to 2.5 ARI)	0	0
0.2 (2.5 to 5 ARI)	12	2.40
0.1 (5 to 10 ARI)	27	2.70
0.05 (10 to 20 ARI)	33	1.65
0.03 (20 to 50 ARI)	39	1.17
0.01(50 to 100 ARI)	45	0.45
0.01(100 to max ARI)	54	0.53
Total AATOC		**8.90**

Source: Hypothetical data

[44] This method is consistent with Austroads' (2013, section 4.4) *Guide to Road Design – Open Channels, Culverts and Floodways*.

Figure 3.2 Estimating AATOC from time of closure by AEP



Using an average measure (ie, AATOC) is a useful simplification. In some cases, it may be appropriate to consider the probability distribution of the disruptions because of an expectation that the costs will differ greatly based on the length of duration or because of the need to consider multiple types of hazards. A related complication is that a single event or multiple hazard events may impact several links in a transport network. Such situations complicate the analysis but do not change the core approach (see section 3.7.4).

The closure time may also differ for light and heavy vehicles. For example, for flooded roads, heavy vehicles may have to wait for an additional time to allow the road surface to have sufficiently dried to have the strength for heavy vehicles.

3.4.2 Duration of closure

The historical data is also useful in determining the typical duration of closure, which can provide a guide for assessing road-user behaviour. For this purpose, we recommend calculating the median duration of closure (MDC) and the average duration of closure (ADC).[45]

The MDC is simply the median value of duration of closure when the road is closed. Using the example data in Table 3.3, the median value is 27 hours, being the average value of the two middle observations.[46]

The ADC is simply calculated as total hours the road has been closed divided by the number of disruptions in the period of evaluation. In the example, this is calculated as:

$$ADC = \frac{(50 + 30 + 24 + 4 + 24 + 48)}{6} = \frac{180}{6} = 30\ hours\ per\ disruption$$

(Equation 3.5)

[45] Other guidance materials (Qld DTMR, 2011; TIC, 2019) recommend calculating just the ADC. We expect the MDC to be a more useful indicator for predicting the likely changes in user behaviour.

[46] When there is an even number of observations, the median is calculated as the average of the two middle observations (in this case the average of 24 and 30 hours).

The MDC and ADC can also be easily calculated from the AEP data example illustrated in Table 3.4 and Figure 3.2. The MDC is the expected duration of closure (EDOC) associated with the midpoint in the AEP range when the road is closed. This can be simply found as the EDOC associated with the AEP that is half the minimum AEP to cause a closure. In the example, the AEP range when the road is closed is from AEP = 0 to AEP = 0.4 (associated with an ARI of 2.5 years), and the MDC is 24 hours (the EDOC when AEP = ½ × 0.4). The ADC can be estimated as the AATOC divided by the average number of disruptions per year. In the example, the average number of disruptions per year is the AEP of the minimum ARI for which a disruption occurs. Thus, the ADC in the above example is 8.9/0.4 = 22.3 hours.

3.4.3 Transport user choice

When there is a disruption, users of the disrupted route face three broad options. They may:

1. divert, assuming a feasible alternative route is available
2. wait for the disruption to be cleared, which may involve:
    a. waiting en route or
    b. postponing the trip
3. cancel their trip, which may include using an alternative mode of transport or using an alternative destination.

The type and magnitude of costs incurred by the users will depend on the behaviour they choose. Users who wait will still take the same route to travel from their origin to their end destination, but they incur an additional waiting-time cost (and other incidental costs) while the route is closed. The waiting cost will also depend on whether the delay is unexpected, causing the users to wait en route, or the delay is expected, enabling the users to postpone their departure. Users who choose to divert will incur higher user costs associated with the diverting route. Those who cancel their trip incur fewer usage costs, but they lose the benefits of undertaking the trip, which we would expect to outweigh their usage costs of taking the trip should the route be open.

To estimate the disruption cost, it is therefore necessary to estimate the proportion of users that divert, wait en route, postpone or cancel. Estimating these proportions is challenging because generally there will not be the data required to make a forecast. Historical data based on previous closures may prove useful; however, comparing data before and after a disruption can be challenging due to the influence of other factors on demand, including traffic growth, seasonal factors and other developments.[47] Surveys of users may also be used to estimate changes in behaviour.

User behaviour will depend on the cost of the options available, which in turn depend on the available alternatives and the likely duration of closure. We would expect that drivers will choose the option with the lowest perceived cost. The longer the diverting route, the more people will wait or cancel their trip. Similarly, the shorter the expected wait time, the more users will wait rather than divert or cancel the trip.

The cost of diversion and waiting may be reasonably well estimated using information on the expected diverting routes and wait times and using the techniques described in sections 3.4.4 and 3.4.5 below. The duration of disruption (as be measured by MDC or ADC) will be an input into these calculations.

[47] There is a small literature that has examined the behaviour changes in response to transport disruptions. This includes Cairns et al. (2002), who studied the traffic impacts in response to planned and unplanned 100 bridge and road closures; Zhu and Levinson (2012), who provide a review of theoretical and empirical studies; and Laird et al. (2014), who draw on evidence from two weather-related disruptions in the UK.

Based on the information available and their judgement, evaluators will need to estimate the proportion of users who choose each type of behaviour vehicle and purpose. A hypothetical example is shown in Table 3.5.

Table 3.5 Driver behavioural choice in the event of road closure (hypothetical example)

	Car – commuting	Car – other work	Car – non-work	Light and medium commercial vehicles	Heavy commercial vehicles	etc
Divert	60%	70%	25%	55%	60%	…
Wait en route	5%	10%	5%	5%	10%	…
Postpone trip	20%	10%	50%	20%	25%	…
Not travel	15%	10%	20%	5%	5%	…
AADT	**2,305**	**400**	**1,100**	**634**	**464**	**…**

The perceived costs, and therefore choices by users, will vary with a number of other factors. Most notably, the costs of waiting and diverting may vary significantly with the vehicle type and the trip purpose. For example, in response to a road closure, we may expect fewer freight vehicles to wait due to the higher cost of waiting. As reflected in the standard parameter values contained in the EEM, the value of time varies by type of vehicle (eg, passenger car, heavy vehicle) and trip purpose (eg, commuting, work travel), and the vehicle operating costs vary by vehicle type and road factors (including speed, gradient and road surface conditions).

The behavioural choice may also depend on other factors, including:

- the type of commodities being transported – for example, vehicles carrying perishable goods are more likely to divert
- the potential for alternative transport modes – for example, in some cases, air transport may be a suitable alternative
- the extent of warning that users receive – for example, in some cases, floods may be predicted following heavy rain
- the location of the disruption, which may influence the costs of waiting.

A possible approach is to use a survey to gather information on how people respond to disruptions and how their response changes over time. An example of using surveys for this purpose is summarised in Box 3.1 below.

Box 3.1 Survey of changes in travel behaviour

Laird et al. (2014) presented evidence from surveys on changes in travel use behaviour following two weather-related disruptions in England in 2013. A summary of one of the surveys (as presented by the authors) related to severe winter weather is provided in the table below.

The survey results highlight the broad range of ways in which people respond and how they vary based on trip purpose. Depending on type of activity, there were large amounts of cancellation, postponement and rearrangement over time to catch up on activities and cases of people changing destinations when returning from work (or other activity). The authors also noted longer trips (over 10 miles) were less likely to be cancelled, and trips in excess of 50 miles were far more likely to be rearranged.

Activity	Delayed start	Delayed finish	Postponed	Cancelled	New destination	Conducted at home	Other	n
Commute	49%	32%	8%	41%	2%	12%	5%	974
Biz travel	21%	17%	41%	41%	2%	5%	4%	126
Return home	26%	46%	16%	16%	4%	0%	5%	74
Health	7%	7%	48%	37%	0%	0%	7%	85
School/Childcare	14%	5%	10%	80%	0%	3%	2%	278
Other care	22%	23%	34%	25%	1%	8%	9%	77
Shopping	16%	8%	46%	34%	5%	5%	2%	250
Sport	3%	1%	24%	75%	1%	0%	0%	113
Leisure	5%	3%	28%	59%	2%	1%	7%	151
Family/Friends	9%	4%	46%	45%	2%	2%	1%	194
Other	12%	8%	15%	24%	1%	1%	11%	95

Source: Laird et al. (2014)

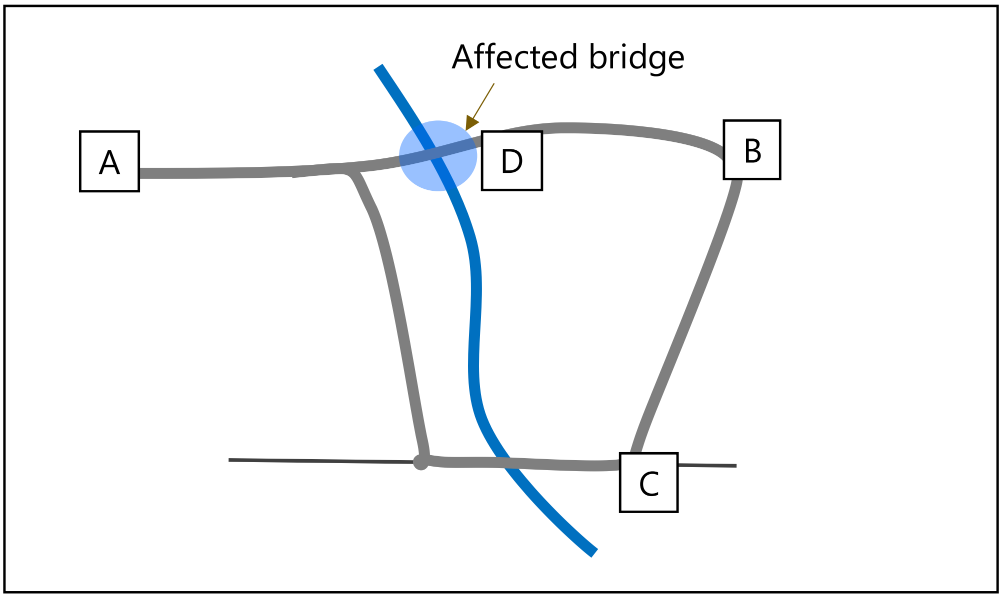
3.4.4 Cost of diversion

A diversion will generally be longer and of a lower standard than the direct route. As a consequence, users taking a diverting route will incur additional travel-time costs and vehicle operating costs. They may also contribute to greater societal costs associated with environmental damage, crashes and congestion. Each of these costs can be estimated using the standard methods documented in the EEM.

The chosen diversion route and consequently the incremental diversion cost will depend on the traffic travel destinations. In the simple example in Figure 3.3 below, the normal route between A and B is via D. In times of flood, the bridge at D is closed, forcing users to take a longer diverting route via C, thereby incurring an incremental travel cost. For trips between A and D, the incremental diversion cost is higher as it requires travelling the route ACBD, which includes the additional backtracking between B and D.

The optimal diverting route may vary by vehicle type and purpose. In particular, some diverting routes may be inappropriate for heavy vehicles due to restrictions (eg, mass limits on bridges) or driver preference. Travel flow data from prior disruptions and/or surveys may be useful to determine the diversion routes taken.

Figure 3.3 Example diverting route



Source: Adapted from TIC (2019)

3.4.4.1 Calculating per-trip diversion costs

The diversion cost can be calculated on a per trip basis as the additional cost to the normal route – that is, the cost per trip using the diverting route less the cost per trip using the normal route.

These costs may be materially different along the diverting route than on the normal route due to a range of factors including the route distance, average speed and road conditions. The average crash costs on the diversion route may be greater because the diverted road is longer and of poorer quality. Variables inputting to the vehicle operating cost calculation can include the road gradient, curvature, roughness and travel speed, which may all vary by route. Consequently, information on the road condition is needed for both direct and diversion routes. Where these costs are expected to be material, they can be estimated using the standard procedures as documented in the EEM.[48]

In general, the standard EEM parameters for calculating the additional travel time, vehicle operating costs and other road-user costs should be used. However, we recommend the value of travel time should be increased by a multiplier for the portion of journeys for which the delay will be unexpected. This multiplier (hereafter the 'unexpected delay time multiplier') reflects substantial evidence that time spent in unexpected delays are valued at a much higher rate than normal travel time.[49] A multiplier is appropriate for both the value of the mode-user's time, reflecting their frustration and disruption to their plans, and the value of the vehicle and freight time, which reflects the disruption to operations and logistics.

