Measuring the social, environmental and economic consequences of bridge failure due to natural disasters

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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To my late Grandfather, a civil engineer by profession, who took immense pride and interest in my PhD; sharing his thoughts and ideas, even during his last few days with us.

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RESEARCH OUTPUT

Journal Articles

Gajanayake, A., Zhang, G., Khan, T. and Mohseni, H. (2020), 'Postdisaster Impact Assessment of Road Infrastructure: State-of-the-Art Review', *Natural Hazards Review*, vol. 21, no. 1, p. 03119002.
((Gajanayake et al. 2020b), Manuscript accepted: 23 May 2019, Published online: 12 November 2019)

Gajanayake, A., Khan, T., & Zhang, G. (2020). 'Post-disaster reconstruction of road infrastructure'. *European journal of transport and infrastructure research*, vol. 20, no. 1, pp 1-16.
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Peer-reviewed Conference Papers

Gajanayake, A., Khan, T., & Zhang, K. (2019), 'Post-disaster decision making in road infrastructure recovery projects: An interview study with practitioners in Queensland'. *National Emergency Response*, 32(3), 14.
((Gajanayake, Khan and Zhang 2019), Paper presented to Australian & New Zealand Disaster & Emergency Management Conference, Gold Coast, Queensland, Australia, 12 – 13 June 2019)

Gajanayake, A., Mohseni, H., Zhang, G., Mullett, J. and Setunge, S. (2018), *'Community adaptation to cope with disaster related road structure failure'*, Procedia engineering, vol. 212, pp. 1355-1362.
((Gajanayake et al. 2018), Paper presented at the 7th International Conference on Building Resilience: Using scientific knowledge to inform policy and practice in disaster risk reduction, Bangkok, Thailand, 27 – 29 November 2017)

Gajanayake, A., Setunge, S., Zhang, K. and Mohseni, H. (2016), *'Measuring social, environmental and economic impacts of road structure failure'*, paper presented to 6th International Conference on Building Resilience.
((Gajanayake et al. 2016), Paper presented at the 6th International Conference on Building Resilience: Building Resilience to Address the Unexpected, Auckland, New Zealand, 7 – 9 September 2016)

Poster Presentations

Gajanayake, A., Mohseni, H., Zhang, G., Khan, T. & Setunge, S., (2017), *'Measuring social, environmental and economic consequences of road structure failure due to natural disasters'*, Bushfire and Natural Hazards CRC and AFAC Annual Conference, Sydney, Australia, 4 – 6 September 2017

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ABSTRACT

With an increase in the frequency and intensity of natural disasters in recent times, the vulnerability of infrastructure assets to such events is a major concern for governments and communities worldwide. The last decade has seen an increase in the number of hydro-meteorological disasters, which have caused major social, economic and environmental impacts on the regions affected. Road bridges tend to be one of the most vulnerable infrastructure assets to hydro-meteorological events, as they are designed to cross water-ways and are built across the natural flow of water. As bridges play a vital role in the recovery of a community after a disaster by providing access to the disaster zone, the reconstruction of damaged bridges is a significant aspect of post-disaster recovery.

The prioritisation and reconstruction of bridges tend to be carried out based on financial and engineering assessments, with very limited focus on the wider social, environmental and economic impacts of the decisions made. This thesis argues that a holistic approach in assessing and prioritising bridge reconstruction will increase the sustainability and resilience of the wider infrastructure system. The ensuing research project, part of the Bushfire and Natural Hazards Cooperative Research Centre, has explored the importance of a more holistic approach to assessing post-disaster reconstruction impacts and has developed a framework that could be followed by academics and practitioners for this purpose.

The research used a mixed-methods approach; it relied on both quantitative and qualitative data in a single study. As one of the main objectives of the PhD was developing a framework that could be used to assess wider impacts, an iterative process was adopted, which helped in continuously improving the framework with the new knowledge that was gathered throughout the course of the candidature. The review of literature revealed that the majority of post-disaster assessments and subsequent decision-making processes tend to pay less attention to the wider social, environmental and economic impacts of road infrastructure failure. The literature that incorporated wider aspects tends to be focussed on specific impact categories, with none of the studies capturing a comprehensive set of impacts. The literature review also provided the opportunity to analyse the different techniques used by scholars to assess wider impacts, in order to select the most appropriate techniques for the purpose of the study.

Potential end-users of the framework were interviewed to understand how decision making in relation to post-disaster infrastructure reconstruction takes place in a practical sense. The interviews helped the researcher to identify how decision making could be optimised in a resource and time constrained post-disaster setting. The practical requirements of the decision makers were considered to develop a more suitable framework, thus increasing its potential adoption among road reconstruction authorities.

The developed framework was applied to a real life disaster situation – a flood – in which two bridges were damaged, and the resulting social, environmental and economic impacts were assessed. As part of the research project, a toolkit based on the framework was developed in

order to carry out this assessment. To the best of the author's knowledge, this was the first instance where a comprehensive set of sustainability related impacts of the failure of rural road bridges were assessed. Results showed that the total sustainability related impacts vary based on where the bridge is located, and impacts could range between 25-30% of the total impacts.

The framework and toolkit were validated through a series of interviews with practitioners and academics working in the areas of infrastructure reconstruction and sustainability. The interviews helped in refining the toolkit to better suit practical applications, without compromising the required theoretical and academic rigour. The reliability of the results obtained through its application in the case studies was tested with a follow-up questionnaire survey to residents in the area and interviews with decision makers working in the region. A further sensitivity analysis of the results was conducted in order to understand how changes in the input values and external variables affect the results. It was found that the socio-economic impacts could be reduced significantly by allowing restricted volumes of traffic to use a bridge rather than being completely closed off during the reconstruction period. A Cost-Benefit Analysis using the developed toolkit could be performed to identify the optimal intervention techniques.

The outcomes of this PhD research can be used by both academics and practitioners in assessing the wider socio-economic and environmental consequences of road infrastructure damage. The toolkit developed through this research is planned to be further modified for use by disaster management and road agencies through a CRC Utilisation Project. The outcomes of this thesis can thus be used by infrastructure engineers to optimise their decision making processes, thereby driving increased sustainability of infrastructure systems and resilience to future disaster events.

1. INTRODUCTION

1.1 Background

Disasters triggered by natural hazards are increasing both in intensity and frequency, causing a large-scale impact on societies and economies globally. In 2019 alone, 396 natural disasters occurred globally, which was slightly higher than the 10-year average from 2009-2018 (CRED 2020). These disasters affected over 95 million people and cost over USD 130 billion in damages. Trends over the last few years show an increase in economic impacts due to disasters although there have been reduced mortality rates (Below R. and Wallemacq P. 2018). The increase in disaster events is mainly due to a rise in hydro-meteorological disasters such as floods, hurricanes and storms, which accounted for over 70% of the events and 68% of the people affected (CRED 2020). In contrast, the number of natural geological disasters such as volcanic eruptions and earthquakes has remained steady over the same period (Guha-Sapir 2016).

Similarly, in Australia, hydro-meteorological disasters such as floods and storms are the most common type of disaster. The estimated average annual cost of damage from hydro-meteorological disasters in Australia and New Zealand is estimated to be above USD 2.5 billion (Guha-Sapir 2016). With rainfall extremes becoming more intense and the probability of combined extreme weather events, the potential for future damage due to hydro-meteorological disasters may keep growing (CSIRO and Bureau of Meteorology 2018).

The increase in hydrological disasters has a direct influence on the vulnerability of road infrastructure, such as bridges, culverts and flood-ways. Such infrastructure is built to cross water-ways, and in times of hydrological disasters can be severely affected (Lokuge et al. 2019). Road bridges also play a major role in the resilience of a society after a disaster event as they directly influence evacuation, rescue and reconstruction efforts by providing access and mobility to communities. The un-usability of such infrastructure can exacerbate the consequences of the disaster on a temporal and spatial scale (Frazier et al. 2013).

Meteorological disasters tend to affect coastal areas more, and such areas are typically more densely populated. As population density rises so does road density, and this in turn increases the vulnerability of road infrastructure to hydro-meteorological disasters (Sahani et al. 2019). This connection is very noticeable especially in Australia, where high flood hazard areas are situated on the eastern coast, which is also where road density is the highest.

It is thus evident that road infrastructure such as bridges, which are designed to cross water-ways, is highly vulnerable to disasters but also critical in enhancing the resilience of a disaster prone community. Thus, the assessment of impacts is the first step towards understanding how communities and economies are affected due to disaster induced damage to bridges. RMIT University is heading a research project under the Bushfire and Natural Hazards Cooperative Research Centre of Australia (BNHCRC) that aims to reduce the vulnerability of road structures to disasters, in order to enhance the resilience of both structures and communities. The PhD research presented in this thesis is a part of this BNHCRC project and focuses on assessing the impacts to communities and economies due to disaster induced bridge failure.

1.2 Significance of the research

The state of Queensland located on Australia's east coast, is one of the most vulnerable states to natural disasters (Coates 1999, Haynes et al. 2017). Within the last decade, Queensland has experienced a number of natural disaster events. The two disasters that caused the biggest damage were the cyclone-flood events that occurred during 2010-11 and again in 2013. The Queensland Reconstruction Authority (Queensland Reconstruction Authority 2011) was established soon after the 2010-11 events to monitor and coordinate the government's program of recovery and reconstruction.

The Australian and State Governments committed approximately $6.8 billion for rebuilding activities after the 2010-11 events. Of the infrastructure damage caused by the event, 80% was to road and transport infrastructure, with 9,170 km of state-owned roads and 89 state-owned road structures being damaged. The investment in road and transport infrastructure was expected to be approximately $4.2 billion spread over a three-year period (Queensland Reconstruction Authority 2011). As these figures only relate to the financial cost of reconstruction of the infrastructure, the wider social, economic and environmental effects of damaged roads could be expected to be much higher. The assessment of social, environmental and economic consequences will be the first step towards understanding such wider impacts and will help in increasing the resilience of disaster impacted communities.

Rehabilitation and reconstruction of road infrastructure plays a vital role as communities strive to recover after a major disaster event (Zhu et al. 2018). This is especially the case when numerous road networks have been damaged following an event and road authorities and reconstruction agencies need to rebuild many damaged structures to achieve the minimum level of accessibility in and out of the disaster zone. For example, due to the 2013 flood event, 43 of 46 bridges were damaged in the Lockyer Valley Regional Council, in south-east Queensland (Setunge et al. 2014). Most of these bridges had been damaged due to a previous flood event in 2011 and had been repaired not long before the 2013 flooding occurred.

With back-to-back disasters occurring in short time horizons and causing damage to multiple road structures, road authorities find it challenging to repair all damaged structures in a short period of time. This is mainly due to various constraints encountered by authorities. These constraints are not only financial but can also include labour and material sourcing challenges (Chang et al. 2012). Such issues affect rural areas more as regional councils will typically lack the financial and political strength to attract all of the required funding for reconstruction. In such situations, road asset owners have no choice but to prioritise the reconstruction of the infrastructure (Pathirage et al. 2012). Decision makers in local councils and road authorities will need to decide which specific bridges are the most significant in a given area and prioritise their reconstruction.

The majority of research on post-disaster decision making processes tends to focus on the structural engineering aspects: evaluating a structure's vulnerability and ascertaining how to increase its robustness (Faturechi and Miller-Hooks 2014). However, it is also important to consider the wider social, environmental and economic aspects of road failure in the post-disaster decision making phase. Research that takes these aspects into consideration rarely considers all three categories together. Most of the work that does consider such aspects focuses only on one single category to complement a structural engineering decision making model.

The PhD research that this thesis is based on identified this gap in research, and makes a major contribution to existing literature in the field of disaster impact assessment of road infrastructure.

This thesis explains how the wider socio-economic and environmental impacts of bridge failure can be measured, and develops a framework that can be used by practitioners in post-disaster reconstruction. The research presented in this thesis focuses on the social, environmental and economic aspects of the failure of road structures and its effects on the resilience of communities.

This is the first time that a project has measured the overall impacts of post-disaster bridge failure and has major practical and policy implications in the field of infrastructure management and engineering.

This thesis builds on the body of knowledge in the field of infrastructure impact assessment in order to develop a framework that could be used to measure the wider impacts of post-disaster road infrastructure failure by incorporating social, environmental and economic (SEE) impacts. Such a framework could be used for a wide array of infrastructure systems and could be modified for use in variety of post-disaster decision making. The development of a holistic model that can be used to quantify SEE impacts would help relevant authorities to reduce these impacts by looking into diverse community adaptation options. It would also drive decisions that are cost effective, promote resilience and minimise impacts on the society, economy and environment.

This research project aims to achieve one of the BNHCRC's objectives: "to reduce the social, economic and environmental costs of disasters". The project will sit within the research area of "Enhancing resilience of critical road infrastructure: bridges, culverts and flood-ways" of the BNHCRC and will address the outcome of "Quantifying social, environmental and economic consequences of failure".

1.3 Aims and Objectives of the Research

The aim of this research is to study the current methods used to measure the SEE impacts of road bridge failure due to natural disasters and to build a comprehensive framework and toolkit that can be used by decision makers to assess the impacts of bridge failure in natural disaster scenarios.

The research questions to be addressed by this project are as follows:

- What are the limitations of the current methods used to measure SEE consequences of disaster-related road failure?
- How can the methods used currently be modified and improved to suit the assessment of impacts of bridge failure?

- How can SEE impacts be integrated into a toolkit to assist in post-disaster road infrastructure decision making?
- How can the developed framework be validated to test for its explanatory power?
- How can the overall negative impacts of post-disaster reconstruction of bridges be reduced?

The research objectives pursued in order to answer the research questions are as follows:

- To understand the current methods and techniques used in consequential impact assessment of post-disaster road infrastructure failure.
- To modify and improve suitable methods in order to measure SEE impacts of disaster-related bridge failure.
- To develop a conceptual framework that can measure and integrate the socio-economic and environmental impacts of bridge failure.
- To develop a toolkit based on the framework that can aid in effective decision making.
- To validate the framework and toolkit by using case studies from a regional disaster-affected area.
- To propose recommendations that can be used by practitioners to reduce overall impacts during post-disaster reconstruction.

The framework developed in this thesis integrates a number of different aspects in order to broaden the understanding of the wider impacts of bridge failure. It is, therefore, more a conceptual than a theoretical framework, as different concepts and theories are put together in order to explain a broader picture of possible relationships (Imenda 2014). A toolkit was developed to test the validity of the framework, while the toolkit can be used by disaster management practitioners to assist in post-disaster decision making.