The EEM currently does not report a cost or method for unexpected delay time. In the absence of an alternative, we recommend using an unexpected delay time multiplier of 3.2, which is the value recommended by the Transport for NSW guidelines,[50] to be applied against the value of mode-user time and the value of vehicle and freight time.

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[48] See EEM (section A6: Crash costs).

[49] See Laird et al. (2014, p. 10) for a brief summary of evidence and sources.

[50] See Transport for NSW (2016, Appendix 4, section 1.4). This multiplier is similar to that recommended for use in the UK (Laird et al., 2014, p. 10).

Due to improved communications on outages, the portion of trips for which the delay is unexpected may generally be small. This may be particularly so for outages that, to some extent, can be predicted. For example, users frequently affected by floods may anticipate when closures are likely to occur.

In estimating these values, it will also be necessary to consider that the disruption may lead to congestion on the diverted routes and consequently slower speeds and higher travel times than are normally recorded on these routes. The impact of congestion can be estimated using the standard techniques and methods contained in the EEM. Where material, allowance should be made also for the congestion costs imposed on normal users of the alternative route. Similarly, some allowance may be given to the additional time associated with turning around at the disruption site.

A simple example is provided in Table 3.6. In this example, we assume the delay is expected, that standard travel-time costs are used, and that the change in crash costs and vehicle emissions by route is negligible. In this example, the incremental diversion cost per trip is $34.87 for heavy vehicles and $14.06 for commuter traffic. For unexpected delays causing diversion, the travel-time cost per trip should be increased by multiplying by the unexpected delay time multiplier, which (assuming a value of 3.2) leads to an incremental diversion cost per trip of $68.54 for heavy vehicles and $31.67 for commuter traffic.

The per-trip additional cost can be used to help inform the likely user behaviour. The perceived[51] incremental cost of diversion becomes a useful key benchmark measure as it should provide an upper limit to the costs incurred by users. That is, we would expect that those who choose to postpone or wait will only do so if the incremental costs to them of doing so are less than the incremental costs of diversion. In the example, we might expect all heavy vehicles to divert given the small incremental diversion time (an additional 13 minutes).

[51] The perceived incremental cost excludes the external costs associated with road-crashes and vehicle emissions. Conceivably, the perceived cost may differ from the actual private cost estimated using EEM parameter values; however, this is best left to the judgement of the evaluator.

Table 3.6 Estimating the increment cost of diversion when delay is expected (hypothetical example)

	Heavy vehicle		Commuter	
	Normal	Diversion	Normal	Diversion
Route taken (refer to Figure 3.3)	AB	ACB	AD	ACBD
Route length (km)	12	20	5	34
Travel time (minutes)	12	25	5	40
Average speed	60	48	60	51
Gradient %	2.00	4.00	2.00	4.00
Value of time (per hour)	$80.00	$80.00	$12.01	$12.01
Travel-time cost per trip	$16.00	$33.33	$1.00	$8.01
A. Incremental travel-time cost per trip		$17.33		$7.01
Vehicle operating costs (cents per kilometre)	173.83	192.00	23.64	24.21
Vehicle operating costs per trip	$20.86	$38.40	$1.18	$8.23
B. Incremental vehicle operating costs per trip		$17.54		$7.05
C. Incremental crash costs per trip	*Negligible – not costed*			
D. Incremental vehicle emissions	*Negligible – not costed*			
Incremental diversion cost per trip (A + B + C+ D)		**$34.87**		**$14.06**

Notes: Hypothetical examples. Value of time and vehicle operating costs calculated using EEM standard values for a heavy vehicle (class HCV-II) and a commuting passenger vehicle (class PC). The value of time for heavy vehicles includes an allowance for vehicle and freight time and the value of time for the mode user.

3.4.4.2 Calculating average annual disruption costs

The incremental diversion costs per trip can be combined with estimates of traffic volumes to calculate the disruption costs associated with diversion.

For any vehicle type, the average annual disruption cost can then be calculated as the product of:

- the average annual time of closure per year (AATOC) (divided by 24 to convert to a days-per-year value)
- the average annual daily traffic (AADT) for the vehicle-type/purpose that normally use the route
- the estimate of percentage of trips that will divert, and
- the incremental diversion cost per trip.

That is, the annual disruption cost from diversion can be expressed as:

$$\boldsymbol{Annual\ disruption\ cost\ from\ diversion} = \sum_i \frac{\boldsymbol{AATOC}}{\boldsymbol{24}} \times \boldsymbol{AADT_i} \times \%\boldsymbol{D_i} \times \boldsymbol{DC_i}$$

(Equation 3.6)

Where $DC_i = Incremental\ cost\ per\ diversion\ for\ vehicle\ type\ \&\ use\ i$

$\%D_i = Percentage\ of\ vehicles\ of\ type\ \&\ use\ i\ that\ divert$

$AADT_i = The\ average\ annual\ daily\ traffic\ for\ vehicle\ type\ \&\ use\ i$

Where it is expected to be material, separate calculations may be made for diverted trips that are unexpected – involving a higher time cost – and those trips undertaken when the diversion is known. Similarly, further segmentation may be appropriate for use of alternative routes or modes.

3.4.5 Cost of waiting

Road users who choose to wait rather than divert incur the costs of waiting. These can be estimated on a per-trip basis as the expected waiting time multiplied by a value of time. As discussed below, they may include an adjustment for accommodation costs if appropriate.

The decision to wait, the wait time and the cost of waiting will be affected by the information available to road users. We would expect that road users would be more likely to postpone their trip if they receive a warning prior to departing. Similarly, road users may be more likely to divert if they are uncertain over the time for the disruption to clear. Accordingly, we recommend categorising and analysing waiting into:

- those who wait en route, due to a lack of prior information, and
- those who postpone their journey and therefore wait at home, work or other location where they can use their time more productively.

The hourly cost of waiting will differ significantly with these alternatives. The total costs of waiting will depend on the expected duration of the event and the viability of other alternatives. When diverting routes are available, we would expect road users to wait (en route or postpone) only when the expected cost of waiting is less than the incremental cost of diversion.

3.4.5.1 Waiting en route

The wait time – and consequently the decision of whether to wait – for an individual user will depend on when they arrive at the closure site. Users are more likely to wait if they arrive closer to the time when the disruption will be cleared. Consequently, when diverting routes are available, the average wait time may be very small.

Consider a disruptive event lasting 4 hours and a set of road users that are indifferent between an expected wait time of 1 hour and taking the diverting route. Assuming there is an even flow of arrivals at the road-closure site (and no trip cancellations), three quarters of the road users encountering the disruption will take the diverting route because they face a wait time of greater than an hour. The remaining one quarter are those that face at most an expected wait time of 1 hour.

Furthermore, when diverting routes are available, the average wait time may not be materially affected by the duration of closure. In the above example, increasing the duration from 4 hours to 8 hours does not change the average wait time because of the diverting route, which is preferable if the wait time is longer than 1 hour. In effect, the cost of taking the diverting route provides an upper-bound to the cost of waiting and determines a maximum expected time that users will wait en route.

On the assumption that there is an even rate of vehicle arrivals at the road closure site, the average wait time may be estimated as half the expected wait time for which users will be indifferent between diverting and waiting (in the example above, half an hour). This may be estimated by comparing the cost of waiting and diverting. Applying the same assumption, the number of users that can be expected to wait en route for any disruption is the number who arrive in the period up to the maximum expected time that users wait.

In light of the above, the total time waiting en route may be best estimated as function of the frequency of disruption. For low-frequency, significant disruptive events (ie, with a long duration of closure), the number of users who wait en route is unlikely to be material. For high-frequency, low-impact events, the cost of waiting may be a significant factor in the analysis.

When there is no viable alternative route or the alternative route is significantly costly, more transport users will choose to wait, and the wait time becomes a more significant factor.

For trips involving waiting en route, we assume that users have undertaken the trip without prior knowledge of the delay, and therefore the delay is unexpected. For such trips, the appropriate cost is the unexpected delay-time cost discussed in the previous subsection.

Consequently, the total waiting en-route cost can be estimated as the waiting multiplied by the average wait time and the travel-time cost. That is:

$$\boldsymbol{Annual\ waiting\ en\ route\ cost} = \frac{\boldsymbol{AATOC}}{\mathbf{24}} \times \boldsymbol{AADT_i} \times \%\boldsymbol{W_i} \times \mathbf{UDTC}_{\boldsymbol{i}}$$

(Equation 3.7)

Where $UDTC_i = Unexpected\ delay\ time\ cost\ per\ hour\ vehicle\ type\ \&\ use\ i$

$\%W_i = Percentage\ of\ users\ that\ wait\ en\ route\ for\ vehicle\ type\ \&\ use\ i$

$\mathrm{AADT}_i = The\ average\ annual\ daily\ traffic\ for\ vehicle\ type\ \&\ use\ i$

3.4.5.2 Prior information and displacement

When road users have prior information about the disruption, they may modify the timing of their trip so as to avoid waiting at the closure site. The avoided waiting time may instead be spent on more valuable activities (eg, at home, in an office or other location). In such cases, the waiting cost is more appropriately described as a displacement cost that reflects the cost of not being able to travel when desired. Per-hour, this displacement-time cost may be significantly less than the waiting-time cost.[52]

In the context of public transport, there have been a number of studies that have examined how the cost of displacement (ie, not being able to travel at the preferred time) compares to the travel-time cost.[53] These studies consistently find that the per-unit cost of displacement time – measured as the time between the preferred travel time and the actual travel time – is much lower than the per-unit cost of travel time.

The ATAP guidelines for public transport reflect research that the per-unit cost of displacement is 0.63 times that of travel time (TIC, 2018, section 4.5). There does not appear to be any similar relevant research that can be used as a guide for the displacement cost for other transport use. We assume that the displacement-time costs may vary significantly depending on the trip purpose and also length of disruption.

For many trips we would expect that the displacement cost will be very low. Some shopping trips, non-urgent appointments and non-urgent freight shipments may be postponed with minimal penalty. For many trips, the displacement cost may not increase materially with additional time – there may be a very small difference in the cost of deferring an appointment or shopping trip by 2 hours, 24 hours or 48 hours. Furthermore, with the exception of freight trips, the timing of clearing a disruption during the night-time hours need not matter. For some other trip purposes, such as commuting, attending an important medical appointment, and freight of perishable goods, the displacement cost may be high, and even higher than the standard wait time. Nevertheless, when displacement costs are significant, users may choose to take an alternative route if available.

For short delays (eg, < 12 hours), the displacement cost per hour could be estimated as a fraction of the standard travel-time cost. In the absence of other information, we recommend assuming the multiplier value

[52] Due to the difference in the displacement-time cost and the waiting-time cost, measures such as improved signage and communication mitigate the cost of disruptions to transport users.

[53] See Wardman (2014, section 4.2) for a summary of the evidence. Wardman (2014, p. 34) reported a displacement multiplier of 0.63.

referred to above for public transport (0.63) or lower. For longer periods of displacement, judgement will be required.

As with waiting en route, the diversion-cost per trip should provide an upper bound for estimating the total postponement cost per trip. That is, the cost of postponement per trip should be no more than the incremental cost associated with diversion.

When the number of trips postponed is expected to be small (eg, less than 5%), it is reasonable to assume that the incremental postponement cost per user is evenly distributed between zero and the incremental diversion cost, and therefore the average incremental cost per postponement is half the diversion cost. When the proportion of trips postponed is significant, this assumption is likely to lead to an overestimate.[54] In such cases it may be useful to further segment road users into reasons for postponement and make estimates by segment for the costs imposed by segment (see approach adopted in following subsection). Using such an approach may lead to the conclusion that for some segments the postponement cost is very small and unrelated to the costs of diversion.

3.4.6 Trips cancelled

In response to a disruption, rather than divert, road users may choose to cancel their trip and/or reduce the number of trips. This may be for a variety of reasons. They may:

- choose an alternative location to meet their need (eg, a consumer may travel to an alternative shopping location; a business may organise delivery from a supplier in an alternative location; a tourist may choose an alternative place to stay)
- consolidate their trips (eg, businesses may choose to undertake larger deliveries and increase inventory levels to offset increased transport costs along the diverting route; similarly, a consumer may take fewer but larger shopping trips)
- not undertake a trip at all (eg, a commuter may choose to work from home; a person may choose to miss a planned social event).

The cost of cancelling may vary significantly depending on the trip purpose and situation. The costs may be very small if a reasonable substitute can be found (eg, work from home, shop in another nearby location). Generally, we might expect that if a user cancels their trip, then the costs of waiting or diverting is greater than the value of the trip. This might not always be the case, particularly for time-sensitive trips. The impact could be significant if it involves missing an event at a specified time (eg, a wedding, sporting event, a medical appointment, a meeting set for a specified time).

When the number of cancellations is small, a potential simplifying assumption is that the cost for ‘not travelling’ users is evenly distributed between the two extremes of:[55]

- incurring no cost (eg, because they were able to find a close substitute activity), and
- incurring the minimum alternative cost, which may be either the cost of diverting or waiting.

However, this approach is likely to overestimate the cost when the number of cancellations is significant and particularly in situations where there are reasonable substitutes for some activities. Consider the following

[54] This assumption of using the mid-point is, in effect, an application of the ‘rule-of-half’, which is based on the approximation that the demand curve for trips is linear. When shifts are significant, the approximating assumption is likely to be unrealistic, leading to a breakdown of the rule-of-half. See Laird et al. (2014) and Nellthorp and Hyman (2001).

[55] Of note, the Qld DTMR (2011) CBA manual assumes the cost of cancelled trips is zero.

hypothetical example using the situation described in Figure 3.3 and Table 3.6 in section 3.4.4. Assume much of the traffic between A and D relates to shoppers travelling from D to A. As a result of the bridge closure, this trip increases from a distance of 5 km to a distance (via B and C) of 34 km. Assume also that those located in D can instead do their shopping in B (a distance of only 7 km). In this case, we would expect most shoppers from D would cancel their trip to A and instead travel the small extra distance to B. The incremental cost in this hypothetical situation is therefore likely to be very small and much less than if the above simplifying assumption had been used.

This issue may be addressed by considering the changes in user behaviour by different segments of users. Using the example above, estimates may be made of traffic that is for commuting and other purposes that have a fixed destination (eg, sporting events) and purposes for which the destination is flexible. Following the segmentation, the even distribution assumption might be applied to estimate cancellation cost for which there is not another lower-cost alternative.

3.4.7 Other user costs

3.4.7.1 Loss of perishables

An additional disruption cost associated with road users diverting, waiting or cancelling trips is the loss of, or loss in value of, perishable goods that are transported as freight. For example, a disruption may result in a loss of milk being processed in rural areas or a delay in fruit and vegetables being delivered to market, diminishing their quality and thus value to consumers. Similarly, the value of other time-sensitive goods (eg, newspapers) may be diminished by delays. The loss in value may be the result of delays en route or a cancellation of trips.

If the loss of perishables is expected to be material, and data (or reasonable estimates) are available, the loss of goods could be estimated as an incremental cost to the transport-user costs of freight. Care is required not to overestimate the cost. We would expect businesses to adapt and make use of diverting routes when they are available. Freight of some perishable goods may be cancelled because the marginal value is small. Where there are no practical alternative routes (eg, a dairy farm is cut off) estimates may be made of the loss of value of the goods not delivered.

3.4.7.2 Accommodation costs

Users impacted by a disruption may need accommodation while waiting for the route to reopen or because they take significantly longer detours. This may be a material factor for drivers of heavy vehicles who are limited by work time requirements and consequently may not be able to reach their destination before needing to rest.[56] In such cases the additional accommodation costs and the additional waiting time may be included as a cost of disruption. Only the net increase in accommodation costs should be considered; that is, consideration should be given to whether the additional accommodation leads to a reduction in need for accommodation at another point in the journey. The time spent waiting may be valued in the same way as waiting time.

Potentially the experience from previous events may be useful in assessing the impact of disruptions; however, it appears unlikely that anything other than anecdotal information would be available to assess the likelihood and significance of such costs.

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[56] See www.nzta.govt.nz/resources/roadcode/heavy-vehicle-road-code/information-for-heavy-vehicle-drivers/work-time-and-logbooks/

3.4.7.3 Cost of using alternative modes

Affected users may mitigate their cost by using alternative modes of transport. This may be a significant consideration for commuters, who as a result of a disruption may switch from taking a train or bus to using private vehicles (see Box 3.2 for an example). In such cases, the incremental costs associated with using the alternatives should be considered using the standard methods. In the case of commuting, this will likely require consideration of congestion, which affects both those diverting to the new mode as well as those who were originally using the mode.

Alternative modes appear less likely to be a consideration for other private vehicle road-use, but conceivably may include rail, air or sea. Excluding emergency services uses, air transport as an alternative to road travel will be an efficient option only in extreme events; for example, for travellers who have ready access to an airport and for travellers who have not commenced their trip by road.

3.4.7.4 Loss of access to essential services

A disruption to transport infrastructure can lead to limited access to essential services. Events such as a flood or earthquake event can result in people being cut off from a hospital and may hinder police and health services reaching particular regions.

In a project evaluation, it is unlikely sufficient data will exist to determine the probability of an event requiring an evacuation. Air transport could be a possible alternative to diversion, waiting, and not travelling, but its use is likely to be limited and may only be used in the case of emergency evacuations or to deliver essential supplies if stocks have run out.

3.5 Other direct costs

3.5.1 Injury or loss of life due to less-resilient infrastructure

Concerns over safety are a significant factor in transport infrastructure design and are reflected in day-to-day management decisions such as road closures for weather.

Potentially, a lack of resilient transport infrastructure could lead to an increase in the risk of injury or loss of life associated with hazard events that lead to disruptions. For example, road users could be injured or killed from roads that are exposed to rockfalls[57] or flooding.

Nevertheless, we expect that injury and/or loss of life will typically not be a material factor in analysis of resilience and that quantification is unlikely to be worthwhile. The frequency of such injuries and deaths from a lack of resilience appears to be small.[58] Though hazards such as rockfalls may be frequent, the precautions undertaken, including temporary road-closures,[59] appear to have resulted in a low frequency of injury and death. Through such measures the costs to safety are reduced at the expense of higher costs from a loss of functioning (which are considered in section 3.4).

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[57] In 2019, a driver was killed by a boulder on a South Island highway (www.stuff.co.nz/national/117427317/rockfall-hits-vehicle-closes-state-highway-near-murchison). In 2018, a man died after being struck by rockfall on State Highway 4 (www.tvnz.co.nz/one-news/new-zealand/man-dies-rockfall-state-highway-4-after-stopping-clear-small-land-slip-near-whanganui).

[58] We are not aware of any public analysis of disaster-related road deaths in New Zealand. There is some Australian analysis associated with flood risk. The TIC (2019) estimated in Australia that flooding-related road deaths were equal to approximately 0.5% of all road fatalities.

[59] An example is documented in the 2019 *Wairarapa Times Age* article 'Hill closures to resume' (http://times-age.co.nz/hill-closures-to-resume/).

Quantification might be undertaken if the route being analysed is a known blackspot for injuries or fatalities. Should the difference in risks to injury and life be deemed material, then the values should be quantified using the standard methods and values for valuing fatalities and injuries. As noted above, the changes in the cost of crashes are also a consideration in estimating the costs of disruption associated with diverted and cancelled trips.

3.5.2 Repair, reinstatement and related costs

Disruption events can impose a variety of costs related to repair and reinstatement of the infrastructure. These costs can vary greatly depending on the severity and type of disruptive event. Disruptive events can range from a mild flood event, causing disruption but no damage, to an earthquake that can result in millions of dollars in damage costs.[60]

The cost to repair and reinstate transport infrastructure can vary between options. Different routes being considered may be exposed to different risks, and more-resilient infrastructure will tend to have lower damage costs due to greater resilience to hazards.[61]

In addition to the repair and reinstatement costs, related costs may include the costs of providing interim solutions (eg, a temporary Bailey bridge).[62] Less-resilient infrastructure may also require more ongoing maintenance to reduce the risk of disruptions. Such ongoing maintenance costs should be incorporated as part of the economic appraisal and may include the disruption costs associated with the maintenance that is undertaken.[63]

Where disruptions are frequent, average historical repair costs may provide a useful guide. However, for many natural hazards, historical data will be insufficient and some forecast will be required. The costs of repair may increase substantially with the severity of the event causing the disruption.

For this reason, the approach to estimating damage costs will more likely involve estimating the probability-weighted average annual repair costs associated with different event severities. This approach recognises that the infrastructure repair costs can vary significantly depending with the severity of the event in a way that cannot be inferred from the frequency or duration of the disruption.

The average annual repair cost can be estimated using cost estimates at several severity levels as determined by the annual recurrence interval (ARI) using a similar procedure to that discussed in section 3.4.1.2). An example (drawn from TIC, 2019) is illustrated in Table 3.7 below. In the example, the left-hand side of the table shows the estimates of the repair costs for different severities as measured by the ARI. This data is then used in the right-hand side table to estimate average annual repair cost for different probability ranges. For example, the average annual repair cost for the ARI range 20–50 years is estimated as the AEP difference for the range (0.05 − 0.02) × the average repair cost ($5 M, $10 M) = 0.03 × $7.5 M = $225,000. The annual average repair cost is the sum of the average annual repair costs for each ARI range.

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60 Disruptions may cause damage to infrastructure or require clearance to reopen the affected route. This is the case for both low-impact, high-frequency events and medium-impact, medium-frequency events. A minor rock slip may not damage a road but may require trucks to be sent to the site to clear the rock slip before the road can be re-opened. Similarly, an earthquake may damage a road that cannot be used until it is repaired.

61 This may not always be the case. Some infrastructure may have a higher rebuild cost if resilience needs to be incorporated.

62 The EEM (section A13.12) provides an example analysis involving a bridge replacement with a temporary Bailey bridge.

63 See, for example, https://times-age.co.nz/hill-closures-to-resume/ (accessed 20 June 2020).

Table 3.7 Example repair costs by flood event

Return period in years (ARI)	~AEP	Repair cost ($M)
5 years	0.2	0
10 years	0.1	1
20 years	0.05	5
50 years	0.02	10
100 years	0.01	15
Max 10,000	0.0001	40

→

(a) AEP difference (ARI range)	(b) Avg. repair cost ($M)	Annual average repair cost = (a) × (b)
0.6 (up to 2.5 ARI)	0	$0
0.2 (2.5 to 5 ARI)	0.5	$50,000
0.1 (5 to 10 ARI)	3	$150,000
0.05 (10 to 20 ARI)	7.5	$225,000
0.03 (20 to 50 ARI)	12.5	$125,000
0.01 (50 to 100 ARI)	27.5	$272,250
Total		**$822,250**

3.5.3 Environmental impacts and other externalities

More-resilient infrastructure can have environmental benefits. One potential benefit is the savings in environmental damage from less material being washed away into surrounding areas and waterways following a severe disruption. An estimate of these costs should be incorporated into the costs of repair as discussed in the previous subsection.

Another source of environmental benefit relates to the avoided costs associated with the use of alternative routes. Often alternative routes are not designed for the heavier traffic flows they receive in the case of the outage, and their increased use may cause an imposition on local communities associated with noise, dust, vibrations, visual amenity, safety and congestion. Where such costs are expected to be significant, they potentially could be valued using data drawn from surveys. Such costs might be estimated on a per-hour-of-closure basis and incorporated into the evaluation by multiplying by the AATOC.

The change in transport use may also cause changes in the cost of other externalities (ie, costs not borne by the transport user). These include externalities associated with congestion, crash costs and vehicle emissions.