1.4 Scope of the Research

This project brings together two broad areas of research: road infrastructure failure and disaster impact assessment, with the intention of understanding the impacts of bridge failure caused by natural disasters. Hence the scope of this project is limited to assessing the SEE impacts specifically caused by damage to road bridges due to natural disasters. The impacts considered for this research exclude structural impacts to bridges that are typically studied in the field of structural engineering and wider disaster impacts that are not caused by damage to road infrastructure.

For the purpose of this research a disaster was identified as an event induced by natural hazards, which may include floods, bushfires, earthquakes, cyclones and landslides. Although all types of disasters were analysed during the research, it was recognized that road bridges were impacted more due to hydrological disasters like floods and therefore this thesis focuses more on flood impacts on bridges. The scope of this research also excludes road network failure due to physical deterioration of structures and terrorist attacks, which do no not fall into the category of natural disasters. Additionally impacts of scheduled road closures or road accidents were excluded from the scope, as impacts in post-disaster scenarios can be significantly different to those in other circumstances (Kurauchi et al. 2009). Such changes can be due to the fact that a disaster event can fundamentally alter people's usual travel patterns, and that behaviour of passengers may not be rational in post-disaster situations (Khademi et al. 2015).

The temporal focus of this thesis is on post-disaster (ex-post) assessment of bridge failure. The assessment of the impacts takes place after the disaster event, when a specific level of damage to infrastructure has been assessed. This is in contrast to pre-disaster (ex-ante) prediction, where different probabilities of damage to infrastructure are predicted based on hypothetical events. This thesis focused on consequence assessment of post-disaster impacts due to road structure failure as such a method takes into account adaptation practices of a community affected by a disaster (Lu et al. 2014), which provides more realistic information that can be used by decision makers.

1.5 Outline of Chapters

The thesis consists of nine chapters, as outlined below.

Chapter 1: Introduction
The first chapter introduces the research project and presents the background and significance of the research together with the contribution to the body of knowledge. This is followed by the aims and objectives of the research and the scope of the research.

Chapter 2: Literature review
The literature review chapter presents the relevant literature in the field of research and a critical analysis of this literature. The literature reviewed covers disaster impact analysis, the economic, social and environmental impacts of road structure failure and methods used to integrate these impacts. The literature review forms the basis for understanding the research gap that is addressed in this thesis.

Chapter 3: Research methodology
This chapter explains the methodology adopted in the research. The research questions of the project are presented and the methodology adopted to address these questions is explained. The chapter also includes how the research gap was identified, the framework developed, data collected and the validation and analysis conducted.

Chapter 4: Analysis of measurement methods
The different methods and techniques that have been used in the literature to measure social, environmental and economic impacts are analysed within this chapter. The main section of this chapter is a review paper that was published by the candidate during the PhD project. This was a critical review paper with in-depth analysis of advantages and disadvantages of the different methods used in the literature. The chapter also includes a section were the methods are analysed for the suitability for this specific project.

Chapter 5: End-user needs assessment and interviews
The next chapter focuses on interviews conducted with potential end-users in order to understand the current methods of practice and their requirements. The results are presented within two papers that were published during the candidature. The final section of the chapter

explains the end-user requirements that underpin some of the theoretical assumptions made when developing the framework.

Chapter 6: Development of an integrated framework and toolkit

Chapter 6 explains the theory and assumptions behind the development of the conceptual framework to measure SEE impacts. The framework relied on analysis of the measurement methods and the end-user requirements obtained through the interviews to select the most appropriate methods to measure and integrate the different types of impacts to a common platform. An explanation of the toolkit that was developed to test the framework is also included.

Chapter 7: Case study

This chapter describes the process of data collection required for the running of the toolkit and the results based on that analysis. The data for the research was based on two case study bridges situated in the Lockyer Valley Regional Council, which is a disaster prone area in regional Queensland.

Chapter 8: Validation and analysis

Chapter 8 presents the analysis of the results that were explained in the previous chapter. The analysis includes a sensitivity analysis carried out in order to identify the most significant drivers of the impacts and a validation of the assumptions based on factual behavioural changes in the case study area. Results of follow-up interviews with potential end-users to understand the practical implications of the research are also included in this chapter.

Chapter 9: Summary, conclusions and recommendations

The final chapter summarises the findings of the thesis and provides concluding remarks. Recommendations for future research areas and important aspects to consider in such instances are also explained.

2. LITERATURE REVIEW

2.1 Introduction

A preliminary literature review was undertaken at the beginning of the research project, in order to understand previous research that had been carried out in this field. The literature review helped to identify and categorise the potential impacts as well as understand the different methods used by scholars to measure these impacts. The review also covered research that measured and combined different types of impacts, which helped in identifying the most suitable methods that can be adopted for this research. A critical analysis of the literature was carried out as part of the project, and is explained fully in Chapter 4.

As this research combines two distinct research areas – road infrastructure failure and disaster impact assessment – the literature review incorporated literature that focussed on both these areas of research. This two-pronged approach gave the researcher a broad understanding of previous research relevant to the project. It also helped to narrow down the process to a more rigorous review pertaining to the scope of the project.

The literature review process lead to the development of a review paper titled *Post-disaster Impact Assessment of Road Infrastructure: A State-of-the-Art Review* and forms the basis of Chapter 4. The focus of this paper was to critically review prior literature on the post-disaster impact assessment of road infrastructure. The paper included a thorough qualitative review of the different methods, and is also relevant to this chapter.

2.2 Initial scoping review

An initial literature review of disaster impact analysis was carried out to understand the different impacts that could occur due to a natural disaster. The focus of this review was to identify all the different types of impacts that may occur due to a natural disaster event. The impacts were categorised as economic, social and environmental based on the common sustainability impact categorisations. This review covered academic journal papers, conference papers, government reports and reports from other disaster management agencies.

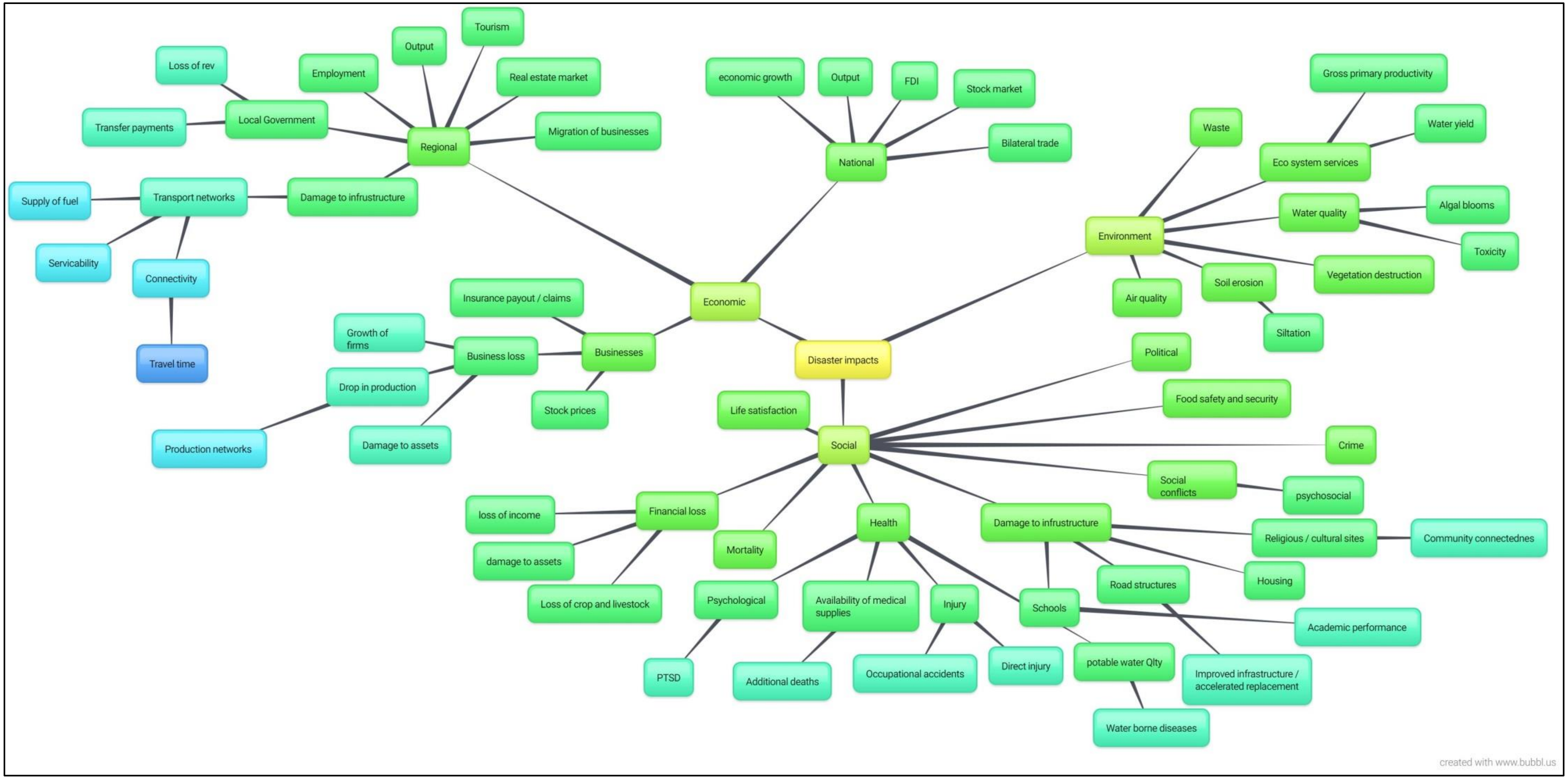
A semantic map based on the initial disaster impact literature was developed (Figure 2-1), which helped the researcher to understand different types of impacts and the relationships between them. As Figure 2-1 illustrates, disaster induced road structure failure could impact all three dimensions of sustainability: social, environmental and economic. In addition, this figure shows how clear boundaries between the three spheres cannot be distinguished as impacts could be interdependent to each other. For example, damage to road infrastructure can impact transport networks negatively, which in turn can lead to social impacts as communities may not be able to access essential supplies; economic impacts affecting wider business and commercial entities; as well as environmental impacts due to increased fuel consumption as longer detour routes are used. As such it was understood that an in-depth analysis and measurement of a comprehensive set of impacts needed to be studied from a multi-disciplinary perspective, without being constrained by academic or professional boundaries.

A review of literature of road structure failure and impacts due to reduced serviceability of roads was carried out. This helped the candidate to identify a list of potential impacts of damage to road infrastructure. This list of potential impacts is presented in Table 2-1. This two-pronged approach of the scoping review included over 300 papers and was the first step to identify the most relevant literature for the purpose of the study. It also provided a good initial grounding for the candidate to embark on a more in-depth and critical review that was required for the project.

Table 2-1 Potential impacts of disaster-related road infrastructure failure

Dimension	Category	Potential impacts
Economic	Direct	Clean-up, emergency relief costs
		Cost of reconstruction
		Disaster relief/reconstruction payments
		Cost of improving resilience of structures through upgrade
		Increased revenue to construction companies
	Indirect	Cost of increased travel time/delay due to reconstruction
		Loss of revenue to public transport operators
		Losses to business due to lower customer traffic, supply chain impacts
		Increased sales for businesses during construction period
		Loss of income to individuals due to reduced access to work
		Increased income to the community due to additional contract work
		Improved resilience as a result of building better
Social	Accessibility	Loss of access to schools
		Loss of access to medical facilities
		Loss of access to markets
		Loss of access to recreational activities
		Time spent away from home
		Extra travel time/delays for community
	Acceptance	Perceived resilience of the new structure
		Aesthetics of the new structure
		Confidence in authorities
	Capabilities	Reduced capabilities of the community
		Life satisfaction
Environmental	Natural Environment	Disposal of debris
		Damage to natural environment/habitat
		Impact on animal life
	Resource use	Non-renewable resources used for reconstruction
		Carbon emissions due to extra travel during construction
		Life cycle impacts due to reconstruction

Figure 2-1 Semantic map of disaster impacts



2.3 Classification of impacts

Disaster impacts have been typically categorised according to four: direct, indirect, tangible and intangible. Direct impacts are caused by the destruction of social, environmental or economic capital by the disaster event (flood water, fire, wind etc.) and occur on a narrow temporal and spatial scale, while indirect impacts are induced by the direct impacts and occur temporally and spatially distanced from the disaster event (Merz et al. 2010).

Tangible impacts are those impacts to items that are commonly bought and sold in a market, which can be easily quantified in monetary terms, while intangible impacts refer to impacts to items that are not commonly traded and hence are difficult to quantify in monetary terms (Stephenson, Handmer and Betts 2013). Intangible impacts could be further divided as social and environmental impacts.

Although the categorisation of impacts according to direct/indirect and tangible/intangible is common in disaster impact analysis, there can be differences in interpretation between scholars. The distinction between whether an impact is tangible or intangible can often be blurry. This is exacerbated by the fact that some scholars try to value social and environmental impacts in monetary terms (Stephenson et al. 2013, Chang et al. 2009), while others deem that monetary values cannot be given to such impacts such as loss of life and other social impacts (Gardoni and Murphy 2009, Lindell and Prater 2003).

The distinction between direct and indirect impacts is much more straightforward; however, some scholars use the term secondary impacts to refer to longer-term impacts. This term has been used to refer to the performance of an economy from a macroeconomic perspective (Pelling, Özerdem and Barakat 2002) and to refer to negative market outcomes affecting businesses (Hiete and Merz 2009).

Although it is common to group disaster impacts according to the categorisation explained earlier, some scholars use different categorisations as environmental, social and economic impacts based on the three dimensions of sustainability (Adeagbo et al. 2016, Dong, Frangopol and Saydam 2014b) or as costs in anticipation, response and consequence based on the three stages of a disaster (Ashe, McAneney and Pitman 2009). The assessment of the literature in this thesis is organised and presented based on the classification illustrated in Table 2.2.

When considering other civil infrastructure systems economic resilience is major aspect that is focused on (Gay and Sinha 2013). The economic approach to civil infrastructure resilience is based on evaluating financial implications of system preparedness, failure, and recovery such as revenue loss, restoration and recovery cost, and economic impact on community activities (Jain and McLean 2009, Qiao et al. 2007, Vugrin et al. 2010, Weick and Sutcliffe 2011).

Both direct costs as well indirect costs of damages like adaptation, preparedness, and mitigation options are included when considering economic impacts of infrastructure (Vugrin and Turnquist 2012). Failure costs are frequently compared with the cost of available mitigation and adaptation options, including emergency preparedness and opportunity costs (Rose 2004a). It is considered that disaster consequences should generally be measured in economic terms, which can provide guidance on benefit-cost ratios, evaluation of investments, preparedness expenses, and other decision-making processes involving economic and financial considerations (Gay and Sinha 2013).

For the purpose of this thesis, economic impacts are considered to be tangible impacts which affect goods or services that are commonly traded in markets, while intangible impacts are categorised as social and environmental impacts. Social impacts are those affecting human society, while impacts affecting the natural environment were categorised as environmental impacts. However, distinguishing whether a disaster induced impact falls into a specific category is not straight forward, as some impacts could affect social, economic and environmental dimensions, as illustrated in Figure 3-1.

It has been pointed out that not all disaster-related impacts are negative (losses), but that some impacts can also include gains resulting from a disaster. Examples of such benefits include benefits flowing to the community in the form of aid, increased employment due to reconstruction activities and enhancement of the natural environment (Smith 2013).

Table 2-2 illustrates some common impacts of disaster-induced road failure. The literature review will be presented according to these classifications for ease of analysis.

Table 2-2 Classification of impacts from road failure

	Type of impact	
Measurement	**Direct**	**Indirect**
Tangible (Economic)	Damage to infrastructure, damage to vehicles, clean-up costs, disposal of debris, disaster and reconstruction aid	Business disruption, loss of individual income, loss of revenue to public transport operators and costs of alternative accommodation, increased income and employment due to reconstruction
Intangible (Social)	Death and injury, loss of items of cultural significance, psychological impacts	Increase in travel time, inconvenience and disruption to community, psychological impacts, loss of confidence in authorities
Intangible (Environmental)	Loss of animal life, damage to habitat, deposit of fertile soil	Resource use for reconstruction, incremental emissions during reconstruction

Note: Modified based on table adapted from Review article: Assessment of economic flood damage by Merz, B., Kreibich, H., Schwarze, R. & Thieken, A, 2010, *Natural Hazards and Earth System Science*, 10, 1697-1724.

The literature on disaster impact studies could be divided into two areas as pre-disaster (ex-ante) impact prediction studies and post-disaster (ex-post) impact assessment. Ex-ante impact prediction is carried out before a disaster event takes place. This involves the modelling of a hypothetical disaster and different probabilities of how road infrastructure may be affected are predicted. The SEE impacts are then predicted based on these different scenarios that have been modelled. Ex-post assessment is carried out after a disaster event and the damage to infrastructure is known.

Ex-ante assessment is generally used for the assessment of the vulnerability and the significance of different road structures before an event. However, such models may not be relevant after an actual disaster event, as the level of damage to a specific structure may be very different to that predicted in the ex-ante models. In addition, ex-ante models generally predict the impacts for one structure or section of a road, while in reality a number of road segments could be damaged due to a disaster. In such situations, the ex-ante models will not be valid as the socio-economic impacts predicted by such models will not be realistic.

Although this thesis focuses on post-disaster impacts, the literature review covers research on both ex-ante and ex-post impact assessment. Such an approach was adopted as it increased the understanding of all possible impacts that could occur and a wide range of measurement techniques used by scholars in the area of disaster impact assessment. The review showed that the majority of literature on road structure failure focuses on structural engineering aspects related to the failure and reconstruction of affected structures (Banerjee and Shinozuka 2008, Ghobarah, Saatcioglu and Nistor 2006, Han et al. 2009). However, with the current emphasis on assessing impacts through an integrated sustainability approach, there has been an increase in research attempting to measure SEE impacts of road infrastructure (Dong et al. 2014b, Gilmour et al. 2011, Gühnemann, Laird and Pearman 2012).

Table 2-3 is a summary of the literature pertaining to impact measurement studies of disaster-related road failure, and these papers are analysed in more detail subsequently.

Table 2-3 Summary of impact measurement studies

Type of impact	Method used	References
Direct tangible (Economic)		
Damage to infrastructure	Cost survey	(Klose, Damm and Terhorst 2015, Negi et al. 2013, Winter et al. 2016a),(Klose, Maurischat and Damm 2016, Donnini et al. 2017)
	Cost modelling	(Dutta, Herath and Musiake 2003, Jaiswal, Van Westen and Jetten 2010, Luna, Hoffman and Lawrence 2008, Penning-Rowsell et al. 2005, Klose et al. 2015)
Indirect tangible (Economic)		
Transport impacts	Network analysis	(Bíl et al. 2015, Bono and Gutiérrez 2011, Chang and Nojima 2001, Ho, Chen and Hu 2012, Jenelius and Mattsson

		2012, Muriel-Villegas et al. 2016, Postance et al. 2017, Kim, Spencer Jr and Elnashai 2008, Nojima and Sugito 2000, Viswanath and Peeta 2003, Shiraki et al. 2007, Shinozuka et al. 2005)
	Transport modelling	(Alipour and Shafei 2015, Enke, Tirasirichai and Luna 2008, Furtado and Alipour 2014a, Mitsakis et al. 2014, Negi et al. 2013, Shen and Aydin 2014, Wen et al. 2014, Wesemann et al. 1996, Winter et al. 2016a, Xie and Levinson 2011, Dalziell and Nicholson 2001, Kiremidjian et al. 2007, Pfurtscheller and Genovese 2016a)
Business impacts	Cost survey	(Boarnet 1996, Hansen and Sutter 1990, Wesemann et al. 1996, Willson 1998, Pfurtscheller and Genovese 2016b)
	Input Output analysis	(Cho et al. 2001, Lee, Kang and Kim 2009, Kim, Ham and Boyce 2002, Ham, Kim and Boyce 2005, Resurreccion and Santos 2013, Gordon, Richardson and Davis 1998, Sohn et al. 2004, Irimoto, Shibusawa and Miyata 2017)
	Computable General Equilibrium analysis	(Chen and Rose 2016, Xie et al. 2014, Shi and Wang 2013b, Tsuchiya, Tatano and Okada 2007, Tatano and Tsuchiya 2008)
Direct Intangible (Social)		
Life loss	Statistical	(Ashley and Ashley 2008, Coates 1999, Diakakis and Deligiannakis 2013, FitzGerald et al. 2010, Yale et al. 2003, Rappaport 2000, Byard et al. 2012)
	Value of statistical life	(Negi et al. 2013, Dong et al. 2014b)
Direct intangible (Environmental)		
	Sediment run-off	(Sosa-Pérez and MacDonald 2016, MacDonald and Coe 2008)
Indirect intangible (Social)		
Community accessibility	Statistical	(Adeagbo et al. 2016, Gordon et al. 1998)
	Accessibility index	(Chang 2003b, Deshmukh, Ho Oh and Hastak 2011, Sohn 2006)
Psychological	Statistical	(Morrice 2013), (Wang et al. 2012)
Social vulnerability	Social Vulnerability Index	(Schweikert, Espinet and Chinowsky 2018)
Indirect intangible (Environmental)		

Reconstruction	Carbon footprint	(Mackie et al. 2014, Padgett and Tapia 2013, Dong et al. 2014b, Schweikert et al. 2018)
	Embodied energy	(Padgett and Tapia 2013, Dong et al. 2014b)
Re-routing	Carbon footprint	(Winter et al. 2016a, Dong et al. 2014b)

2.4 Direct tangible impacts

Direct tangible impacts are those impacts that occur due to direct damage to the specific road structure and will include such costs as road clean-up, debris disposal, damage to infrastructure and damage to vehicles on the road at the time of the disaster.

Scholars have used two different methods to measure direct tangible impacts based on the availability of data. While some scholars (Klose et al. 2015, Winter et al. 2016a, Negi et al. 2013, Klose et al. 2016, Donnini et al. 2017) use empirical data to measure the direct impact of road failure others use a cost modelling approach (Luna et al. 2008, Jaiswal et al. 2010, Dutta et al. 2003, Penning-Rowsell et al. 2005).

Cost surveys utilise empirical data from relevant sources to measure the direct tangible impacts and are the most commonly used method to assess the disaster costs at a regional or national level (Vranken et al. 2013, Walkinshaw 1992, Wang, Summers and Hofmeister 2002). The direct impacts measured under this method will typically include clean-up costs and damage to infrastructure.

The cost modelling approach utilises loss functions for specific components of a structure or stage damage curves to estimate the damage to the entire structure based on various external factors and then uses standard market prices to assign monetary values. Although most cost modelling approaches have been used for pre-disaster assessments, (Klose et al. 2015) use cost modelling in post-disaster analysis since primary data could not be sourced. However, most of this literature focuses mainly on the damage to the infrastructure while no assessment of the clean-up and disposal costs are included.

Researchers have also used various damage indices and scales to estimate direct tangible impacts to infrastructure assets (Blong 2003, Hill and Rossetto 2008, Petrucci 2010). Scholars who rely on damage indices to estimate direct damage to infrastructure present the damage through an index value on a categorical scale which provides an estimate of damage, with a single value in the index normally representing a range of % losses or numerical values standardised to a 0–1 scale (Blong 2003). Researchers rely on construction costs per square metre, and approximate replacement ratio which is used to estimate the cost of repairing or replacing damaged infrastructure.

2.5 Indirect tangible impacts

Most indirect impacts of the failure of road structures stem from the reduction in accessibility, connectivity and mobility due to the un-usability of the structure after a disaster. The indirect tangible impacts identified through the literature are an increase in travel time, business disruption due to lower customer traffic and supply chain disruptions, loss of individual income, loss of revenue to public transport operators and the cost of alternative accommodation. All these impacts have common or proxy markets and hence can be measured in monetary terms without much trouble.

2.5.1 Transport related impacts

One of the major indirect impacts due to road failure is the transport related impacts and thus there has been a multitude of studies looking at the transport impacts both on individuals and businesses. Two distinct approaches have been used by scholars assessing the transport impacts where some use transport network analysis (Bíl et al. 2015, Bono and Gutiérrez 2011, Muriel-Villegas et al. 2016, Chang and Nojima 2001, Ho et al. 2012, Postance et al. 2017, Jenelius and Mattsson 2012), while others use transport modelling techniques (Negi et al. 2013, Wesemann et al. 1996, Mitsakis et al. 2014, Shen and Aydin 2014, Wen et al. 2014, Winter et al. 2016a, Xie and Levinson 2011, Alipour and Shafei 2015, Furtado and Alipour 2014a, Enke et al. 2008, Pfurtscheller and Genovese 2016a).

Transport modelling techniques typically estimate the changes in travel time after a disaster through surveys or mathematical models. Transportation modelling tools are commonly used to estimate the number of people using a particular mode of transport, and similar models are used to estimate transport related impacts in post-disaster scenarios.

Transport network analysis is a branch of network theory that analyses a transport system from a graph theory perspective by considering the network as sets of nodes and links. The use of network theory to analyse transport systems can be advantageous in disaster scenarios, as it can be used in conjunction with geographical data of disasters and has grown in popularity in recent times with the advances in Geographic Information Systems (Ducruet and Lugo 2013).

Distinctions in approaches could be seen in determining the changes in travel behaviour in both these methods. Some scholars use static models assuming that travel patterns would be similar to pre-disaster times (Nojima and Sugito 2000, Viswanath and Peeta 2003, Kim et al. 2008), while others use dynamic models to account for changes in behaviour after the disaster (Shinozuka et al. 2005, Shiraki et al. 2007, Kiremidjian et al. 2007, Dalziell and Nicholson 2001). Due to the accessibility of data prior to the disaster event, most mathematical models have been used for prediction of impacts and some scholars have modified such studies to assist in prioritising reconstruction (Chang et al. 2010, Furtado and Alipour 2014b, Khaki et al. 2013).

It could be understood that network analysis and transport modelling can be used to measure transport related impacts of disasters, but both have been used in a contrasting fashion by scholars. Although the use of network theory to analyse transport systems can be advantageous in disaster scenarios, only a few scholars have presented the impacts in monetary terms

(Postance et al. 2017). This is mainly due to the fact that network analysis is used to assess the accessibility of a network from a transport engineering rather than economic focus. In contrast, assessing the monetary aspect of impacts in transport modelling studies is common, although the output of such models can be varied based on the reliability of the data used.

2.5.2 Business impacts

Road failure can also lead to businesses being affected due to supply chains being hampered, and is an area where research has been carried out previously (Boarnet 1996, Hansen and Sutter 1990, Wesemann et al. 1996, Willson 1998, Pfurtscheller and Genovese 2016b, Cho et al. 2001, Kim et al. 2002, Ham et al. 2005, Lee et al. 2009, Resurreccion and Santos 2013, Gordon et al. 1998, Sohn et al. 2004, Chen and Rose 2016, Xie et al. 2014, Shi and Wang 2013b, Tsuchiya et al. 2007, Tatano and Tsuchiya 2008). The literature review shows that three different techniques have been used to ascertain the business impacts, which are cost survey, Input-Output (IO) analysis and Computable General Equilibrium (CGE) analysis.

The most widely used method to measure the impact of road failure on businesses has been to obtain information directly from businesses through questionnaires and surveys (Wesemann et al. 1996, Hansen and Sutter 1990, Willson 1998, Boarnet 1996) or through secondary sources such as press reports, which include interviews and statements from businesses (Pfurtscheller and Genovese 2016a). While the majority of the previous research concentrated on obtaining information from businesses that were directly affected by a disaster, (Boarnet 1996) also obtained information from businesses located 50 miles from the disaster zone, which was used as a control group for analysis.

Input-Output (IO) analysis views the economy as a system, where industries receive inputs from other industries, and produce outputs for either other industries or final consumers, and is represented through a commodity flow table (Figure 2-2). The table is depicted as a matrix, with four sub-matrices. The matrix shows the how the goods and services from the relevant industries in the rows are used by the industries shown in the columns and its effect on the final demand for goods and services within the economy (McLennan 2006).

This focus on business interdependencies makes IO analysis well suited to measure indirect impacts of a disaster on an economic system (Hammond et al. 2015). The natural disaster is typically conceptualised as a shock to the previously stable system and the impact to businesses is estimated through the final effect on demand in the system (Safarzyńska, Brouwer and Hofkes 2013). The loss of a transport link could be modelled by changing the trade coefficients in the IO system (Irimoto et al. 2017).

IO analysis has been used to measure the business related impacts of road failure both for pre-disaster prediction studies (Cho et al. 2001, Ham et al. 2005, Resurreccion and Santos 2013, Kim et al. 2002, Lee et al. 2009) as well as for post-disaster studies (Sohn et al. 2004, Gordon et al. 1998). Although IO analysis is well suited to measure indirect system-wide impacts to businesses in highly interdependent economic areas over the medium to long term, the exact impacts due to transport disruptions are hard to model. In addition, the data and modelling that is required for IO analysis can result in over analysis for areas that are not highly interconnected industrially.