The most significant external cost is likely to relate to increased congestion on the alternative routes. Using the procedure outlined in the previous section, the impact of the congestion (in terms of travel time and vehicle operating costs) should be incorporated in the analysis of the incremental diversion cost. Allowance will also need to be made for the additional cost imposed on those who typically use the alternative route. This additional congestion cost can be estimated using standard travel-cost methods.[64]

Generally, we would not expect other externalities to be material to the investment appraisal decision, but allowance may be made for these as part of transport cost analysis. Note, there will also be some change in externalities associated with trips cancelled, which may include a reduction in transport use and/or some trips going to alternative destinations.

[64] This issue may be particularly significant in considering the resilience of public transport. For example, a closure of a rail line could result in a substantial increase in additional road traffic.

3.5.4 Impact on essential services

3.5.4.1 Impact to related essential infrastructure

Land transport infrastructure and related systems are typically integrated with other infrastructure assets and systems.[65] Some transport infrastructure provides a conduit for other services including energy, telecommunications, water and wastewater. A failure of the infrastructure can cause a disruption to these other services. For example, an earthquake that causes a bridge collapse could result in power and water outages to a region. A related issue is that the disaster event causes a loss of road access that hampers the ability to quickly access and restore utility infrastructure that is damaged by the event.[66] The cost of such outages may be so significant as to potentially far outweigh the disruption costs associated with a loss of functionality of the transport infrastructure.

More-resilient infrastructure may prevent such disruption to utility services and/or facilitate faster repair of such services and, where relevant, these benefits should be considered in a transport investment appraisal.[67]

3.5.4.2 Emergency services and the emergency response

A disruption may result in reduced access for emergency services, inhibiting their response to the disaster that caused the disruption. For example, an earthquake that creates the need for emergency services may also cause disruptions to the road network, thereby hindering the emergency response. A potentially significant cost of less-resilient infrastructure is in it not functioning following an event that requires a response from the emergency services. Keeping the roads open for fire engines and other emergency service vehicles is particularly important for mitigating the impact of wildfire. Similarly, less-resilient transport infrastructure could restrict evacuation (eg, in the case of a flood).

Quantification of these benefits of resilient transport infrastructure for emergency services would be challenging but may be worthwhile for high-impact events. It would require forecasting the demand on emergency services for hazards with different severities and considering how the social costs would change if the transport infrastructure being considered was simultaneously disrupted. Interviews with emergency service stakeholders may be informative.[68] Analysis of historical data (eg, in the case of flooding) may also be beneficial.

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[65] The UK HM Treasury (2015, p. 11) notes:

> *The UK's infrastructure has been described as both a network of networks and a system of systems. [This] view states that individual infrastructure assets and networks are dependent upon each other in order to function effectively as part of an infrastructure systems. In turn the infrastructure systems interact with other systems that support our society and economy, such as health, education, justice and defence systems*.

[66] The interdependency of transport with other systems is examined in a series of disaster (natural and man-made) case studies examined by Kim et al. (2018). Their findings highlight the importance – and thus value – of resilient transport systems in disaster response and recovery.

[67] The MERIT tool can be (and is currently being) used to examine the economic impacts of the disruption in key services. Furthermore, we understand it is designed to model coincident and cascading hazards and applies an all-of-infrastructure approach in its assessment that recognises infrastructure is a system of systems. As noted in section 5.2.2, care is required to ensure that the outputs are appropriate to be incorporated into the CBA.

[68] See Brabhaharan et al. (2006) for an example.

3.6 Indirect impacts

3.6.1 Disruption costs to non-users

Disasters and other disruptions can impact more than just the users of infrastructure. For example, a transport disruption such as a bridge closure may prevent key inputs being delivered to a business in another location, prevent tourists using a hotel, or cause commuters to be less productive by keeping them from their normal place of work.

Where alternative routes are available, such impacts may be minimal and/or reflected in the costs of the diversion. These impacts may be estimated using the standard economic analysis techniques considered in the previous sections. Consider a disruption that substantially increases the costs for a business to receive inputs to a production process. If the margin made by the business is in excess of the additional transport costs, then we would expect the business to pay the additional transport costs to ensure delivery. In such a case, there is no reduction in production, and the welfare loss to the business is equal to the additional transport costs, which are estimated using the standard analysis. Similarly, we might expect that when a business does not pay the additional transport costs and reduces production, it chooses to do so because their loss is less than the additional transport costs. In either case, the welfare loss is captured in the standard analysis.

In some situations, diversion may not be practical, and some businesses may experience a loss in operability that reduces the level of production. The production loss to non-users (the businesses) is an indirect effect from a transport disruption and can be a result of upstream and downstream linkages through supply chains.[69]

3.6.1.1 Situations where indirect disruption losses may be relevant

There are some situations where the indirect disruption losses to non-users may need to be considered.

First, there may be no alternative route and no reasonable substitute. An example is a disruption that restricts access to critical transport infrastructure such as a port (or airport) and so prevents a business from getting goods to market or obtaining necessary intermediary goods. Waiting may also not be practical because the goods are perishable (or more generally the inventory costs are high) or they need to be delivered by a certain time.[70]

Similarly, disruption may prevent commuters arriving to work in time, affecting worker productivity and disrupting production processes. In such cases, the direct transport user costs, borne by the commuter, may be small compared to the lost productivity costs, borne by the employers. Box 3.2 describes a case study on the disruptive storms in 2013 that includes the impacts on worker productivity.

Second, it may not be practical for the businesses indirectly affected to pay for the additional transport costs. Consider a situation whereby a supplier utilises a freight company to ship goods to another business. Assume that the collective margin made by each party (the two businesses and freight company) exceeds the increase in transport costs but the margin made by any individual party does not. In this situation, the delivery would only proceed if the parties can come to an agreement. However, the transaction costs of

[69] These effects from upstream and downstream linkages through supply chains are also known as industrial effects. There can also be induced (or consumption) effects as a result of changes in household consumption stemming from changes in household income; however, the relevance for a CBA will tend to be small unless unemployment is significant.

[70] In effect, this situation reflects a lack of an adequate benchmark for estimating the cost of disruption.

reaching agreement may prevent this from happening. Another example is in the tourist sector, where the benefit to a community from an additional tourist is far in excess of the additional transport costs experienced by the tourist. Similarly, a fall in worker productivity following a disruption may be inefficiently large because employers find it impractical to provide optimal incentives to their employees to overcome the transport disruptions.

In such cases, it may be appropriate to incorporate estimates of the lost production as a cost of disruption. This might potentially be estimated by considering the lost output net of any reduction in costs that would have been used in producing the output. Surveys may be helpful in determining the impact. If they are used – given some of the factors below – we recommend that estimates of production loss are obtained from businesses.

Care is required in undertaking such analysis. The reduction in productivity (net of intermediate costs) may be less than first might appear, as there are a number of possible mitigating and offsetting effects.

- Businesses may be able to absorb short-term disruptions through use of inventory, and quickly adapt by using alternative supply sources (or alternative routes).
- Businesses not affected by the disruption (eg, those in other locations) may be able to absorb some of the production loss.
- The incentive, and therefore the effort, to mitigate the effects of the disruption is likely to be greater among those activities and workers for whom the potential loss is greater. Consequently, the average value of worker hours lost is likely to be less than the average value of all worker hours. Higher-margin businesses have a greater incentive to ensure that they can keep production going despite the disruption. Similarly, businesses and the employees themselves have an incentive to ensure that the more-productive workers are able to continue working during a disruption.
- As communication technology improves, organisations and their employees may become more resilient to transport disruptions.

Some sectors will be less resilient than others to transport disruptions. The tourism sector may be particularly vulnerable to disruptions that prevent tourists visiting a location because practical routes to some tourist destinations are limited.

Box 3.2 The transport impacts of the 20 June 2013 storm

In a joint study, the Ministry of Transport, Waka Kotahi, KiwiRail and Greater Wellington Regional Council analysed the impact of a storm on the night of Thursday 20 June 2013 that severely affected Wellington's transport network.

The storm had immediate and flow-on effects for commuters in the region. To support the analysis, the Ministry of Transport undertook a survey to assess changes in behaviour. The survey data indicated that around 27.1% of the respondents did not go to work as intended due to transport disruptions on Friday (21 June 2013) falling to 3.6% and 2.3% for the following Monday (24 June 2013) and Wednesday (26 June 2013) respectively. Around half of the disrupted workers indicated they were able to work from home.

The study estimated that the storm resulted in around 200,000 work hours lost on the day after the storm and another 120,000 in the following days. The production loss due to reduced worker hours was estimated to be $1.7 to $5 million based on the average hourly earnings and an adjustment to reflect that the output loss would be temporary.

Source: Ministry of Transport (2013)

3.6.1.2 The use of economic impact analysis tools

Indirect impacts are often analysed using regional economic impact modelling that analyses how impacts in one sector affect other sectors. Such tools may be useful in helping to understand the impact of disasters, but great care is required before using them for undertaking a CBA. Standard regional economic impact analysis is not compatible with CBA, and there is a risk that the use of such tools leads to double counting.

Where economic impact analysis has been used to analyse disasters, such analysis has typically been conducted on the broad effects of a disaster and not just the impact on the transport network. Some analyses have adopted the approach of applying multipliers from IO tables to estimate the indirect effects of changes in one sector on other sectors.[71] The use of IO multipliers is not desirable for analysing positive shocks to a local economy due to the existence of resource constraints. When used with care they may have some value in analysing negative shocks. Computable general equilibrium (CGE) models are more complex and have also been used. A key limitation of both IO models and CGE models is in modelling how sectors of the economy adjust over time.

MERIT – which employs CGE modelling – has been used to estimate the direct and indirect effects in a number of ex-post studies (eg, Market Economics, 2016, 2017). MERIT has been designed for analysing disruptions and has several advantages over the CGE and IO models. In particular, MERIT is designed to capture the out-of-equilibrium dynamics that occur following major disruptive events, thereby enabling it to model how the economy transitions over time in response to the disruption.

A challenge in using economic impact analyses for welfare analysis is that typically the outputs of such analyses are not direct measures of welfare but are rather broader economic measures that are related to welfare. Typically, the most relevant outputs of economic impact analyses are the effect on GDP or regional value-added. However, as noted in the Treasury's *Guide to Social Cost Benefit Analysis*, while effects on GDP are often equated with national welfare, GDP doesn't measure welfare (New Zealand Treasury, 2015, p. 47). The Treasury guide notes a few issues, including that GDP measures production and not income and that it includes benefits accruing to foreigners. Consistent with these reasons, it notes that gross national disposable income (GNDI) is a macro-economic measure that more closely corresponds to national welfare.[72] In accordance with this recommendation, a recent report employing MERIT (Smith et al., 2019, p. 9) includes changes in GNDI as a proxy welfare measure.[73]

However, GNDI is also not a direct measure of welfare. As noted by the Treasury, changes in GDP (and other national account measures) do not capture non-market effects, which in the case of transport impacts will mean that changes in consumer welfare associated with increases in travel time and externalities such as road-accidents are not included. Such impacts can be estimated directly through traditional methods.

Changes in GDP and GNDI may also deviate from changes in welfare for other reasons. In addition to changes in surplus, changes in GDP and GNDI reflect changes in the use of labour and capital. To use these measures in estimating welfare changes, it is necessary to net off the change in the opportunity cost of employing these resources. For example, GDP/GNDI can increase as a result of employees working longer hours to produce a greater level of output; however, this increase comes at an 'opportunity cost' to the employees, reflected in the value they place on the loss of leisure time. The welfare change with the GDP/GNDI increase needs to be the net of the employees' opportunity cost (known as their 'reservation

[71] See Box 3.2 for an example.

[72] GNDI = GDP plus net income flows from abroad (ie, difference between income received from and income transferred to non-residents, including voluntary transfers). See Vaggi and Capelli (2014) for a discussion.

[73] We understand the Dynamic Economic Module of MERIT is currently being upgraded to include additional wellbeing metrics.

wage'). If there is no change in the capital and employee employed, then (all else being equal) the change in GDP/GNDI should closely reflect the change in welfare.

The reservation wage of the employees who lose work may be very small, reflecting that there are large impacts to wellbeing from being involuntarily underemployed or unemployed. Consequently, a reduction in GDP/GNDI associated with a reduction in production and employment may closely reflect the welfare loss.[74]

The issue is closely related to one of distributional impacts of disasters. A disruption can lead to a change in the location of economic activity with a loss of production/employment in some locations but an offsetting increase in the production/employment in others. For example, a disruption that causes a diversion around a tourist town will cause a loss to the tourism businesses in the town and potentially result in a loss of employment. However, the loss of business may be entirely offset by an increase in business in another location. In this example, the change in employment and GDP/GNDI may be small but the welfare losses may be significant as the reservation wage (opportunity cost) of those losing work may be significantly less than the reservation wage of those gaining additional employment.

3.6.2 Wider economic benefit impacts

3.6.2.1 Agglomeration (long-term wider economic impacts on economic development)

In addition to the short-term immediate impacts, hazard events can have long-term growth impacts. For example, businesses may consider relocating from an area where transport infrastructure is frequently affected by flooding.[75] Generally, such impacts are incorporated in the standard economic analysis. The costs to the business affected may be calculated as the additional transport and inventory costs they incur. Attributing additional value may result in a double counting of benefits. Similarly, more-resilient infrastructure may result in increased land values; however, as discussed in the EEM (pp. 2–10) such benefits should be 'excluded from the evaluation because they represent a capitalisation of the direct benefits from reduced travel costs which have already been calculated, and including them would be double counting'.

Potentially, more-resilient transport infrastructure could lead to greater industry concentration and, consequently, benefits of agglomeration; that is, benefits that reflect, for some activities, that clusters of firms and workers are more efficient when spatially concentrated. For example, an increase in the resilience of transport infrastructure could lead to a greater concentration of businesses operating in an area. Such agglomeration benefits should be considered in the evaluation, where relevant, using the procedures outlined in the EEM (sections A10.2–10.4).[76]

3.6.2.2 Imperfect competition

Imperfect competition effects refer to wider economic benefit impacts that arise when a transport improvement causes output to increase in sectors where there are price–cost margins (see EEM section

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[74] Arguably the wellbeing impacts of being involuntarily unemployed can be so great that the adjustment for the reservation wage may be zero or even negative. Furthermore, there are spillover effects of unemployment to the community related to empathy and social impacts. Bartik (2012, p. 11) summarises 'the opportunity cost of the reduced leisure of the newly employed could be close to zero or even negative, after we adjust for stigma and empathy-based spillover effects', and that the employment benefits may be multiples of the direct effects (ie, wages paid).

[75] The UK HM Treasury (2015, p. 16) gives the example that 'successive failures in the same network or location may result in a business opting to invest or locate abroad to ensure business continuity.'

[76] Agglomeration benefits of resilience were not discussed in the public papers we reviewed but were considered in a study provided to us in-confidence.

A10.5). To account for the value of the price–cost margin from the additional output, the EEM recommends applying an uplift factor of 10.7% of business user benefits.

Conversely, we might consider whether a transport disruption that temporarily increases transport costs and decreases output will lead to similar additional reductions in welfare. For example, a disruption that increases the cost of freight could lead to reductions in output and a loss of the associated margin.

For short-term disruptions, where alternative routes are available, we would not expect the imperfect competition effects to be material. This is because in the short-term, retail prices tend to be ‘sticky’; that is, relatively unresponsive to short-term shocks in the cost of supply.[77] Evidence suggests that this is particularly so for imperfectly competitive markets, where price–cost margins are most significant.[78] Consequently, in response to short-term price changes, we expect that for the higher-margin industries there would be minimal change in output in response to temporary increases in transport costs. We expect the most significant price changes, and consequently production changes, to occur in the more competitive industries, where margins are small.

For longer-term disruptions (eg, > 3 months), an increase in transport costs is more likely to lead to a change in prices and levels of production. The impact of longer disruptions is discussed in section 3.7.1.

3.6.3 Disaster preparedness (eg, inventories)

In response to hazard events (imminent and unexpected), those affected (eg, households and businesses) may stock additional inventories. These and other preparedness activities are an additional cost of less-resilient transport infrastructure. However, they should also serve to reduce the costs associated with a disruption when it does occur.

A potential benefit of more-resilient infrastructure is that it could enable local businesses and the broader community to reduce the level of excess disaster preparedness. Conceivably, this benefit could be valued through a survey; for example, a survey of businesses on the excess inventory they hold. With this information, the evaluator could estimate the holding cost of inventory. However, we expect this will only be a material consideration in exceptional circumstances.

3.7 Further considerations

This subsection discusses further considerations that may arise for more complex situations.

3.7.1 Adaptation over time

The length of time of disruption is an important factor in undertaking the economic appraisal. Over longer periods of time, road users and those indirectly affected by disruptions may adapt to a change in transport availability and costs. Businesses may adapt by changing suppliers, increasing inventory levels to reduce transport costs, changing business processes, changing the road-fleet, and/or changing transport modes.

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[77] Parker (2013), who examines price-setting behaviour in New Zealand, provides a useful summary of the potential reasons for price stickiness. These include: the cost of changing prices (known as ‘menu costs’), explicit contracts, implicit contracts, coordination failure, pricing thresholds and a range of non-price factors. The author (p. 23) also notes:

> *Firms may be reluctant to change their price if they believe that the current shock is only temporary in nature. In this case, the optimal price would also be temporary and any price change would need to be reversed in the near future. Firms may choose to avoid both price changes, resulting in price stickiness.*

[78] See Andersen et al. (2015, section III).

Similarly, commuter and general traffic may adapt by increasing time spent working from home or changing work and shopping locations.

As a result of these adaptations, the daily costs of a transport disruption should decline over time. This should be reflected in changes in road-user behaviour. In particular, we might expect over time a reduction (relative to the baseline case) of the number of vehicles using the alternative route as more trips to the original destination are cancelled in preference to other destinations. Consequently, when a disruption is a significant impost to transport users (eg, as was the case described in Box 3.2) and/or for a significant period of time (eg, for 2 weeks or more), it is advisable to consider the effects of adaptation. This may involve gathering data (eg, through use of surveys) or conducting additional modelling to estimate how behaviour, and subsequently costs, may vary over time.

For significant disruptions (in impact and/or time), the evaluator may consider the use of the MERIT model (or another tool that uses general equilibrium modelling) to assess how businesses adapt to changes in transport costs (see example in section 4.2.3).

One note of caution: adaptation can involve additional costs to transport users that may need to be considered. For example, in response to an extended disruption, a business may incur additional costs to change processes (eg, hold greater inventories) so as to offset the increase in transport costs.

3.7.2 Distributional impacts

Transport disruptions and, conversely, investments in resilience may have distributional consequences that are not reflected in a standard economic analysis. For example, a disruption may result in tourists taking a different route to the benefit of one group of tourist operators (eg, in the provision of accommodation and hospitality services) but to the cost of another group. In the simple example depicted in Figure 3.3, the disruption to the bridge may result in a loss in revenue to cafés in Town A offset by an increase in business to cafés in Town C as tourists are forced to take the diverting route. In this simple example, one business's loss (in Town A) is offset by another business's gain (in Town C).

In a standard CBA, such impacts are typically ignored as there is no change in expenditure and – using standard methods – no change in welfare, because the loss to one party is offset by an increase to another.

However, there may nevertheless be a welfare loss as, from a welfare perspective, the impact of the loss of income to one party may be greater than the impact of the gain in income to the other. The distributional effects can be significant. For a town that relies on tourism, the impact of a transport disruption may result in the closure of a business and a loss of employment, which in turn has costs for society.

Distributional effects are acknowledged in both the EEM and the Treasury CBA guidelines. The EEM (section A17) notes:

> *An analysis of the distribution of benefits and costs among different groups of people is not required for the economic efficiency evaluation of the project. However, reporting of the distribution of benefits and costs, particularly where they relate to the needs of the transport disadvantaged, is part of the funding allocation process.*

Given the potential significance, we recommend that, where distributional effects might be expected to be material, at minimum, a qualitative assessment of the distributional effects should be undertaken. A quantitative assessment might consider reporting the extent of wealth transfer and the employment effects. Distributional effects might be a particularly significant consideration where the disruption would affect areas with transport-dependent industries (eg, tourism) and/or with high unemployment. For example, a quantitative assessment of the distributional effects might quantify the loss of income to a region from a reduction in tourist flows.

3.7.3 Service expectations and use of surveys

The expectations of the community with regard to the availability of a particular route can become a consideration. As noted in the EEM (section 10.8, p. 517), 'There are benefits in providing a greater assurance to road users and communities that they will be able to depend on a particular route (such benefits can be expressed in a survey of road users' willingness to pay).' Similarly, there is value in providing assurance that disruption events will be addressed quickly to reduce the uncertainty over the time to recover. As noted earlier in section 1.2, Waka Kotahi sets threshold levels for the acceptable number of road closures per year.[79]

An implication is that a community's willingness to pay (WTP) for greater assurance – or willingness to accept (WTA) lower assurance – may be higher than the costs that would be estimated via the travel-cost methods discussed in previous sections.[80] In large part, such differences may reflect the difficulty in accurately capturing the costs of disruption to a community using travel-cost methods based on standard parameter values.

In situations where service expectations are expected to be important, evaluators may consider using surveys to complement the traditional travel-cost method analysis. Potentially, road users may be surveyed to assess the value of resilience. They may be particularly useful when it is difficult to estimate disruption costs based on travel-cost approaches. For example, a survey may be used to estimate the impact to residents and local businesses when there are no alternative routes.

Most commonly, respondents are asked about their WTP for some improved level of service. However, in cases where the project involves ensuring infrastructure meets an established standard, then it is arguably more appropriate to value the cost of not meeting the standard using respondents' views on their WTA the lower standard.[81] WTA values tend to be higher than WTP values.

Surveys on the WTP for resilience may also be used in situations where the standard travel-cost method is difficult to apply (eg, due to a lack of data).[82]

Where surveys are used to complement the travel-cost methods, care is required to ensure there is no double counting. For example, the loss of income for a business directly affected by a disruption may be partially offset by a gain in income for a business in another location. Care is also required to ensure that the estimation of costs is comprehensive and that the estimates capture the loss to the community affected.

Another use of surveys is to provide an input into the standard travel-cost methods described above. As noted earlier, they may be useful for understanding road-user behaviour and more generally how people and businesses respond to a transport disruption. Another common use is to understand travel patterns so as to help predict which diverting routes may be selected.

[79] These levels vary by closure period, One Network Road Classification, and whether there is an alternative route.

[80] This concept is reflected in some of the literature but is not contained in any guidance material we have reviewed.

[81] See MacDonald et al. (2010) for a more in-depth discussion relating to changes in service standard for the urban water sector.

[82] Masiero and Hensher (2011) surveyed logistics managers of medium to large manufacturing industries to elicit the freight transport costs associated with a temporary road closure.

3.7.4 Multiple hazards and networks of infrastructure

3.7.4.1 Multiple hazards

Those conducting economic appraisals may encounter situations involving multiple hazards that may affect one or more routes in a road network. Evaluators may need to consider the potential for simultaneous closure of multiple roads in a network, potentially as a result of a single hazard event – such as an earthquake or flood affecting a region – or multiple hazard events. Furthermore, some roads and road networks may be exposed to a range of hazards (eg, earthquake, snow and ice, road crash) and in some instances the likelihood associated with disruptions may be correlated.