CGE models build upon general equilibrium theory that combines behavioural assumptions of rational economic agents with the analysis of equilibrium conditions (Böhringer, Rutherford and Wiegard 2003). A CGE model is a system of equations used to model an economy at national level and is a natural outgrowth of IO models. CGE analysis can assist the analyst to model the natural behaviour of an economy. CGE models use an iterative algorithm analogous to the coupled IO model and use standard economic non-linear production functions to model the economy. The typical steps in CGE analysis is depicted through Figure 2-3.

A CGE model assumes that the economy is in equilibrium, a state where economic forces are balanced and will remain unchanged in the absence of external influences before the disaster, and then compares the post-disaster equilibrium to the pre-disaster equilibrium to measure the effect of the event on the economy. The first step in a CGE analysis is to understand the disaster event thoroughly so that the required model design and data requirements are identified. The second step involves the use of economic theory, based on macroeconomic equations, in order to lay out key economic mechanisms that drive the results in the more complex numerical model. Data work, model formulation, and implementation then delivers the framework for numerical analysis.

Figure 2-2 Structure of Australian IO Tables

	To / *From*	*Row prefix*	*Intermediate Demand*					*Intermediate usage (sub-total)*	*Final Demand*							*Final Demand (sub-total)*	*Total supply (grand total)*
			Agriculture, etc	*Mining*	*Manufacturing, etc*	*Construction*	*Services*		*Final consumption expenditure —private*	*Final consumption expenditure —government*	*Gross fixed capital expenditure —private*	*Gross fixed capital expenditure —public enterprises*	*Gross fixed capital expenditure —general government*	*Increase in stocks*	*Exports of goods and services*		
	Column prefix		01.01-04.00	11.01-16.00	21.01-37.01	41.01-41.02	47.01-93.01		Q1	Q2	Q3	Q4	Q5	Q 6	Q 7		
Intermediate inputs	Agriculture Mining Manufacturing, etc. Construction Services	01.01-04.00 11.01-16.00 21.01-37.01 41.01-41.02 47.01-93.01	QUADRANT 1 INTERMEDIATE USAGE						QUADRANT 2 FINAL DEMAND								
	Intermediate inputs (sub-total)																
Primary inputs	Wages, salaries and supplements Gross operating surplus Commodity taxes (net) Indirect taxes n.e.c. (net) Sales by final buyers Imports	P1 P2 P3 P4 P5 P6	QUADRANT 3 PRIMARY INPUTS TO PRODUCTION						QUADRANT 4 PRIMARY INPUTS TO FINAL DEMAND								
	Australian production																

The shaded areas correspond to aggregates shown in the National production account.

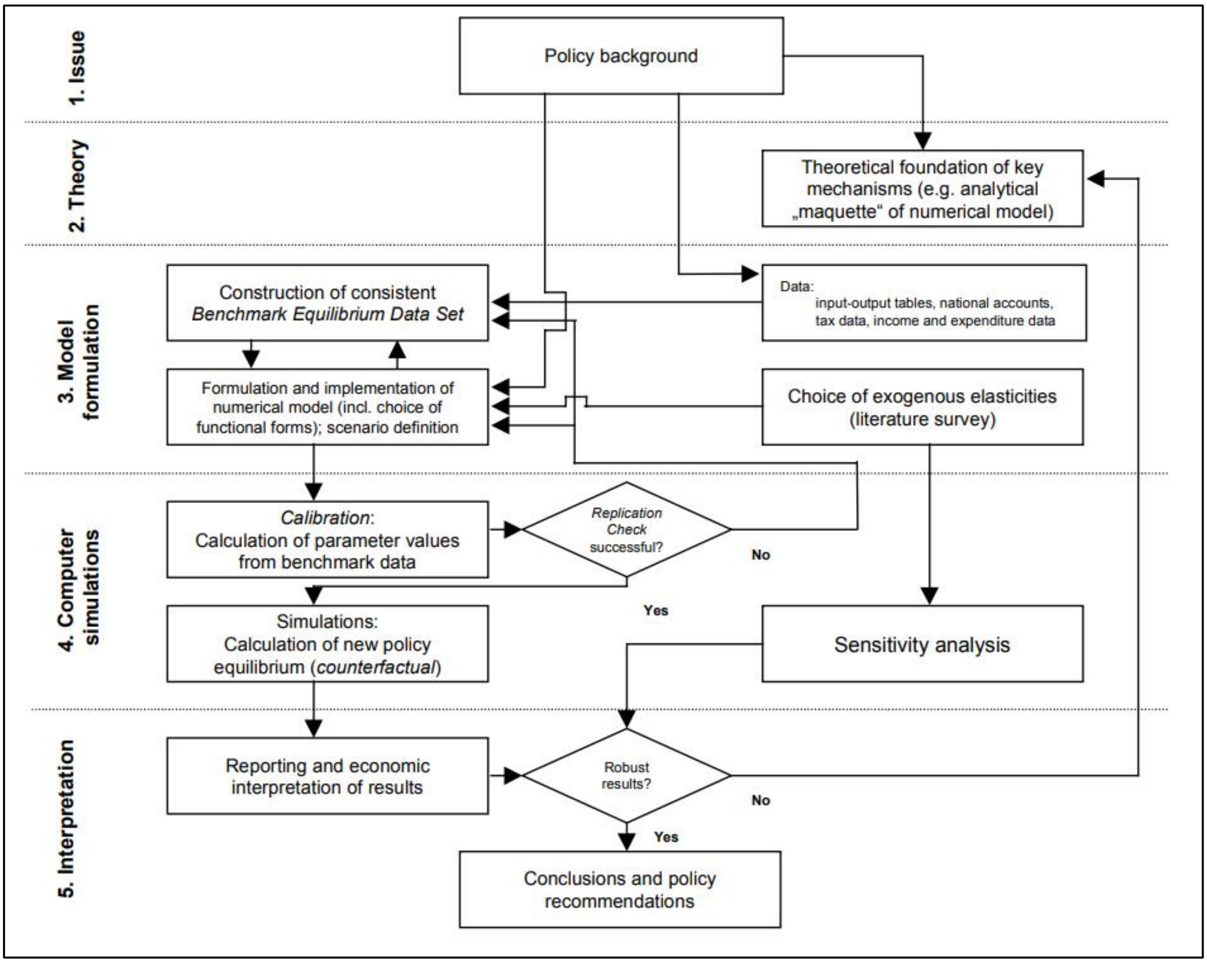
(/ shading) corresponds to aggregates shown as the components of 'gross domestic product' at market prices.

(\ shading) corresponds to aggregates shown as the components of 'expenditure on gross domestic product'.

Source: McLennan, W. (2006), '*Information paper: Australian national accounts: Introduction to input-output multipliers*', No. 5246.0, Australian Bureau of Statistics

Scholars have typically analysed the effect on businesses due to road network failure by analysing how the disaster would affect the transportation sector of an economy, either through the estimation of damage to the network (Xie et al. 2014, Chen and Rose 2016) or through the use of a transport model (Shi and Wang 2013b, Tatano and Tsuchiya 2008, Tsuchiya et al. 2007). CGE analysis takes a very wide scope and hence is appropriate for indirect impact assessment at state or national level, and could be said to be better suited for the analysis of system-wide transportation disruptions rather than disruptions to specific road infrastructure.

Figure 2-3 Steps in CGE analysis



Source: Böhringer, C., Rutherford, T. F. and Wiegard, W. (2003), '*Computable general equilibrium analysis: Opening a black box*'.

2.6 Direct Intangible impacts

The direct intangible impacts of road structure failure can be identified to be any direct social or environmental impacts resulting from a road structure being damaged. These can typically be any deaths or injuries to people while travelling on the road and any environmental impacts due to the failure of infrastructure.

2.6.1 Direct social impacts

The direct social impact of road failure includes any deaths or injuries to people while travelling on a road structure. There have been numerous scholars who have studied road related deaths due to disasters such as floods (Coates 1999, Ashley and Ashley 2008, Diakakis and Deligiannakis 2013, FitzGerald et al. 2010, Yale et al. 2003), cyclones (Rappaport 2000) and bushfires (Byard et al. 2012). All of them analyse road related deaths from a sociological perspective, with a focus on the entire disaster event rather than specific road structure.

Research that includes life loss to assess the total social impacts of road failure has converted deaths into a monetary value based on disaster relief payments for deceased persons (Negi et al. 2013) or statistical estimates for the value of a life (Dong et al. 2014b).

2.6.2 Direct environmental impacts

Possible direct environmental impacts due to disaster affected road structures could be water contamination due to chemical run-off from roads, destruction of natural habitat and natural life due to the washing away of structures and the disposal of debris from damaged structures (Srinivas and Nakagawa 2008). It has also been found that such disaster debris accumulated on roads could cause further indirect impacts due to the blockage of roads, and thus impede rescue operations in the aftermath of the disaster (Kobayashi 1995).

Most previous literature in the disaster waste area has focussed on the total amount of waste and debris generated by disasters, although no waste estimation methods or quantification of waste specifically from road infrastructure is available (Brown, Milke and Seville 2011). Some researchers have assessed specific environmental impacts such as sediment run-off from unpaved roads due to flooding (MacDonald and Coe 2008) and an increase in sediment run-off from roads affected by wildfires (Sosa-Pérez and MacDonald 2016). However these papers focus only on a specific environmental impact and do not consider any other types of impacts or the most important type of environmental impacts.

2.7 Indirect intangible impacts

The indirect intangible impacts associated with road failure relate to impacts induced by the road failure that affect factors not commonly traded in a market. These impacts could be broadly divided as social and environmental impacts and will be analysed separately in this section.

2.7.1 Indirect social impacts

Researchers have adopted two distinct approaches to assess the social impacts of road failure, where one group takes a qualitative approach to understand the proportion of people affected and how their mobility has been affected (Gordon et al. 1998, Adeagbo et al. 2016) while others attempt to quantify impacts with the use of accessibility indices (Chang 2003b, Deshmukh et al. 2011, Sohn 2006).

Differences in approaches that use accessibility indices can also be identified, as (Chang 2003b) only considers the post-disaster rail network and analyses the changes through a system minimum distance ratio, while (Deshmukh et al. 2011) take into account a wider range of community activities and incorporate the level of assistance that a particular type of infrastructure offers the community. Another approach is to use the Social Return on Investment for decision makers to assess the benefit that a specific reconstruction effort will have on the society (Barutha et al. 2017).

Accessibility indices can be seen to be a better measure of indirect social impacts as it shows the magnitude of the reduction in accessibility due to road failure and provides a final measure that is comparable across different cases. Accessibility indices may include both the tangible and intangible transport related impacts. However, such a method will require more in-depth data and thus will need greater resources than a simple statistical data collection method.

Another major type of intangible impact is the psychological impact on communities experiencing a disaster. However, only a limited number of researchers have attempted to assess the influence of transportation related impacts on mental stress. (Morrice 2013) looked at the psychological impacts on disaster affected individuals based on the ability for them to return to their homes, while (Wang et al. 2012) analysed the impact of the distance from the epicentre on psychological effects on children. Although both these studies assess the influence of accessibility, they do not attempt to capture specific road failure related psychological impacts.

Authors have also analysed the vulnerability of different population sub-groups faced with infrastructure damage (Schweikert et al. 2018). Such analysis uses Social Vulnerability Indices to assess the levels of vulnerability of sub-populations in order to estimate the potential disparity between population groups to recover after a disaster. Psychological impacts could also stem from the sight of damaged infrastructure and transport related debris after the disaster, which can have a negative psychological effect on residents of the area (Hu et al. 2019).

2.7.2 Indirect environmental impacts

The indirect environmental impacts caused by road failure will include incremental impacts on the natural environment that occur after the initial time of the disaster. Some environmental impacts that may occur are extra resources used for reconstruction, air pollution, noise pollution and carbon emissions due to extra travel time during construction (Bueno, Vassallo and Cheung 2015).

(Mackie et al. 2014) calculated the carbon footprint of the repair of bridges that were damaged due to earthquakes, while (Padgett and Tapia 2013) have considered embodied energy and carbon dioxide emissions as environmental indicators for bridge retrofit. Although these studies focus on long-term environmental impacts, it should be noted that the indicators used are limited and do not consider a broad array of environmental impacts.

In their assessment of indirect economic impacts, (Winter et al. 2016a) included carbon emissions from additional fuel consumption due to the usage of alternative roads and congestion during the construction phase. However, these carbon emission figures were not presented as a carbon footprint but instead quantified in monetary terms using estimated abatement costs. Although such a method does not present the global warming potential explicitly, it gives an opportunity to compare environmental impacts with economic impacts.

Thus it can be seen that the indirect environmental impacts of road failure have been assessed only in a handful of studies, and even then, only the global warming potential has been calculated.

2.8 Integration of impacts

The review exemplifies that most researchers have focused on assessing a specific category of impacts, which may be due to the specific research interests of the scholars, objectives of the research proponent and limitations in resources allocated for the project. Table 2-4 summarises the different methods that have been used by scholars to combine the different types of impacts, while a further analysis of these methods follows.

Table 2-4 Summary of integration techniques

Type of impacts incorporated	Method	References
Direct and indirect tangible (Total economic)	Total monetary impact	(Cho et al. 2000, Jaiswal et al. 2010, Negi et al. 2013, Winter et al. 2016a, Sohn et al. 2004)
	Cost Benefit Analysis	(Maze, Crum and Burchett 2005, Pfurtscheller and Genovese 2016b)
	System risk curve	(Shiraki et al. 2007)
Socio-economic	Severity Assessment Tool	(Deshmukh et al. 2011)
	Cost Benefit Analysis	(Shinozuka et al. 2005, Zhou, Banerjee and Shinozuka 2010)
	Life Cycle Cost	(Sobanjo and Thompson 2013, Decò and Frangopol 2011)
Environmental economic	Multi Criteria Analysis	(Tapia and Padgett 2016)
SEE	Monetary conversion	(Dong et al. 2014b, Giunta 2017)
	Multi Criteria Analysis	(Padgett, Ghosh and Dennemann 2009, Schweikert et al. 2018)

As road failure can bring about a variety of impacts, it is important to analyse how scholars have combined these varied impacts. It was identified that most scholars have simply concentrated on measuring a certain type of impact and hence amalgamation has been used sparingly. The most commonly used amalgamation is of tangible impacts. Some scholars have measured the total tangible impacts by taking into account both the direct and indirect impacts

(Negi et al. 2013, Winter et al. 2016a, Jaiswal et al. 2010, Cho et al. 2000), while others have measured indirect impacts to conduct Cost Benefit Analysis (CBA) to assist in decision making processes (Pfurtscheller and Genovese 2016b, Maze et al. 2005). A contrasting approach is followed by (Shiraki et al. 2007), who calculate system risk curves by estimating the direct damage and indirect transport impacts utilising fragility curves and a network model. (Sohn et al. 2004) calculated the business and transport related impacts of a hypothetical earthquake; this and is one of the only studies that focus on a comprehensive set of indirect impacts. However, it does not consider the direct tangible impacts.

Some researchers have also focused on assessing the socio-economic impacts of road failure, and differences in methodology could be seen across these projects. (Deshmukh et al. 2011) use a Severity Assessment Tool to estimate the socio-economic impact on the communities and industries due to reduced serviceability, while others have used CBA (Zhou et al. 2010, Shinozuka et al. 2005) or Life Cycle Cost (Decò and Frangopol 2011, Sobanjo and Thompson 2013) to estimate the impacts of potential disasters on bridges.

Scholars who combine tangible and intangible impacts convert social and environmental impacts to monetary values so that they can be assessed together with tangible impacts and form the basis for CBA. Social impacts are typically valued using a human capital approach, which assigns values to human lives based on the average contribution a person would have on the potential output of the economy, also known as the statistical value of life (Negi et al. 2013, Stephenson et al. 2013, Chang et al. 2009, Dong et al. 2014b) while environmental impacts can be valued using non-market valuation methods such as stated preference and revealed preference techniques.

A major drawback of such valuation methods is that by assigning monetary values, environmental and social capital can be considered to be directly tradable with financial capital, which can be very misleading. This has led some scholars to move away from monetary valuation and to use integration methods such as Multi Criteria Analysis and Cost Utility Analysis (Hajkowicz 2008). Such methods analyse different options in order to optimise a particular decision (Tapia and Padgett 2016, Padgett et al. 2009) and hence tend to be more appropriate for decision making processes rather than impact assessment.

Variations in integration techniques among scholars can be identified where (Dong et al. 2014b) integrate the SEE impacts by converting the social and environmental impacts to monetary values while other scholars present the social and environmental impacts in non-monetary values in order to conduct a multi-objective prioritisation (Schweikert et al. 2018, Padgett et al. 2009). A similar approach is used by (Tapia and Padgett 2016), who consider the influence of environmental and economic impacts on a multi-objective optimisation of a bridge retrofit under threat of a disaster.

2.9 Post-disaster reconstruction processes

Post-disaster reconstruction processes of road infrastructure typically differ from routine rehabilitation or new infrastructure projects given the expedited nature of reconstruction required (Le Masurier, Rotimi and Wilkinson 2006). Reconstruction processes have been studied by several scholars and it has been found that the availability of resources after a disaster event can be a major influencing factor (Chang et al. 2012). Other factors that influence reconstruction are legislation (Rotimi et al. 2009), coordination between government agencies (Le Masurier et al. 2006) and stakeholder engagement processes adopted (Crawford, Langston and Bajracharya 2013).

Reconstruction of road infrastructure activities are generally carried out based on disaster management and recovery plans, which are specifically designed for this purpose. The lack of a clear disaster management plan can delay the reconstruction activities due to lack of clarity in responsibility and authority (Pathirage et al. 2012, Lin Moe and Pathranarakul 2006). However, it has been found that most regions or countries develop such plans as a reactionary effort after a major disaster event (Palliyaguru and Amaratunga 2008). It can be concluded that, as decision making in post-disaster context differs from routine infrastructure decision making, that practitioners need use methods that account for wider socio-ecological impacts of their decisions, just like they would in new infrastructure projects.

2.10 Discussion and research gaps

This analysis reveals that although research assessing post-disaster impacts of road structure failure has been carried out for about 30 years, most studies tend to focus on a single type of impact, and assessments have typically covered a few significant disaster events, which tend to have drastically different characteristics. In addition, these papers are spread across several disciplines focusing on different types of impacts and therefore pose a challenge for a comparative analysis to be carried out.

The review also demonstrates that most of the research on post-disaster impacts focuses on earthquakes and floods, while research focusing on hurricanes, landslides and bushfires is sparse. The majority of the research has been conducted in the USA and focuses mainly on the impacts of earthquakes and hurricanes, while research conducted in European countries tends to focus on landslides and floods. A handful of research has been conducted in the Asia Pacific region, most of which focuses on earthquakes in Japan. Thus it can be understood that there is a gap in research focussing on bushfires and floods, specifically in an Asia Pacific context. Most of the impact assessment of post-disaster road failure focuses on urban settings. There is very little literature on road related impacts that could occur in more rural and less connected areas.

The literature review illustrates that the majority of research on disaster related road failure focuses on measuring tangible impacts, while the literature on assessing intangible impacts is less. The intensity of a disaster is often perceived based on the size of the economic loss and the number of deaths caused by the event, hence measuring the tangible impacts may be given priority over intangibles. As all types of tangible impacts could be presented using one single measure, i.e. dollar value, economic impact assessments are easily understood and accepted by the general public, which may have increased their usage in disaster damage assessment. This is in contrast to intangible impacts, which can have numerous different indicators and do not have a commonly accepted method of amalgamation, making them harder to interpret.

Although different models have been used to assess economic impacts, the basic principles of economic loss assessment are widely agreed upon by academics. However, there is much debate on how best to measure social and environmental impacts and if they could be measured together with economic impacts.

Prior research on post-disaster impact assessment has largely focused on the tangible impacts of a disaster, where researchers have adopted established economic and transport impact assessment techniques. While such studies may help governments and aid organisations to better prepare for recovery programmes, it shows that comparatively less research has been conducted on measuring the intangible impacts of a disaster. It is also evident that there is a lack of research on the environmental impacts both direct and indirect, and that future work in this area will add a lot of value to disaster impact analysis.

This review demonstrates that prior research tends to focus more on assessing specific impact categories, which has led to a gap in the research aimed at measuring the overall impacts of road failure. Research that has looked at wider impacts tends to focus on pre-disaster impact prediction rather than post-disaster assessment.

This chapter highlights the fact that there is no common methodology that has been developed or adopted to measure overall social, environmental and economic impacts due to road failure in a post-disaster context. Future research in this area could focus on the development of a comprehensive methodology to measure overall impacts and amalgamate them into one common platform.

In addition to developing a methodology, future research needs to be conducted on measuring the total impacts of post disaster road failure, which includes a comprehensive set of social, environmental and economic parameters. How these different types of impacts are defined and measured and how they could be presented together using a common metric would be an important aspect to consider when carrying out such an assessment.

Based on the review conducted and the research gaps identified, the following directions were chosen in order to address the objectives of this research.

- To focus on post-disaster impact assessment, which provides an opportunity to consider behavioural changes and community adaptation techniques
- To focus on the impacts of road infrastructure failure in regional areas
- To analyse a broad group of impacts without focussing on a limited set of impact categories

- To incorporate intangible impacts, especially environmental impacts within the assessment framework
- To combine the different impact types so that a more holistic view of the impacts could be analysed
- To develop a conceptual framework to measure and integrate social, environmental and economic impacts

2.11 Summary

This chapter presents the literature in the area of post-disaster impact assessment of road infrastructure. Literature related to pre and post-event assessment, as well integration methods were analysed. The literature review shows that there is a lack of research assessing socio-ecological impacts while no commonly accepted methods have been used to integrate different impact categories. The gaps in literature identified in this chapter have been used to formulate the objectives of the PhD. A more critical in-depth analysis of the literature identified in this chapter was carried out and is presented in Chapter 4.

3. RESEARCH METHODOLOGY

3.1 Introduction

This chapter explains the methodology adopted in this research. Initially the research design is elaborated to give the reader a background of the research. The research questions of the project are presented, and the methodology adopted to address these questions is explained. The chapter also explains how the research gap was identified, the framework was developed, the data were collected, and the validation and analysis of results. The main methodological tools adopted in this research are interviews, case study and a sensitivity analysis.

This research project is a part of the BNHCRC where the basic need for the project was identified under the sub project "Enhancing resilience of critical road infrastructure: bridges, culverts and flood-ways". The research falls into the broad discipline of Sustainable Engineering, as the problem that is to be solved includes the consideration of natural and environmental systems, and of social systems and institutions (Allenby 2014). The research is inter-disciplinary, covering the disciplines of civil engineering, transport engineering, disaster impact analysis and sustainability assessment.

3.2 Research design

The research design is a plan for the collection, measurement, and analysis of data, created to answer specific research questions (Sekaran and Bougie 2016). A well planned out research design will pave the way for a systematic research process, which will accurately address the research questions thus reflecting high quality of research. In explaining the research design of this study five key elements have been looked at: research strategies, extent of researcher influence, study setting, unit of analysis and time horizon. How each of these elements were addressed within the research design of this PhD project is explained in detail below.

3.2.1 Research strategies

The research strategy will help the researcher to meet the research objectives and to answer the research questions. As such the choice of the particular strategy adopted will depend on the research objectives and the type of research questions. In addition, practical aspects of the research like data sources and time constraints will affect the strategy chosen. The types of research strategies could be categorised broadly as experiments, survey research, ethnographic studies, case studies, grounded theory, action research and mixed methods.

This research has elements of both basic and applied research principles. However, it could be argued that the research is more applied in nature as its main objective is to solve an existing problem, and brings together existing knowledge for this purpose (Sekaran and Bougie 2016). Given such an objective, the appropriate research strategy was to use a mixed methods approach, as it focused on collecting, analysing, and mixing both quantitative and qualitative data in a single study. The mixed methods approach allows more than one research method to be used to address the research problem and to use different types of data (Sekaran and Bougie 2016). Such a method was vital for this research as the data analysed included both quantitative and qualitative data. The mixed method approach incorporated surveys, ethnography and a case study in order to answer the different research questions.

3.2.2 Extent of researcher interference

The extent of interference by the researcher depends on the type of research questions: whether they are exploratory, descriptive or causal research questions. The research questions of this study were exploratory in nature as the topic was complex and not much detail was known about the particular area. As exploratory research relies on qualitative approaches to data gathering such as discussions, interviews and/or case studies there was minimal researcher interference. The exploratory nature of the study meant that the focus of the research was broad at the beginning and became narrower with time and that the results may not always be generalizable (Sekaran and Bougie 2016).

3.2.3 Study setting

Study setting looks at whether the research is carried out in the natural environment where events occur (non-contrived settings) or in artificial environments also known as contrived settings. As the objective of the research was to understand the sustainability impacts due to bridge failure it was decided that the best setting would be a non-contrived setting. As such the research strategies adopted were based on the most suitable for field studies, which were interviews and case studies. The non-contrived setting also provided a good opportunity for the researcher to understand how post-disaster reconstruction is conducted, in order to propose methods that can optimise decision making.

3.2.4 Unit of analysis

The unit of analysis refers to the level of aggregation of the data collected in the data analysis stage of the study. The unit of analysis can range from individuals, dyads, groups, organisations and cultures. It is important to decide on the unit of analysis as the research questions are formulated, since the data collection methods, sample size and variables included in the framework needed to be determined by the level of data aggregation. As two stages of data analysis was carried out, the unit of analysis for the study needs to explain both the data analysis techniques.

The unit of analysis for the interview data was organisations, as the objective of the interviews were to understand how post-disaster reconstruction is approached and the assessment techniques adopted within relevant organisations. As such, personnel from different divisions within organisations were interviewed, to obtain an organisational wide perspective. The unit of analysis for the case study was decided to be a specific group of residents who were impacted by bridge closure in a disaster affected region. As such, questionnaire surveys and secondary data analysis pertaining to the relevant group were conducted.

3.2.5 Time horizon

The time horizon of the study refers to the time period under observation and the temporal period in which data is collected for the study. If data is gathered just once, over a period of days, weeks or even months such a study is referred to as a one-shot or cross-sectional study. In contrast, studies where data is collected at two or more points in time are called longitudinal studies. This research was a cross-sectional study as the data collection was carried out just once.

3.2.6 Ethical considerations

As the research involved using humans as subjects to collect data, written approval from the College Human Ethics Advisory Network of the RMIT University, College of Science, Engineering and Health was needed. Formal approval for the application (SEHAPP 75-17) to conduct the research was obtained in October 2017. The ethics approval covered the interviews and questionnaire surveys to be run in the communities, which are explained later in this chapter. The letter granting ethics approval, participant information sheets, the list of interview questions and the questionnaire are included in appendices A to D of this thesis.

3.3 Research process

The research process followed to address the specific research questions of the study is explained in detail below. This process is illustrated through the methodological framework shown in Figure 3-1.