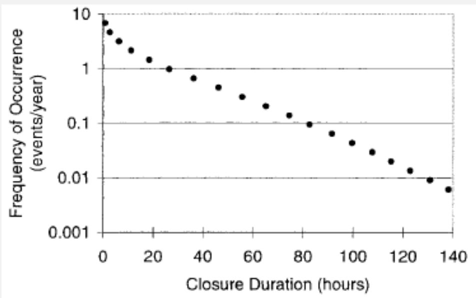
Such cases add significantly to the complexity of the analysis. However, the same basic approach of applying a risk-weighted analysis of costs of disruptions still applies. For example, an evaluator may follow the approach of:

1. identifying the potential hazard events and their likelihood of occurrence having regard to the extent that the likelihood of events may be correlated
2. identifying a range of feasible disruption scenarios (which may include coincident outages to multiple roads in a network, potentially from the same or different hazard events)
3. estimating the disruption cost of each scenario
4. calculating a risk-weighted estimate of the disruption cost.

A useful example that follows such an approach is described in Box 3.3 below. It describes a New Zealand study that considered multiple hazards to a road network. Where there are multiple sources of risk, simulation techniques, such as Monte Carlo analysis, are likely to prove useful.[83]

Box 3.3 Using the probability distribution rather than averages to estimate road-user impact

Dalziel and Nicholson (2001) investigated the disruption costs associated with hazards that could close the Desert Road section of New Zealand's major north–south road link, State Highway 1. The authors considered multiple hazards (including storm, earthquakes, snow and ice, and road crashes) and the risk of disruption to multiple sections of the road network. Rather than simply using average time and duration of closure, they examined the probability distribution of road closure for a suite of hazards. For each hazard and event magnitude, a probability distribution was developed (see graph) using historical data and a Monte Carlo simulation.



To analyse the impact of the network, the authors considered the costs associated with 22 road-closure scenarios (using similar techniques to those described in sections 3.4 to 3.6). The results were used to analyse the likely benefits of a number of mitigation options.

Source: Dalziel and Nicholson (2001)

83 Austroads' (2002) *Economic Evaluation of Road Investment Proposals: Risk Analysis* provides a useful example and guidance.

3.7.4.2 Infrastructure inter-dependency

Evaluators may need to consider the interdependence of infrastructure systems (eg, road, rail, utilities) whereby disruption to one asset may cause or be correlated with disruption and failure of others. There can be:[84]

- cascade impacts (within systems), whereby a failure in one part of a network has a significant impact on the rest of the network (eg, a failure in one road leads to severe congestion in another)
- displacement impacts (between systems), whereby a failure in one infrastructure system affects another system (eg, a power failure affecting the rail network)
- correlated failures, whereby disruptive events could be correlated over time with other disruptive events (eg, a storm may result in high winds, which could disrupt electricity transmission, and heavy rain, which could flood and disrupt transport networks).

MERIT, which has been designed to analyse systems of infrastructure, may be used to analyse the impacts. Potentially, such interdependencies could be modelled using scenario methods as described above.

3.7.5 Other means of achieving resilience

As reflected in the Waka Kotahi Resilience Framework, resilience is achieved through multiple objectives. A key implication is that the resilience benefits within an infrastructure option will depend on the effectiveness of other factors. For example, costs of disruption can be reduced through improvements in other systems such as better emergency services, faster repair times and/or more coordinated responses that reduce disruption time.[85]

We recommend that where the costs of disruption are significant, consideration should be given to whether the costs of disruption might be reduced through complementary investments. This is potentially very important for large-scale disruptions. A more cost-effective solution may be achieved through increased resources on other resilience objectives. Furthermore, the analysis conducted for the CBA may potentially be useful in identifying and evaluating cost-effective measures to reduce the cost of disruptions.

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[84] As noted by the UK HM Treasury (2015, p. 16).

[85] This perspective is reflected in the 2018 Government Policy Statement on land transport, which states:

> *The 4R approach reflects that there are a range of potential pre- and post-event options, and investment opportunities, for minimising the impacts of disruption to the transport system. Investment can therefore be focused in different areas, such as strengthening or modifying assets, providing alternative routes or modes, or enabling a quicker response or rebuild.* (New Zealand Government, 2018, p. 18)

4 Manawatū Gorge case study

This section examines the resilience in the context of a section of State Highway 3 (SH3) through the Manawatū Gorge (MWG). The section of highway (hereafter 'SH3-MWG') is useful for a case study. The route has been subject to several disruptions that have resulted in road closures from a few hours to several months and is now closed indefinitely following a landslide in April 2017. The road has also been the subject of significant analysis, including a pilot study in the use of MERIT in 2016.[86] In 2018, Waka Kotahi completed a business case (New Zealand Transport Agency (2018c), hereafter 'the MWG Business Case') examining alternatives[87] and from this identified a preferred option to replace SH3-MWG.

In the following subsections, we provide a background to SH3-MWG, use the existing data and analysis to consider the costs of disruption, and review how the issue of resilience was incorporated into the MWG Business Case.

4.1 Manawatū Gorge context

SH3-MWG (see Figure 4.1) has provided a link between the Manawatū region and the Wairarapa and Hawke's Bay region and served as the main highway connection between the east and west coast for the central region of New Zealand.

SH3-MWG is vulnerable to geological disruptions such as landslides and slips. This has been the case since its first construction in 1872 and with its subsequent improvements. There have been frequent closures in the past, which have had negative impacts including economic, social, safety and a lack of certainty for communities that rely on the route. SH3-MWG has been closed since 2017 after two major landslides had completely blocked the road and forced its closure. Due to ongoing instability within the gorge, a decision was made in July 2017 to remove all contractors from worksites in the gorge for safety reasons and indefinitely close the road (at least in its current form).

Prior to its closure, it was one of the few routes that connected the western and eastern sides of the Ruahine and Tararua ranges and was identified as making a significant contribution to the 'social and economic wellbeing of these regions by connecting major population centres, supply chain infrastructure, amenities and employment' (GHD Advisory, 2018a, p. 8).[88] In 2016 the average daily traffic on SH3-MWG was 7,620 vehicles, of which 11.3% were heavy commercial vehicles (HCVs).

Since its closure, traffic has been diverted through two existing alternative routes: Saddle Road and Pahiatua Track. However, these routes were not designed to cater for the increase in traffic flows over long periods, and especially high volumes of HCVs.

A rail line used for freight transport also runs through the gorge. The rail line is on the opposite (northern) side of the gorge to the road. It has also been affected by slips but is currently operational.

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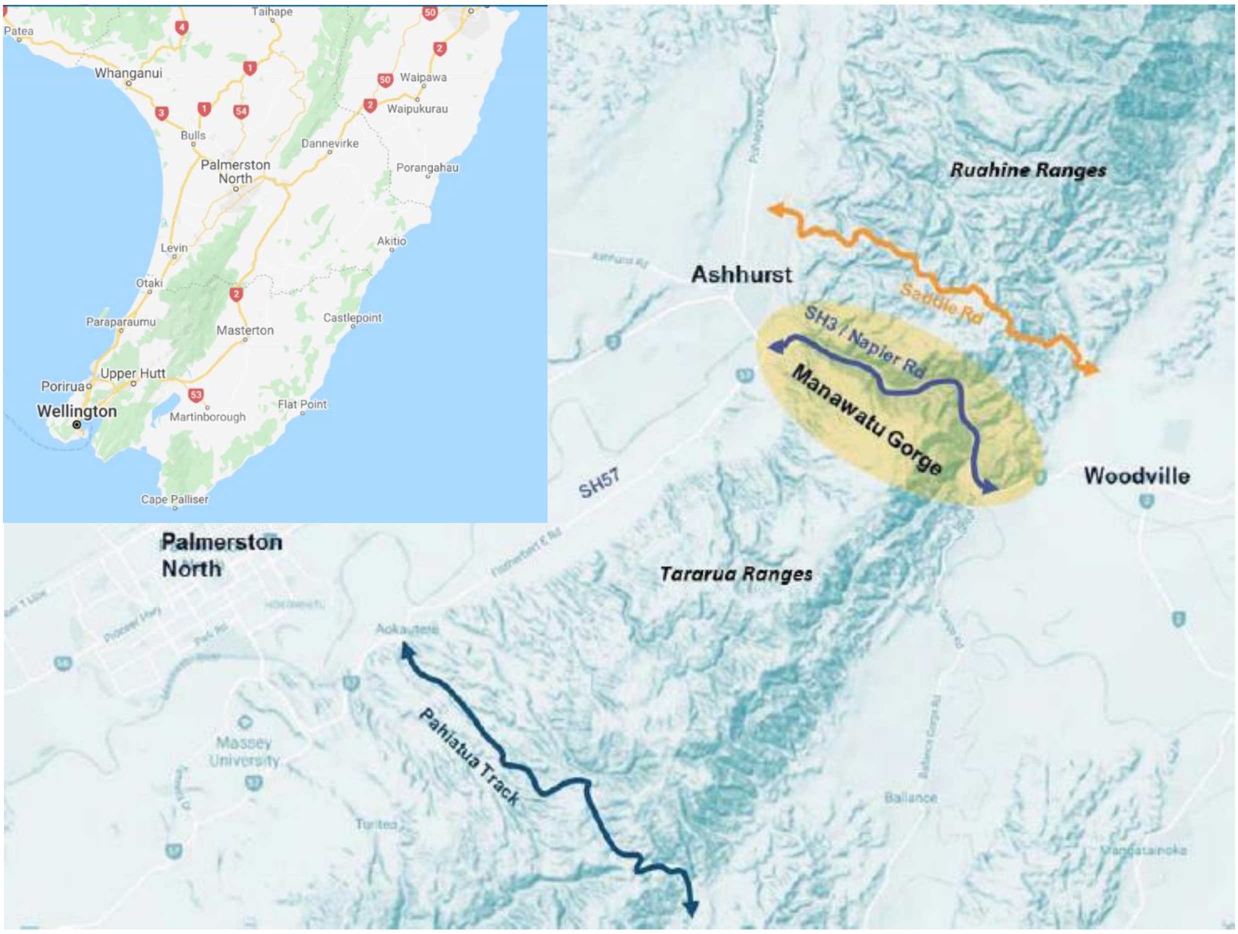
[86] Other prior work includes a case study by Imran et al. (2014) in which they applied a proposed 'Transport Resilience Indicator Framework' that incorporates six key dimensions of transport infrastructure resilience: engineering, services, ecological, social, economic and institutional. Application of the framework was based on qualitative and quantitative data captured from interviews and secondary sources.

[87] The MWG Business Case and more details about the project can be found at https://www.nzta.govt.nz/projects/sh3-manawatu/.

[88] The main communities serviced by SH3-MWG are Woodville (pop. 1,400), Ashhurst (pop. 2,800), Dannevirke (pop. 6,000) and Palmerston North (pop. 80,000).

Figure 4.1 Map of the Manawatū Gorge



Source: GHD Advisory (2018a, p. 5). Inset map from www.journeys.nzta.govt.nz/traffic (accessed 19 June 2020).

A review has been conducted into options for replacing the road. From a long-list of 18 options – including a do-minimum of upgrading the Saddle Road alternative route – four options were shortlisted for a detailed assessment and a preferred option was recommended. Reinstatement of the current SH3-MWG was not shortlisted as it was assessed as not being viable 'due to long-term resilience issues and a high level of imminent and longer-term risk of ongoing slope failures impacting the road operations and user/operator safety'.[89]

4.2 Expected costs of disruption of the existing route

In this subsection we evaluate the costs of disruption associated with SH3-MWG, following the methods described earlier. For this analysis we examine the hypothetical position of evaluating the expected costs of disruption as at the beginning of 2017 prior to the road closure. In effect, we aim to estimate the hypothetical benefits of a resilient replacement of SH3-MWG prior to the 2017 disruption.

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89 GHD Advisory (2018a, p. 35). Following the 2017 slips, SH3-MWG was assessed as being too unstable to work on as the gorge is still subject to significant risk of slips and landslides in two active locations.

4.2.1 Frequency and duration of disruption

To assess the expected costs of disruption, it is necessary to develop estimates of the frequency and duration of closures. In the case of SH3-MWG, there is a long history. It has been subject to frequent disruptions (see Table 4.1) that have forced its closure. While some closures have only lasted a few hours, the closures can be significant, lasting from several days to over a year.

On average since between 1985 and 2016 (ie, prior to the most recent closure), there have been around 1.4 closures per year, with an average annual time of closure equal to 18 days (423 hours). The average duration per closure between 1985 and 2016 is 13 days.