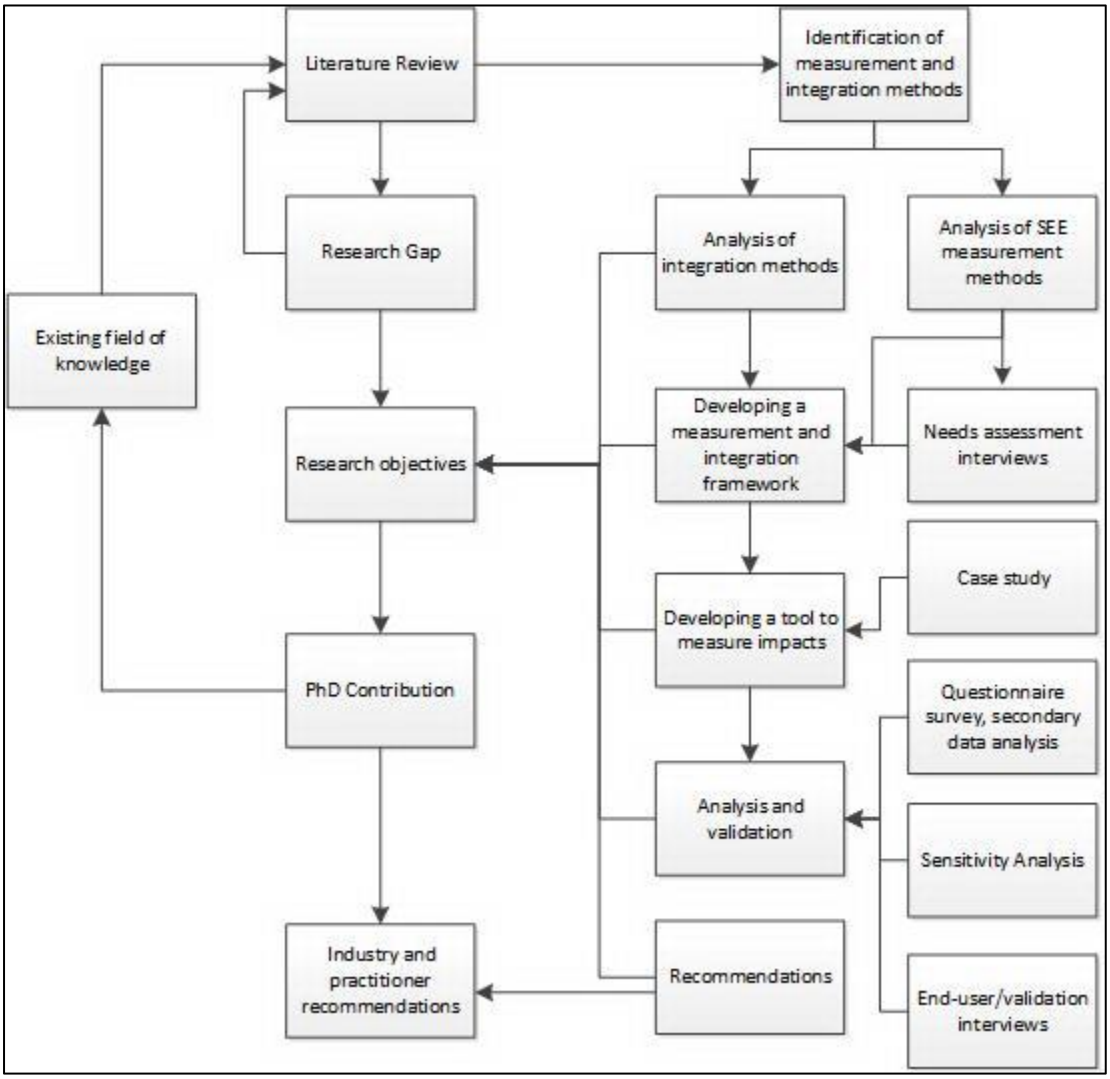
The research questions developed for this project are:

- What are the limitations of the current methods used to measure SEE consequences of disaster related road failure?
- How can the methods used currently be modified and improved to suit the assessment of impacts of road structure failure?
- How can the SEE impacts be integrated into a toolkit to assist in post-disaster road infrastructure decision making?
- How can the developed framework be validated to test for its explanatory power?
- How can the overall negative impacts of post-disaster reconstruction of road infrastructure be reduced?

A Sustainable Engineering and systems-thinking approach was utilised to address the specific research questions. Sustainable Engineering takes into account the social and environmental impacts of engineering projects, and recognises that good engineering practices are critical in improving environmental and social performance across a globalising economy (Allenby et al. 2009). Similarly, Systems Engineering seeks improvements at the scale of integrated systems, rather than piecemeal optimisation. In this approach, sustainability outcomes could be part of the design objectives to be met or could be included as constraints to the optimisation problem (Seager, Selinger and Wiek 2012). Sustainability assessment in this context refers to the integration of different methodologies in a manner that is geared toward obtaining an analysis that incorporates a variety of management aspects in which the sustainability implications can be focussed upon (Chang 2011).

As this research was seeking to measure a wide-ranging set of sustainability impacts caused by bridge failure, the use of a sustainable engineering approach was vital. The adoption of this approach helped in making recommendations that could be used by practitioners to improve social and environmental aspects in post-disaster reconstruction. Similarly, as the recommendations focused on holistic, integrated decision making a systems-thinking approach was adopted throughout the research process.

Figure 3-1 Methodological framework of the research



The Engineering method was applied to define the problem and to come up with a solution. This was based on five steps highlighted and discussed below (Neumann 2016).

1. Needs assessment and problem definition
2. Establishment of design goals
3. Generation of alternative solutions
4. Evaluation of alternative solutions
5. Selection of a solution and recommendations

3.3.1 Needs assessment and problem definition

A needs assessment was identified as the first step to approaching this problem, as it was important to understand the end-user requirements of the research outcomes. It also helped in defining the existing problem faced by decision makers in the infrastructure management sector. These decision makers were identified as infrastructure managers of local councils, road authorities and reconstruction agencies involved in post-disaster road network rehabilitation. The basic problem that was to be solved was identifying the wider impacts of road failure in order to help in more effective decision making. This meant that the final decisions would aim to minimise the social, environmental and economic impacts and not focus only on the financial and engineering aspects.

Problem definition

Reviewing the literature on sustainability impacts showed that many of the impacts are interrelated, and that minimising one type of impact could affect another type of impact negatively. Such problems could be categorised as "wicked problems", which may not have one definitive solution given the formulation of the problem (Rittel and Webber 1973). They are one extreme form of a dynamic problem, which change with time and fast enough to influence the solution (Dowling, Carew and Hadgraft 2010). Some characteristics of wicked problems as identified by (Rittel and Webber 1973) are

1. There is no definitive formulation of a wicked problem

2. Wicked problems have no stopping rule. That is, they are problems that are ongoing. They need to be managed, not solved.

3. Solutions to wicked problems are not true or false, but good or bad.

4. There is no immediate and no ultimate test of a solution to a wicked problem.

5. Every solution to a wicked problem is a 'one-shot operation' because there is no opportunity to learn by trial and error; every attempt counts significantly.

6. Wicked problems do not have an enumerable set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.

7. Every wicked problem is essentially unique.

8. Every wicked problem can be considered to be a symptom of another problem.

9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. That is, the problem looks different to every stakeholder.

10. The planner has no right to be wrong.

Based on the definition and these characteristics, it was identified that the problem that was to be solved through this research was a wicked problem. Similarly, it has been identified that road construction (Rittel and Webber 1973) and solutions to public transport issues (Dowling et al. 2010) were typical examples of wicked problems. Though they may seem to be a static engineering problem, the interaction and knock-on effects on wider social and economic dimensions mean that the solutions need to be more dynamic in nature, as exemplified in wicked problems.

As wicked problems have no single ultimate solution, the best strategy to overcome the problem was to frame the problem correctly. This meant that extra effort was put into exploring the design space in order to come up with the most suitable solution for the problem at a given time (Stauffer and Ullman 1991). Exploring the design space includes understanding the problem, clarifying the design criteria and exploring alternative solutions in detail. (Stauffer and Ullman 1991) argue that the accuracy of the solution could be improved if the problem was defined more precisely at the very early stages of the project. This invariably led to an iterative process that needed to be followed by the researcher in order to continuously improve on the different solutions that came up.

Needs assessment

Needs assessment interviews, with potential stakeholders, were carried out as the first step to understanding the end-user requirements of the project. This also helped to retain the objectivity of the project and design a framework that will be appropriate for the end-users. This was deemed necessary as it is not the views of the researcher that is important but the views held by the stakeholders. Stakeholder engagement helped to understand the stakeholders' views and the context within which the particular project will be embedded so that a more relevant framework could be developed (Allenby 2014).

3.3.2 Establishment of design goals

Based on the interview results and previous literature review, the design goals for the framework were established. The design goals of the framework were highly dependent on the context of the project and the selected scope. As the results of the analysis could be biased by selecting different boundaries (Allenby 2014), care was taken to choose the most appropriate boundary for the project based on the stakeholder and end-user requirements identified in the needs assessment interviews.

3.3.3 Generation of alternative solutions

The different methods that had been used in prior literature to measure and combine different types of impacts were analysed at this stage. This included methods or models that were used in disaster impact analysis, transport impact analysis and sustainability assessment. The different methods that were identified generated varying solutions that needed to be evaluated.

3.3.4 Evaluation of alternative solutions

The different methods identified were critically analysed based on their advantages and disadvantages considering a number of factors (Brooks and Tobias 1996). These factors included the expected results of the model, future use of the model, ability for verification and validation and resource requirements. Alternative solutions were developed using these different methods so that the final decision on the most appropriate and relevant method could be identified. Publicly available data and data available to decision making authorities were used to generate these solutions. The data collected included cost estimates, transport and traffic volume and other socio-economic data that could be used to value the SEE impacts of road failure. Section 3.4.4 explains the data collection process in more detail.

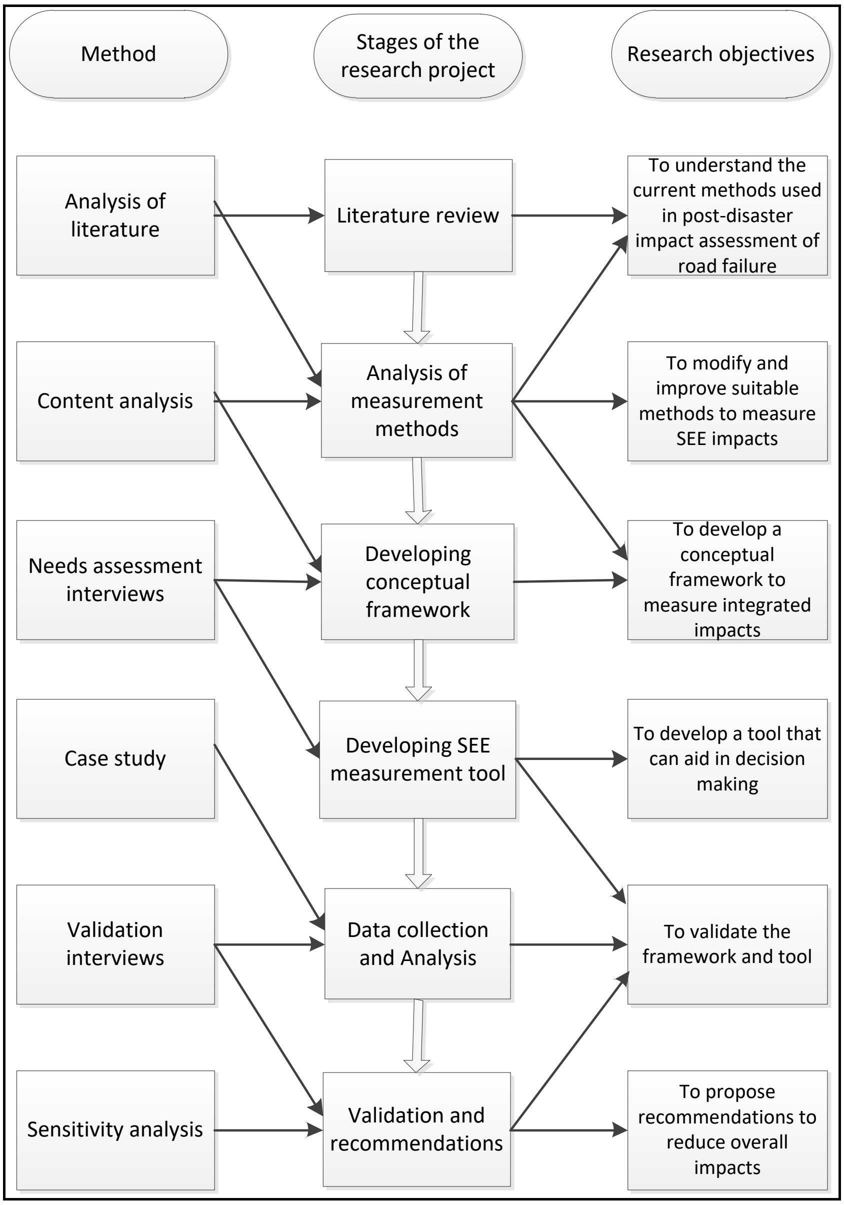
3.3.5 Selection of a solution and recommendations

At the final stage, the most suitable methods that should be adopted for the framework were selected. This selection was based on the data obtained through needs assessment interviews, critical analysis of the different methods and the suitability of them to the context and scope of the project. This however was not considered the final decision as validation of the framework was conducted later in the research. The final framework and toolkit presented was based on iterated improvements and modifications at each stage of the research project.

3.4 Research methods

The research project can be categorised in to 6 stages as illustrated in Figure 3-2. The methods utilised in each of these stages are explained in more detail in this chapter.

Figure 3-2 Methodology adopted to address research objectives



3.4.1 Analysis of literature

As the basic need for the research had been identified through the BNHCRC project, a comprehensive literature review was conducted to understand the existing knowledge in the field, to identify the research gaps and to narrow down the scope of the project. The literature review was not limited to road structure failure due to natural disasters, but covered three broad areas: road structure failure, disaster impact analysis and sustainability impact assessment.

The literature on natural disaster impacts served to help broaden the understanding of the potential impacts of a disaster and to come up with an exhaustive list of potential impacts of disaster related road structure failure that needed to be considered in the research. Thereafter the literature was narrowed down to those that specifically address sustainability impacts of disaster related road structure failure. An in-depth analysis of the methods used in such work and the advantages and disadvantages of those methods were also analysed. The literature was reviewed on a constant basis throughout the project to ensure that the research outcomes were up-to-date with any advances in the field. The literature review was explained in Chapter 2.

3.4.2 Content analysis

A broad selection of literature was analysed in order to identify potential impacts arising from natural disasters. This review focused on literature covering all areas of disaster related impacts and the identified impacts were categorised into social, environmental and economic impacts. The categorisation into social, environmental and economic was based on the fact that sustainability is typically viewed as an interaction of these three spheres, and that such a categorisation helps in understanding the concept of sustainability in the field of engineering in more depth (Carew and Mitchell 2008). This categorisation helped the researcher to identify the areas where less research had been carried out.

A semantic map of all types of disaster impacts was developed (section 2.2). This helped the researcher to visualise how the social, environmental and economic elements are affected by a disaster and to understand the inter-relationships between these elements. Finally, an exhaustive list of potential impacts due to disaster related road structure failure was generated. Although this list was initially based on the literature review, it was constantly updated as new impacts were identified in the data gathering stages of the project.

The different methods used by scholars to measure the different types of impacts were listed. These methods were categorised based on the direct, indirect and tangible, intangible impact classification proposed by (Merz et al. 2010). A content analysis of the different methods used by previous researchers was conducted in order to assess the suitability of each method to capture the total impacts under a given category. The analysis considered four factors that were identified by (Brooks and Tobias 1996) that should be considered when selecting a model. These factors are: expected results of the model, future use of the model, ability for verification and validation and resource requirements.

The analysis of the different techniques used by researchers to measure sustainability impacts helped in identifying the most appropriate techniques in different contexts. This analysis was the basis for the selection of the specific methods and techniques that were used in the developed framework.

3.4.3 Needs assessment interviews

A needs assessment was identified as the first step in approaching this problem as it was important to understand the end-user requirements of the research outcomes. As the research was exploratory in nature, qualitative research methods were chosen as the most appropriate at this stage of the project. Qualitative research views the world through the eyes of the participants in order to answer the research questions and contribute to empirical knowledge (Neuman and Robson 2014). Exploratory / in-depth interviews were chosen as the best method to obtain the relevant information as they are a pipeline to transmitting knowledge (Holstein and Gubrium 2004) and are intended to tap individual experiences that the researcher may not be aware of (Charmaz 2003). Exploratory interviews can broaden and deepen the plan of research by facilitating new dimensions that were earlier not visited by the researchers. In-depth interviews also help interviewers with involvement in the research design and in developing hypotheses (Oppenheim 2000). In-depth / exploratory interviews help to develop ideas and research hypotheses rather than obtaining quantitative facts and statistics.

In order to maintain the representativeness and the quality of the responses the respondents were informed that it was not their personal views that were sought but the organisational or departmental views (Alvesson 2010). The interview questions and a Participant Information Sheet were emailed to the respondents a week prior to the interview. The interviews were typically 30-60 minutes in length and were conducted face-to-face at a meeting room at the interviewee's office.

A low degree of structure for the format of the interviews was deemed to be suitable for the purpose of the study. This meant that it was easier to encounter new and unexpected views as the interviewer can use a broad range of ideas, experiences and observations (Alvesson 2010). However, it is important that the researcher has a clearly defined topic and has a clear idea of what kind of information is required for the topic (Foddy 1994). Failure to do so, may result in the interview digressing on a path unproductive for the purpose of the research.

A non-random sampling method was used to select participants for the research. This allowed the selection of respondents with specific characteristics; those individuals involved in road reconstruction either directly through decision making processes or indirectly in vetting and stakeholder engagement processes. Such a technique helped the researchers formulate theory and is referred to as theoretical sampling (Robson 2002).

Interviews with potential end-users were carried out in order to understand the current practices with regard to post-disaster road impact assessment. These interviews were carried out with personnel from local councils, road authorities and disaster reconstruction authorities who are typically involved in post-disaster decision making. The interviews also helped the researcher to understand the requirements of practitioners and how they expected to use the tools that will be developed through the project. The interview findings were used to develop the conceptual framework of the research project. This method helped in developing a toolkit that was catered to practitioners while being academically rigorous.

A total of 18 potential end-users from seven different organisations were interviewed (Table 3-1). The majority of the interviewees were from Queensland as the developed framework was tested on a case study in Queensland. However, to increase the generalizability of the findings, stakeholders from Victoria were also interviewed. The interviews were analysed using qualitative data analysis methods. The results of the interviews from Queensland were analysed and compared against those from Victoria to identify similarities and differences based on geographical setting. The two different states were selected for the interviews as the types of disasters affecting the two states were different; Queensland is more flood prone, while Victoria is more bushfire prone.

Table 3-1 Interview participants

Participant	Organisational Sector	Work Division	Geographical Jurisdiction
P1	Local Government	Infrastructure Works and Services	Queensland
P2	Local Government	Disaster Management	Queensland
P3	Local Government	Economic Development	Queensland
P4	Local Government	Environment Management	Queensland
P5	Local Government	Environment Management	Queensland
P6	Local Government	Community Development	Queensland
P7	Local Government	Community Development	Queensland
P8	State Government	Reconstruction Operations	Queensland
P9	State Government	Transport operations	Queensland
P10	State Government	Transport operations	Queensland
P11	State Government	Transport Asset Services	Victoria
P12	Local Government	Infrastructure Projects	Victoria
P13	Local Government	Infrastructure Projects	Victoria
P14	Local Government	Construction (New Works)	Victoria
P15	Local Government	Asset Management	Victoria
P16	Local Government	Asset Services	Victoria
P17	Local Government	Asset Management	Victoria
P18	Local Government	Asset Management	Victoria

3.4.4 Case study

The appropriateness of the framework was tested by developing a toolkit that can be used to measure the social, environmental and economic impacts in real-life disaster situations. This toolkit was used to measure impacts in a disaster affected area in regional Queensland. The Lockyer Valley Regional Council was selected to conduct the case study as this is a highly flood-prone region and was affected by back-to-back floods in 2011 and 2013. In addition, the selection of Lockyer Valley for the case study also provided an opportunity to assess impacts of road infrastructure failure in rural areas, which was a gap that was identified in the literature review.

The Lockyer Valley region was selected for the case study as it is a regional area that had experienced repetitive flooding events, which had caused major impacts to road infrastructure. As most of the previous work measuring wider impacts of damage to road infrastructure has concentrated on urban areas, this research project focussed on a more regional area. Impacts were presumed to differ between urban and regional areas as there is generally a lack of alternative routes in regional areas and because reconstruction may take longer in regional areas as opposed to more urban settings. Impacts in regional areas will also be spatially narrow, thus making it easier to measure.

Testing the framework through a case study approach aided in identifying the suitability of the framework in a real life disaster situation. Such a method was considered the most appropriate for the research project as it allowed to test relevance of the framework from the end-user practitioners' point of view. The toolkit and the case study also provided the opportunity to test the framework for its explanatory power. This was important as the framework needed to be theoretically founded and also relevant to be used in the disaster management sector.

Two bridges that were damaged during the 2013 floods were selected to conduct the case study. The two bridges were selected after consultation with the Infrastructure Works and Services Department of the LVRC based on the importance of the locations and the availability of data specific to those structures. Both bridges were completely damaged during the 2013 floods and were reconstructed.

The Thistlethwaite Bridge is situated on the Grantham Winwill Road, a major arterial road servicing a productive vegetable cropping district and the Stanbroke Meat Processing Plant, the region's largest employer. The Clarke Bridge is located in a more rural setting and provides access to the Thornton State School. The two bridges are located in two diverse areas in the Council, with the Thistlethwaite Bridge located in a more densely populated, economically vital area while the Clarke Bridge is located in a more rural setting. Both bridges were timber bridges and were replaced by concrete structures after they were damaged in the floods.

The data requirements for populating the toolkit were identified based on the specific methods selected. The data that was used for this purpose was identified as sets of data that would be typically available soon after the disaster event. Such data was obtained from publicly available data sources like the Australian Bureau of Statistics, Austroads and the Department of Environment and Energy, as well as from non-public data sources like the Lockyer Valley Regional Council and the Queensland Reconstruction Authority. The non-public data typically included population statistics, road use data and general socio-economic data of the area.

The case study also included a questionnaire survey that was administered to the residents living in proximity to the study area. The objective of this questionnaire was to understand the behavioural changes of the residents after the disaster and to validate the results of the toolkit against real life impacts to residents.

3.4.5 Validation interviews

Follow-up interviews with potential end-users (Table 3-2) were carried out to independently validate the relevance of the framework and the toolkit in post-disaster reconstruction processes. This involved a set of follow-up interviews with the stakeholders that were interviewed at the scoping stage of the project. The interviews included the presentation of the toolkit and the running of different scenarios for the interviewees to understand the application of it. Interviewing the same group of stakeholders was considered to be important as the project was designed based on the requirements mentioned by them. These interviews were used to validate the framework and the toolkit that was developed through this PhD research.

Table 3-2 Interview participants – potential end-users

Participant Code	Designation	Organisation
P20	Executive Manager - Infrastructure Works & Services	Lockyer Valley Regional Council
P4	Coordinator - Environment and Pest	Lockyer Valley Regional Council
P2	Manager - Disaster Coordination	Lockyer Valley Regional Council
P6	Community Development & Engagement Officer	Lockyer Valley Regional Council
P9	District Director – Program Delivery and Operations	Department of Transport and Main Roads
P19	Manager Technical Services	Department of Transport and Main Roads
P8	Director - Engagement and Technical Services, Operations	Queensland Reconstruction Authority
P21	Director – Resilience Policy	Queensland Reconstruction Authority

Academic researchers working in relevant fields were also interviewed as a method of validating the theoretical assumptions used within the framework and to get academic opinion on the relevance of the framework. The participants for these interviews were chosen from across different disciplines and specialisations to obtain feedback from diverse points of view. The participants were first asked to focus more on the specific section of the tool, which was within their area of expertise to ascertain the theoretical rigour of the specific techniques.

Table 3-3 List of academic researchers interviewed

Participant Code	Area of expertise	Affiliation
P22	Infrastructure resilience and Sustainable Engineering	School of Engineering, RMIT University
P23	Earthquake Engineering and Natural Hazard resilience	School of Engineering, RMIT University
P24	Traffic engineering and Transport modelling	School of Engineering, RMIT University
P27	Life Cycle Assessment and Waste & resource efficiency	School of Industrial Design, RMIT University
P26	Infrastructure interdependency and resilience	School of Property, Construction and Project Management, RMIT University

3.4.6 Sensitivity analysis

Sensitivity analysis was carried out in order to study how the model output values are affected by changes in model input values (Loucks and Van Beek 2017). Sensitivity analysis, analyses the importance of imprecision or uncertainty of model inputs in a decision-making or modelling process and can be used to explain how uncertainty in the outputs can be apportioned to different sources of uncertainty in the model input. A two-step approach was adopted for the sensitivity analysis. The first step was to identify significant input variables that would need to be analysed while the second step was a one-at-a-time sensitivity analysis of the identified significant variables. A further what-if scenario analysis of changes to qualitative assumptions was also employed to validate the model.

The results obtained by using the toolkit to estimate the SEE impacts in the Lockyer Valley region were analysed in order to identify which factors influenced the level of impacts the most. The results obtained in the previous section were used to identify the most significant types of impacts. A further analysis of those impacts helped to identify their significant drivers and to understand the most relevant data requirements for a similar model. Further validation of the model was conducted by comparing the results obtained with previous research on the different impact categories and other ex-ante impact assessment studies carried out. A sensitivity analysis of the significant impacts was also carried out.

Two levels of validation were conducted as part of this PhD research. The first step was to test the validity of the different techniques used within the tool. The validation helped in understanding the reliability of the techniques to represent the different types of impacts in a reliable manner. The assumptions within the toolkit and the different techniques utilised within the toolkit were tested for their validity based on data collected from the case study area. This data included a questionnaire survey delivered to residents in the area to understand how the damage to bridges affected their daily lives. Further secondary data was also collected from newspaper articles, websites and interviews with local council officers to ascertain the level of impacts at the community and business level.

3.5 Summary

The research methodology used in this project is based on Sustainable Engineering principles and was carefully chosen so as to address the research questions identified. A literature review was conducted to identify the research gaps and to understand the current state of the art in the field. A framework to measure the social, environmental and economic impacts of road infrastructure failure was developed based on the context of the project. A toolkit to test this framework in a real life disaster situation was developed and was tested through a case study in a regional flood affected area in Queensland. The toolkit was validated through follow-up interviews, questionnaire surveys and secondary data relating to the impacts to the community in the case study region.

4. ANALYSIS OF MEASUREMENT METHODS

4.1 Introduction

This chapter presents the analysis of the different measurement and integration methods that were carried out for the purpose this research. The different methods and techniques used in prior literature to assess social, environmental and economic impacts due to road structure failure were critically analysed in order to select the most appropriate methods that could be used for the development of the framework. The analysis related to the following research objectives identified for the project:

- To understand the current methods and techniques used in consequential impact assessment of post-disaster road infrastructure failure.
- To modify and improve suitable methods in order to measure SEE impacts of disaster related bridge failure.
- To develop a conceptual framework that can measure and integrate socio-economic and environmental impacts of bridge failure

The analysis was carried out in two steps. The first was to carry out a thorough analysis of the theoretical foundations, assumptions and data requirements of all methods used by scholars in post-disaster impact assessment. This helped in identifying the advantages and disadvantages of the different methods and to understand in which contexts they had been used in prior research. This analysis resulted in a review paper, which was published during the candidature period. Section 4.2 presents the published paper which has been formatted to be consistent with the thesis.

The second step was to select the most suitable methods that were to be used to measure sustainability related impacts in a post-disaster context. The results of the needs assessment interviews (presented in Chapter 5) influenced which methods were selected. The interviews highlighted the requirements of practitioners involved in post-disaster road infrastructure decision making. This second step is explained in detail in section 4.3. The selection process considered both the end-user requirements as well as the theoretical foundations of the different models that were being integrated and this resulted in developing the conceptual framework.

4.2 Post-disaster impact assessment of road infrastructure: state of the art review

Gajanayake, A., Zhang, G., Khan, T. and Mohseni, H. (2020), *'Postdisaster Impact Assessment of Road Infrastructure: State-of-the-Art Review'*, Natural Hazards Review, vol. 21, no. 1, p. 03119002.
https://doi.org/10.1061/(ASCE)NH.1527-6996.0000343

Abstract

Road infrastructure is a vital aspect in transportation systems, and can be severely impacted due to disasters. Post-disaster impact assessment is vital for the repair and reconstruction of such infrastructure, which is constrained by budget and time. This review provides a detailed analysis of prior literature on post-disaster impact assessments of road infrastructure. The related methods used in the literature were analysed based on their classifications, such as social, environmental and economic impacts of road failure. It was determined that although a wide range of methods have been used to assess economic impacts, there is still a lack of research measuring environmental and indirect social impacts. Prior literature has also highlighted that the use of bottom-up models to assess socio-economic impacts are more relevant in the aftermath of a disaster. This paper presents a systematic review of the literature, and guidelines for selecting the most appropriate method to assess impacts. This review aims to provide a framework of reference for researchers and government authorities involved in post-disaster impact assessment and decision making related to road infrastructure.

Introduction

Disasters triggered by natural hazards are increasing both in intensity and frequency, causing large-scale impacts on societies and economies globally. The annual average number of disasters worldwide over the ten-year period from 2006 to 2015 was 376. These disasters caused close to 70,000 deaths and damages worth USD 138 billion annually. The increase in disaster events is mainly due to a rise in hydro-meteorological disasters such as floods, hurricanes and storms over the past 30 years (Guha-Sapir 2016).

The increase in hydrological disasters has a direct influence on the vulnerability of road infrastructure such as bridges, culverts and flood-ways. Such infrastructure is built to cross waterways, and can therefore be severely affected in times of hydrological disasters. Road networks and transport-related infrastructure play a vital role in the resilience of a society after a disaster event, as they directly influence evacuation, rescue and reconstruction efforts by providing access and mobility to communities. The unserviceability of such infrastructure can exacerbate the consequences of the disaster, both on temporal and spatial scales.