Table 4.1 Historical landslide occurrences (1940–2017)

Period	Number of disruptions	Period closed
1940	27	Not available
1968–69	12	Not available
1978–80	36	Not available
1985–86	1	2 days
1990	1	8 days
1995	3	67 days
1998	1	7 days
2004	28	70 days
Aug 2011–Sep 2012	1	360 days
others 2004–2012	6	Not available
2015	1	30 days
2017	2	Since April 2017
Average annual		
1940–2016	1.5 per year	Not available
1985–2016	1.4 per year	18 days per year

Source: GHD Advisory (2018a, pp. 17–18)

4.2.2 Alternative routes

The alternative routes to SH3-MWG for road users who wish to cross the ranges are the Saddle Road (north of the gorge) or the Pahiatua Track (south of the gorge). Both are non-highway connections. Neither route was designed to cater for the level of traffic travelling on SH3-MWG or for HCVs. A comparison of SH3-MWG relative to the alternatives is provided in Table 4.2 below.

Traffic flowing between the north and south of the island may also use SH2, thereby avoiding the area around Palmerston North.

Table 4.2 Summary of routes

	Manawatū Gorge	Saddle Road	Pahiatua Track
Description	Traverses through the gorge, flat gradient, shortest distance	Traverses north of the gorge through the Ruahine Range	Traverses south of the gorge through the Tararua Range
AADT	7,620	150	2,214
% heavy road vehicles	11.3%	0%	0%
Length (km)[90]	14.1	18.0	50
Average travel time (minutes)	13.0	21.6 (general traffic) 28 (freight)	36
Average speed (km/hr)	65	50 (general traffic) 39 (freight)	83
Maximum gradient	Flat	16%	15.8%
Deaths and serious injuries per 100 million vehicle kilometres travelled	11.5	9.4	14.4
Injury crashes per 100 million vehicle kilometres travelled	43.2	26.1	39.0

Source: GHD Advisory (2018a, pp. 9–11)

SH3-MWG was preferred to the key alternatives. It is an 8 km winding route that allows for no overtaking,[91] and due to the curving geometry of the route, traffic slows to between 50 to 70 km/h. However, the travel times are relatively short compared to the alternatives, and the road is flat, which made it ideal for HCVs.

As shown in the table, the alternative routes are significantly longer (both in distance and time travelled) and have a steep gradient (both above 15% in sections). Compared to SH3-MWG, the Saddle Road detour takes 9 minutes longer on average to travel for general traffic and 15 minutes longer on average for freight. Furthermore, the use of the Saddle Road forces traffic to go through the Ashhurst town centre, which affects community noise, safety and amenity and adds to community disruptions and impacts.

An analysis conducted for the MWG Business Case estimated that approximately 85% of the through traffic uses Saddle Road. The business case assumed that commuters from Pahiatua to Palmerston North prefer the Pahiatua Track route as it is geographically closer, but all other traffic north of Pahiatua is likely to use the shorter and faster Saddle Road detour.

SH3-MWG has a poorer safety record (with more deaths and serious injuries) than the alternatives; however, this may be due to the typically much lower volumes of traffic, and safety issues have been raised as a concern with the closure.

[90] Between SH3 at Ashhurst and Woodville.

[91] The road is 7 m wide with each lane measuring 3.5 m with no shoulder lane. Since the 1940s, there has been significant construction and widening of the road. The geology and carving of the Tararua Range coupled with previous road widening has undercut the gorge walls.

4.2.3 Estimating the expected costs of disruption

4.2.3.1 Changes in road-user costs

The above data can be used to develop estimates of the costs of disruption using the methods and techniques described in section 3.

The first step is to estimate the incremental cost of the diverting routes. Using the standard techniques in the EEM and the data provided in Table 4.2, we have provided estimates of these (in Table 4.3 below) for two types of vehicles and purpose. The evaluator may be expected to estimate the diversion costs for a broader range of vehicle types and purposes.

The additional cost per trip is reasonably small for commuting. The incremental cost for HCVs is significantly greater (due to the higher value of time and vehicle operating costs) but still likely to be small relative to the value of the trip being undertaken.

The estimates below have been made assuming there are no material congestion costs that lead to increases in travel times. We understand congestion is unlikely to be a material issue; however, potentially the increased HCV traffic on the Saddle Road route may lead to slower traffic for light vehicles as well.

Table 4.3 Incremental cost per trip of diversion by route

	SH3-MWG		Saddle Road		Pahiatua Track	
	Commuter traffic	HCV I	Commuter traffic	HCV I	Commuter traffic	HCV I
Value of time cost	$2.60	$2.60	$4.32	$37.33	$7.21	$48.00
Vehicle operating costs	$3.30	$13.58	$4.59	$22.81	$12.97	$66.71
Total road user cost	**$5.91**	**$16.18**	**$8.91**	**$60.14**	**$20.18**	**$114.71**
Incremental values						
Value of time cost			$1.72	$34.73	$4.60	$45.40
Vehicle operating costs			$1.28	$9.23	$9.66	$53.14
Total incremental cost			**$3.00**	**$43.96**	**$14.27**	**$98.53**

Notes: Analysis conducted using EEM values. The value of time cost for freight vehicles is the sum of the 'Values of time by trip purpose' (EEM Table A4.1(b)) and 'Values of vehicle and freight time' (EEM Table A4.2). Vehicle operating costs have been estimated using EEM Table A5.11 'Running cost by speed and gradient regression coefficients'.[92]

As noted above, the period of closure has ranged from a few hours to many months. Given the availability of the alternative routes and the potential for extended delays, we would not expect any vehicles to wait en route for the disruption to be cleared; rather, vehicles already en route would continue on the journey via the diversion route.

We also expect that news of a disruption would be communicated to vehicles quickly and that within a day no road users would begin their journey without knowledge of the road's closure. Given the alternatives and the long duration of closures, we would expect the number of trips postponed would also be small.

[92] The gradients on the Saddle Track and Pahiatua Track vary from flat to ~16%. As the relationship between the vehicle operating costs per km and gradient is non-linear, the total vehicle operating costs depends on how the gradients vary. We have roughly estimated that for the purpose of calculating the vehicle operating costs, the routes have an equivalent constant gradient of around 8%.

There would be an additional cost incurred to those road users who encounter the road closure en route and have to backtrack out of SH3-MWG before proceeding to the diverting route. However, this cost appears small. Only a small number of vehicles would be affected. For example, assuming it takes 2 hours to establish the diversions, the expected number of vehicles affected (ie, that have to backtrack) would be in the order of 640 vehicles.[93] The impact per vehicle would also not be overly significant as SH3-MWG itself is only 14 km and is in close proximity to the start and end of the Saddle Road.

In light of the above information, we would expect that the immediate effect of a disruption is for the vast majority of trips to continue using the alternative routes.

There is some data on trips taken along the alternative various routes before and after closure of the recent 2017 disruption. However, the data is difficult to reconcile. A transport assessment undertaken in 2018 reported the following challenges.

- At the time, significant works were being undertaken on the Saddle Road involving total road closures or directional closures. This limited the ability to source clean AADT volumes for the traffic split between the Saddle Road and Pahiatua Track.
- There is likely to be some change in traffic flow to using SH2 rather than SH3 and SH57.
- There is a need to apply seasonal adjustments to traffic flows to compare data at different times of the year.

Post-closure measures found higher volumes than expected were using the less-favoured Pahiatua Track route, but this was possibly due to the works on the Saddle Road. Given the information limitations, it was assumed that in normal times the post-closure traffic flow was as shown in Table 4.4. We assume that all HCV traffic would use the Saddle Road alternative route.

Table 4.4 Change in traffic flows assumed

Route	Pre-closure (2016)	Post-closure (assumed)	Change
SH3-MWG	7,620	0	−7,620
Saddle Road	150	6,370	6,220
Pahiatua Track	2,214	3,614	1,400
Total	**9,984**	**9,984**	**0**

Source: Based on the MWG Business Case (New Zealand Transport Agency, 2018c, Appendix G)

The change in volumes can be multiplied against the incremental road-user costs by vehicle type and purpose to derive an estimate of the additional road-user costs incurred. We estimate these to be in the order of $74,000 per day (2019 dollars) using 2016 traffic flow data. That is, the direct road-user benefits of a resilient SH3-MWG were it open are $74,000 per day of prevented outage. Over the course of a year this would be equal to around $27 million.

However, taking the hypothetical position of the road being currently open and applying the AATOC of 18 days, the expected annual cost as at the beginning of 2017 (when SH3-MWG was open) is equivalent to

[93] Based on the AADT of 7,620 vehicles per day.

around $1.3 million per year. Over 40 years, with an allowance for traffic growth this equates to a present value of $33 million.[94]

These costs to road users further increase if there are disruptions to the diversion routes that coincide with the disruption to SH3-MWG. We do not have information on the frequency of disruptions to the alternative routes; however, we understand this to be a material issue. The MWG Business Case evaluated the sensitivity of the business case results to additional disruptions to the Saddle Road (see section 4.3 below). When disruptions to the Saddle Road occur, road users would be forced to use the significantly longer Pahiatua Track. In such cases, the costs to road users would increase further.

We would expect that over time businesses and people would adapt to the higher travel costs and reduce their reliance on the route across the ranges. Road freight may take different routes (eg, some of those travelling to and from Wellington may choose the SH2 route), businesses may change the location of suppliers, and fewer people may choose to commute across the ranges. All else being equal, such changes in behaviour serve to reduce the cost of disruption.

4.2.3.2 Other costs of disruption

In addition to the direct road-user costs, there are other costs of disruption to consider. The most salient cost is the cost of repair/reinstatement. As noted earlier, reinstatement of SH3-MWG has been ruled out due to safety and stability issues.

The diversion of the road-user traffic has had additional effects.

The closure of SH3-MWG has caused a significant increase in traffic through the centre of the town of Ashhurst. This has come at a substantial community cost with residents saying that their lifestyle has been adversely affected by the increase in traffic, which is causing concerns over noise and safety.[95] We are not aware of any attempts to value this disruption cost; however, potentially this might be done through the use of surveys.

The disruption has also resulted in a substantial drop in traffic through the town of Woodville (near the east side of SH3-MWG). This has not been welcomed as it has led to a subsequent loss of revenue for businesses located in Woodville. The closure of SH3-MWG has been associated with a number of businesses in Woodville closing from a reduction in revenue from through-traffic.[96] We would expect that the loss of revenue to businesses in Woodville would be offset by road users increasing their expenditure elsewhere. Nevertheless, we would expect that, in terms of welfare, the negative impact to the Woodville business owners and community would be greater than the positive impact to businesses elsewhere, due to the costs associated with closing a business.

We do not anticipate any other indirect effects due to the availability of the alternative route.

4.2.3.3 Analysis of SH3-MWG closure using MERIT

In 2017 Waka Kotahi engaged Market Economics to adapt its economic assessment tool (MERIT) so that it can be applied to road outages. Market Economics ran a pilot version of MERIT for the closure of SH3-

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[94] The MWG Business Case includes estimates of traffic growth that vary over time, which are equivalent (for the purposes of economic analysis) to an annual growth of 3.42% per annum over 40 years.

[95] ‘Ashhurst residents say traffic caused by Manawatu Gorge closure is hurting their town’, *1 News*, 4 February 2019. www.tvnz.co.nz/one-news/new-zealand/ashhurst-residents-say-traffic-caused-manawatu-gorge-closure-hurting-their-town

[96] ‘Businesses failing while waiting for Manawatu Gorge solution’, *Stuff*, 17 July 2017. www.stuff.co.nz/business/95807843/businesses-failing-while-waiting-for-manawatu-gorge-solution

MWG. Results were analysed employing the assumption that the period of closure was 6 months from 31 August 2011 to 1 March 2012 and that the cost of repair was $23.5 million.

MERIT was used to calculate the total net change in GDP over periods of 3 months, 6 months and 1 year following the road outage. It also reported the average total cost per day. The results are summarised in Table 4.5 below.

MERIT's outputs include the increase in costs of road freight of $48,200 per day. These appear to be of a similar magnitude to the estimates made above.[97] It estimated the road outage of 6 months would lead to a GDP reduction over the course of a year of $6.3 million ($34,200 per day). The authors note that the results may seem lower than what may intuitively be expected because the alternative route does not create significant travel-cost increases and does not substantially change travel patterns. Of note, the model does not capture the loss of value of perishable goods, or social non-market costs such as non-work travel time.

The results highlight the ability of firms to adapt to the changes in travel costs. The change in GDP as % of the change in the increased costs of road freight was 72% over the course of a year. This suggest that firms were able to offset the increase in travel costs. Also, the estimated loss in GDP fell from 3.4 million over the first 3 months to 3.1 million over the second 3 months.

Unfortunately, it is not possible using the published information to determine the change in welfare. A possible explanation for the relatively small impact to GDP is that the disruption leads to longer working hours, which, although leads to greater employee compensation, comes at a cost of reduced leisure time.

Table 4.5 Modelling of impact of MERIT

	3 months ($$_{2007}$mil)	6 months ($$_{2007}$mil)	1 year ($$_{2007}$mil)	Total cost per day road out ($$_{2007}$000)
Increase in costs of road freight				
Manawatū-Wanganui Region	1.3	2.6	2.6	14,200
Rest of New Zealand	3.1	6.2	6.2	33,900
Total	4.4	8.7	8.8	48,200
Household travel to work	0.0	0.1	0.1	500
Net change in GDP	−3.4	−6.5	−6.3	−34,200
Change in GDP as % of change in costs of road freight	−77%	−75%	−72%	

Source: Market Economics (2016)

4.3 The Manawatū Gorge Business Case analysis

The MWG Business Case included two pieces of analysis involving the evaluation of resilience.

Of greater relevance to investment appraisal, the business case incorporated a sensitivity analysis on the CBA that considered the impact of further disruptions to the Saddle Road from weather events and slips. In the base 'do minimum' case, an outage of the Saddle Road would force usage of the Pahiatua Track, thereby increasing road-user costs.

97 A direct comparison cannot be made as the details of the assumptions used in the MERIT model are not available.

The impacts of the outages were quantified using the standard method described above assuming that all the traffic that was travelling on the Saddle Road is diverted to the Pahiatua Track for the period of the outage. The approach provides a simple example of how sensitivity analysis can be incorporated.

Table 4.6 Closures to Saddle Road from weather events and slips

Scenario	Description	Days using Pahiatua Track	Change to business case net present value
1	10 one-day outages	10	+$29.6 million
2	5 one-day outages + 2 one-week outages	19	+$48.9 million
3	5 one-day outages + 1 one-week outage + 1 one-month outage	42	+$98.4 million
4	10 one-day outages + 1 one-week outage + 1 one-month outage	47	+$109.2 million
5	1 three-month outage	90	+$201.7 million

Source: MWG Business Case (New Zealand Transport Agency, 2018c, section 6.4)

The MWG Business Case also included an assessment of the resilience of the four short-list options utilising a multicriteria analysis following a Waka Kotahi guideline. This is included in Appendix A for reference. Being a multicriteria analysis, it does not involve the valuation of the costs and benefits associated with resilience, and the results cannot be integrated into an economic evaluation. Nevertheless, it is useful in helping to identify hazards to be considered.

5 Conclusion and areas for further research

5.1 Conclusion

This report has examined the approaches and methods for incorporating resilience into investment appraisal. To date, the topic of resilience has received minimal attention in technical investment appraisal guidelines in New Zealand and in other jurisdictions. New Zealand, given its relatively high exposure to natural disasters, has reason to be a leader in the field.

The benefits of resilience can be estimated as the expected reduction in costs of disruption. These disruption costs include direct costs to transport users and other stakeholders directly and indirectly impacted.

The methods to estimate these and the factors to consider will vary by situation. The simplest situations are where the expected disruptions are short (less than a week), there is historical data (on the frequency and impact of disruption) and there are alternative routes available, which can be used as a basis for estimating the costs to users. In such cases, the expected costs of disruption (and therefore the benefits of resilience) primarily relate to the change in user costs, which can be calculated by applying standard parameters to estimates of changes in user behaviour and estimates of the frequency of disruption.

The situation can be more complex. Three features of disruptions pose challenges for investment appraisal:

- First, while uncertainty is a feature of all investment appraisal, it is particularly critical for analysis of high-impact, low-frequency events. For this reason, it is important that the uncertainty associated with resilience analysis is recognised in sensitivity analysis.
- Second, disruptions involve significant, sudden impacts to transport networks and consequently to behaviour. Care is required in estimating how road users react to change. People and businesses can adapt over time to disruption to reduce the costs they incur. This adaptation should be considered when evaluating behaviour.
- Third, in some situations, where there are no practical alternative routes, it is difficult to apply standard travel-cost methods and it may be necessary – with care – to use other bespoke methods to estimate the cost of disruption.

5.2 Areas for further research

The areas identified for further research relate to:

- the costs to road users of deferring travel, called displacement costs
- the integration of economic impact analysis into transport investment appraisal
- the approach to incorporating distributional impacts into the evaluation of resilience
- the behavioural responses to disruptions.

5.2.1 Displacement costs

Further work is required on displacement costs; that is, the costs to road users associated with deferring travel. The cost of displacement time should be significantly less than wait times that are based on road users waiting en route. There is some public literature on the displacement costs associated with public transport; however, we are not aware of any useful public information on the cost to people and businesses of modifying their transport plans, such as information on the impact to businesses of postponing a trip by a few hours or days. A useful research project would involve surveying businesses to understand how flexible they are, and the cost of modifying travel plans. This may involve seeking views on what change in travel costs would prompt businesses to defer travel.

5.2.2 Integration of economic impact analysis

More work is required to enable evaluators to integrate the tools of economic impact analysis into transport evaluation. Economic impact models such as MERIT may fill an important gap in understanding the indirect impacts of disruptions and how the direct and indirect impacts change over time.

However, MERIT (and other regional economic impact models) are not in a form that – currently – can be easily integrated into standard transport investment appraisal analysis. The key issues are as follows.

- The core model outputs are not direct measures of welfare. The most useful common output measure produced by MERIT is the change in value added (as measured by GNDI or GDP). However, these measures do not account for opportunity cost, and changes in these variables may differ from welfare as a result of changes in the level of employment and/or capital resources employed. The model outputs are potentially extremely useful if they are supplemented with other results that could be extracted from the modelling. We understand that there are many additional metrics that exist in MERIT that could be extracted for this purpose and that, furthermore, the Dynamic Economic Module of MERIT is being updated to be able to report on the four capitals in the Living Standards Framework.
- The documentation that accompanies the MERIT model is not designed for use by an evaluator applying the model to undertake a CBA. The results would be more easily interpreted if the model produced the key assumptions, additional outputs and sensitivity analysis of the outputs to the key assumptions.

Going forward, we recommend that Waka Kotahi seek to work with model developers to address these issues. This would likely involve:

- ensuring the model outputs incorporate the additional data required (eg, changes in employment and capital expenditure and other metrics) to enable users to calculate welfare changes
- developing user documentation that explains how the outputs can be used in welfare analysis, such as CBA.

5.2.3 Distributional impacts

Distributional impacts are generally not closely analysed in transport investment appraisal. However, the relative suddenness and severity of disasters may mean they warrant greater attention in analyses involving resilience. A major transport disruption may have severe consequences for local businesses and communities that, as a result of loss of income, suffer from business closures and a loss of work. In standard economic appraisal, the loss of income in one location may be offset by an increase in another; nevertheless, from a welfare perspective (ie, total impact on wellbeing), the welfare losses associated with reduced employment in one location may far exceed the gains from increased employment in another.

We recommend that Waka Kotahi undertake a project to consider whether and how distributional effects should be incorporated into investment appraisal.

5.2.4 Behavioural responses to disruption

The costs of disruption depend significantly on how transport users respond to a disruption and how their behaviour changes with the length of the disruption. To date, there is limited information on how users have responded. Conducting surveys of transport users is a potentially useful method, particularly on routes where there has been a history of disruption. Further research on the process to undertaking such surveys and how they may be used would be beneficial.

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Appendix A: Multicriteria analysis (MCA) of the SH3-MWG options

The Manawatū Gorge Business Case included an assessment of the resilience of the four short-list options utilising a multicriteria analysis (MCA) following the Waka Kotahi guideline *Resilience of State Highways – Recommended Regional Assessment Methodology for Low Frequency Hazard Exposure* (Mason and Brabhaharan, 2016).

The summary results of the analysis are included below.

Table A.1 Manawatū Gorge – Transport performance results – Resilience

Resilience	Do minimum	Option 1	Option 2	Option 3	Option 4
Floods	15	1	1	1	1
Slips	25	25	25	25	25
Seismic	30	30	30	30	35
Network	10	0	10	0	0
Total score	**80**	**56**	**66**	**56**	**61**
MCA score	-	✓✓✓	✓	✓✓✓	✓✓

Source: GHD Advisory (2018b, p. 31)

The methodology applied above was developed for use in programme business cases. While informative, the MCA cannot be easily integrated into an economic evaluation as it does not involve the valuation of the costs and benefits associated with resilience. The above analysis indicates that Option 3 is preferable to Option 4 in terms of resilience but does not indicate the difference in value. Consequently, the analysis could not be used to determine whether Option 3 would be preferable to Option 4 if, hypothetically, the net present value of Option 4 was higher than Option 3. Rather, the value of the MCA of resilience has been to reaffirm the preferred option. Furthermore, the scoring within the MCA itself is subjective. Based on the weights applied, Option 4 rates better than Option 2; however, this is as a result of Option 2 rating 10 in terms of network.

Box A.1 Waka Kotahi guideline *Resilience of State Highways – Recommended Regional Assessment Methodology for Low Frequency Hazard Exposure*

Waka Kotahi provides a recommended regional assessment methodology for low-frequency hazard exposure to inform the development of programme business cases.

The methodology involves an evaluation of two resilient state dimensions:

- **availability state** – level of access after the event, representing the level of service
- **outage state** – the duration of reduced access at the above availability state.

Resilience assessment – availability state (*Resilience of State Highways* guidelines)

Level	Availability state	Availability description
1	Full	Full access (perhaps with driver care)
2	Poor	Available for slow access, but with difficulty by normal vehicles due to partial lane blockage
3	Single lane	Single lane access only with difficulty to poor condition of remaining road
4	Difficult	Road accessible single lane by only 4×4 off-road vehicles
5	Closed	Road closed and unavailable for use

Resilience assessment – outage state (*Resilience of State Highways* guidelines)

Level	Outage state	Outage description
1	Open	Full access (perhaps with driver care)
2	Minor	Condition persists for up to 1 day
3	Moderate	Condition persists for 1 day to 3 days
4	Short term	Condition persists for 3 days to 2 weeks
5	Medium term	Condition persists for 2 weeks to 2 months
6	Long term	Condition persists for 2 months to 6 months
7	Very long term	Condition persists for > 6 months

Source: Mason and Brabhaharan (2016)

Appendix B: Glossary

AADT	annual average daily traffic
AATOC	average annual time of closure
ADC	average duration of closure
AEP	annual exceedance probability
ARI	annual recurrence interval
ATAP	Australian Transport Assessment & Planning
CBA	cost–benefit analysis
CGE	computable general equilibrium
EDOC	expected duration of closure
EEM	*Economic Evaluation Manual*
GDP	gross domestic product
GNDI	gross national disposable income
HCV	heavy commercial vehicle
IIM	inoperability input–output model
IO	input–output
LSF	Living Standards Framework
MCA	Multicriteria analysis
MDC	median duration of closure
MERIT	Measuring the Economics of Resilient Infrastructure Tool
MWG	Manawatū Gorge
Qld DTMR	Queensland Government Department of Transport and Main Roads
SH3-MWG	State Highway 3 – Manawatū Gorge
TIC	Transport and Infrastructure Council
UK	United Kingdom
US	United States
WTA	willingness to accept
WTP	willingness to pay