The State of Queensland, Australia was severely affected by flooding events during 2010-2011. The national and state governments committed approximately 6.8 billion Australian Dollars (AUD) for rebuilding activities after these events. It was estimated that 80% of flood-related infrastructure damage was to road and transport infrastructure, with 9,170 km of state-owned roads and 89 state-owned road structures being damaged (QRA 2011). As these figures only relate to the financial cost of reconstructing road infrastructure, the wider social, economic and environmental effects of damaged roads are likely to be much higher. In this light the assessment of social, environmental and economic consequences will be the first step towards understanding the wider impacts of road failure, and its effects on the resilience of communities.

Decisions on post-disaster reconstruction tend to be made based on assessments carried out before the actual event occurs. This is done by modelling a hypothetical disaster and then running different scenarios, in order to predict the likely impacts of a similar disaster event. Such pre-disaster (ex-ante) impact prediction of road structure failure is widely used both in the Civil Engineering and Economics disciplines (Dutta et al. 2003, Jaiswal et al. 2010, Enke et al. 2008, Kiremidjian et al. 2007, Mitsakis et al. 2014). However, the impacts estimated using such methods may vary from actual post-disaster impacts due to changes in behavioural responses after a disaster (Ardekani 1992, Danczyk et al. 2017, Giuliano and Golob 1998, Lu et al. 2014, Zhu, Levinson and Liu 2009, Zhu et al. 2010) and the reliability of the standard loss functions used (Kellermann et al. 2015, Bubeck et al. 2011). For example, (Klose et al. 2015) found that the actual cost of landslide repairs can vary by up to 18.7% when compared with estimated costs. It is thus evident that ex-ante impact prediction, as important as it is for decision making purposes, may not result in reliable estimates of road network failure in real life disaster situations. Consequence assessment of post-disaster (ex-post) impacts due to road structure failure can take into account adaptation practices of a community affected by a disaster, to provide more realistic information. This information could be used by state authorities to prioritise post-disaster reconstruction in a manner that minimises socio-economic impacts on the community.

Previous review articles in the area of disaster management have analysed literature on disaster impacts on wider socio-economic systems without a specific focus on road infrastructure (Hammond et al. 2015, Brown et al. 2011, Meyer et al. 2013, Markantonis, Meyer and Schwarze 2012). Most review articles focus only on the economic impacts, with less consideration for social and environmental impacts (Greenberg, Lahr and Mantell 2007, Kousky 2014, Merz et al. 2010, Okuyama 2007, Lazzaroni and van Bergeijk 2014). Review papers that focus on impacts of transport and road infrastructure either do not consider the impacts in a post-disaster context (Bueno et al. 2015, Kabir, Sadiq and Tesfamariam 2014, Wang et al. 2018b), are limited to assessing the functionality of road infrastructure systems (Faturechi and Miller-Hooks 2014, Mondoro, Frangopol and Liu 2017) or focus on a specific type of impact like post-disaster logistics optimisation (Caunhye, Nie and Pokharel 2012) without considering the wider socio-economic impacts. Previous review papers have not dealt with the wider social, environmental and economic impacts of disaster-induced road failure.

The purpose of this paper is to review recent research which has focussed on assessing impacts of disaster induced road infrastructure failure from social, environmental and economic viewpoints in order to identify gaps in knowledge and future research directions in the area of disaster impact assessment. The assessment of social, environmental and economic impacts are commonly referred to as sustainability impact assessment (Ness et al. 2007); this has been increasingly viewed as a tool to aid in the shift towards sustainable post-disaster recovery (Berke, Kartez and Wenger 1993, Pope, Annandale and Morrison-Saunders 2004, Drolet et al. 2015). This review compares different methods in which sustainability impact assessment of post-disaster road failure has been carried out and provides new insights as to how a comprehensive ex-post impact assessment can be conducted.

Methodology of literature review

Database

The method adopted for this paper was to provide a critical review of prior literature to identify relevant research outcomes based on the inclusion criteria. A critical analysis of the publications was undertaken in order to identify the prominent methods used for the assessment of social, environmental and economic impacts relating to disaster situations. A scoping review was carried out using the Scopus and Google Scholar databases, using various combinations of key search terms. The terms were selected based on their relevance to the study and by analysing the key words listed in the most relevant papers. These terms included “disasters”, “natural hazards”; “road structures”, “road infrastructure”, “road networks”, “bridges”; “impacts”, “sustainability”, “economic impacts”, “social impacts” and “environmental impacts”. The Google Scholar database yielded a higher number of items as it is an open-source platform, which covers numerous databases. The overall search focused on academic publications including journal articles, conference papers and technical papers published between 1990 and 2018.

The title of each search result was read in order to identify its relevance. Thereafter the abstracts of those papers were analysed to identify their relevance to the specific scope of the study. A manual search of the publications that were identified in this manner was conducted by going through the citing and cited works in each publication. Using both these methods, publications that were relevant to the scope of the study were selected for the final analysis. The publications were only included in the analysis if they included an assessment of social, environmental or economic impact of road failure.

Scope of review

Literature focussing on the social, environmental and economic impacts of road infrastructure failure in a post-disaster context was reviewed. The review excludes research on the structural and engineering impacts of infrastructure failure. Further, studies that consider wider impacts of disasters but which do not focus on road infrastructure were excluded. In addition, methods to assess social, environmental or economic impacts of road failure within a larger economic impact assessment were analysed. The reviewed literature covered research on land transport networks and relevant infrastructure supporting these networks, but did not consider air or water transport systems.

Human reaction to a disaster could be analysed based on four temporal phases; mitigation, preparedness, response and recovery (Comfort, Ko and Zagorecki 2004). This paper analyses literature that focusses on the two latter stages, and the term post-disaster impacts is used to refer to impacts at both these stages. In this paper a disaster is identified as an event induced by natural hazards including floods, bushfires (wild fires), earthquakes, cyclones (hurricanes/typhoons) and landslides. Accordingly road network failure due to physical deterioration of structures and terrorist attacks was excluded from this analysis.

The scope of this paper does not consider research on impacts of scheduled road closures or road accidents, as impacts in post-disaster scenarios can be significantly different to those in other circumstances (Kurauchi et al. 2009). Such changes can be due to the fact that a disaster event can fundamentally alter people's usual travel patterns, and that behaviour of passengers may not be rational in post-disaster situations (Khademi et al. 2015).

Classification of disaster impacts

Historically, disaster impacts have been classified based on two criteria (Merz et al. 2010). The first criterion distinguishes between direct and indirect impacts. Direct impacts are caused by the destruction of social, environmental or economic capital by the disaster event (flood water, fire, wind etc.). In contrast, indirect impacts refer to secondary occurrences induced by the direct impacts; these often occur temporally and spatially distanced from the disaster event.

The other distinction is between tangible and intangible impacts. Tangible impacts relate to impacts caused to items that are exchanged in a market environment and therefore can be easily quantified in monetary terms. Intangible impacts, on the other hand, refer to impacts on items that are not commonly exchanged in a market and hence are more difficult to quantify in monetary terms (Stephenson et al. 2013). Environmental, social and economic impacts can be classified as tangible or intangible impacts but the degree of capture (from low to high) of these impacts varies in tangible terms. Typically, economic impacts will be considered as tangible, while intangible impacts encompass social and environmental impacts.

Although the classification of impacts according to these two criteria is common in disaster impact analysis, there can be differences in interpretation among scholars. Tangible and intangible impacts are terms frequently used in the literature; however, to date, there is no consensus on distinguishing tangibles from intangibles. This is exacerbated by the fact that some scholars try to value social and environmental impacts in monetary terms (Stephenson et al. 2013, Chang et al. 2009), while others deem that monetary values cannot be given to impacts such as loss of life and other social impacts (Gardoni and Murphy 2009, Lindell and Prater 2003).

The distinction between direct and indirect impacts is far more straightforward. However, some scholars use the term 'secondary impacts' to refer to longer-term impacts. This term has been used to refer to the performance of an economy from a macroeconomic perspective (Pelling et al. 2002) and to refer to negative market outcomes affecting businesses (Hiete and Merz 2009). Indirect impacts have, at times, been further distinguished as primary and secondary indirect impacts (Van der Veen, Vetere Arellano and Nordvik 2003). These terms are often used interchangeably and without precision.

Although it is common to classify disaster impacts according to the categorisation explained above, some scholars use different classifications as environmental, social and economic impacts based on the three dimensions of sustainability (Adeagbo et al. 2016, Dong et al. 2014b). This method of classification can be considered as complementary to that explained above. Here, economic impacts refer to tangible impacts while the social and environmental impacts are part of the intangible impacts. (Ashe et al. 2009) distinguish costs as costs in anticipation, response and consequence based on the three stages of a disaster. However, classification of costs in this manner has limited utility as this review is focused purely on post-disaster impacts.

Disaster-related impacts may not necessarily be negative (losses); gains can also result from a disaster. Such benefits can include benefits flowing to the community in the form of aid, increased employment due to reconstruction activities and enhancement of the natural environment (Smith 2013).

The assessment of the literature in this paper is organised and presented based on the classification illustrated in Table 4-1. This categorisation encompasses the direct/indirect and tangible/intangible classification typically used in disaster impact assessment and the social, environmental and economic aspects, which are used in sustainability impact assessment. This classification also helps in identifying the most suitable techniques to measure the different types of impacts in each of these categories.

Table 4-1 Classification of impacts from road failure

Measurement	Type of impacts	
	Direct	**Indirect**
Tangible (Economic)	Damage to infrastructure and vehicles, clean-up costs, disposal of debris, disaster and reconstruction aid	Increase in travel time, business disruption, loss of individual income, loss of revenue to public transport operators and cost of alternative accommodation, increased income and employment due to reconstruction
Intangible (Social)	Death and injury, loss of items of cultural significance, psychological impacts	Inconvenience and disruption to community, psychological impacts, loss of confidence in authorities
Intangible (Environmental)	Loss of animal life, damage to habitat, deposit of fertile soil	Resource use for reconstruction, incremental emissions during reconstruction

Note: Modified based on Ref. (Merz et al. 2010)

Direct tangible (economic) impacts

Direct economic impacts occur due to the destruction of infrastructure by the disaster event and can be measured easily in monetary terms. Direct tangible impacts related to road structures will include costs of road clean-up, debris disposal, damage to infrastructure and damage to vehicles on the road at the time of the disaster. Research focusing on assessing the direct tangible impacts of road failure has used two different techniques. These two methods are cost surveys and cost modelling, which are analysed below.

Cost survey

A cost survey aims to retrieve empirical cost data for disaster events through targeted data mining (Klose et al. 2015). Data sources for cost surveys can range from official archived records to surveys in the area of the disaster. Cost surveys are a commonly used method to measure the direct tangible impacts of disasters, and are widely used to assess the costs of a disaster at regional or national level (Vranken et al. 2013, Walkinshaw 1992, Wang et al. 2002, Bíl et al. 2015). The direct impacts related to road infrastructure measured under this method will typically include clean-up costs and damage to infrastructure. Although estimating the clean-up cost of a disaster can be straight-forward if empirical data are available, the cost of the damage can be harder to estimate. Scholars have generally used the repair, reconstruction or replacement cost of a structure as a proxy value for the cost of damage (Winter et al. 2016b, Negi et al. 2013, Klose et al. 2015, Klose et al. 2016).

When using cost surveys to measure direct costs, the richness of data available from the relevant authorities directly influences the accuracy of the estimates. (Klose et al. 2015) found that authorities only maintained records of reconstruction costs that exceeded USD 70,000. (Negi et al. 2013) could only obtain costs in relation to labour and machinery usage, and could not obtain costs of materials used for reconstruction. Moreover, obtaining data for more recent events has been found to be considerably easier than for less recent events (Winter et al. 2016b). The relevance of the data is an important aspect to consider, and attention needs to be paid in connecting correct project cost with a specific asset (Klose et al. 2015).

Reconstruction work after a disaster may include upgrades to the structure, which did not exist at the time it was destroyed. In such instances (Stephenson et al. 2013) argue that it is important to use the depreciated value of the asset at the time of the disaster rather than the reconstruction cost when assessing damage to infrastructure. They propose to use a percentage of the replacement or repair cost as an estimate of the depreciated value of the asset. Such a calculation assumes that replacement or repair of the infrastructure will upgrade the asset to a level better than the state it was in when the disaster struck. Though such an assumption is valid, using a flat rate to discount all assets may not be accurate as some assets may be older than others and therefore have a lower depreciated value than newer assets. However, (Klose et al. 2015), (Negi et al. 2013) or (Winter et al. 2016b) have not calculated the depreciated value of the assets; instead, they have simply used the replacement cost to value direct economic impacts. Interestingly, (Klose et al. 2015) found that over 55% of the damage costs relate to mitigation, which may include further upgrades to the infrastructure.

Another direct tangible cost that should be considered is the damage to motor vehicles while using the road. (Negi et al. 2013) have considered the cost of two vehicles that were damaged while travelling on the road when a landslide was active. However, most of the research on direct costs has not included any specific costs related to motor vehicle damage. The literature does not specifically state if such costs were not considered or if vehicles were not damaged during the disaster. This highlights the importance of specifying what forms of potential impacts were considered, even though all such impacts may not have occurred for a given case.

Cost modelling

In the event that empirical data are not available, cost modelling has been used to estimate the cost of damage to infrastructure (Klose et al. 2015). This method identifies specific items that need to be repaired or replaced and attributes monetary values to these items by using current market prices obtained from construction cost data bases or proxy costs. This method is similar to methods used in ex-ante impact prediction, where loss functions for specific components of a structure or stage damage curves for the entire structure, are used to estimate the damage (Luna et al. 2008, Jaiswal et al. 2010, Dutta et al. 2003, Penning-Rowsell et al. 2005). The cost modelling approach could be considered a more accurate method in comparison to ex-ante prediction, as it does not rely solely on pre-event forecast data, but strives to incorporate as much empirical data as possible and uses standard cost data only in instances where empirical data are unavailable.

There has been a debate on the use of different price estimates when calculating direct tangible impacts. Price estimates can be an influential factor in disaster impact assessment as prices of materials and labour can be expected to increase due to shortages immediately after a disaster (de Silva 2011). (Kousky 2014) argues that the use of current market prices may overestimate construction costs. (Hallegatte and Przyluski 2010) opposes this view by stating that the use of post-disaster prices is more realistic as it takes into account the real economic situation prevailing in the area at the time. (Negi et al. 2013) uses current market prices to present the impacts while (Winter et al. 2016b) and (Klose et al. 2015) adjust post-disaster prices to account for inflation.

Summary

In summary, it has been shown that the use of a cost survey to measure the direct tangible costs is more reliable than cost modelling techniques. However, the richness of the data available will influence the accuracy of the assessment. In instances where data are not available two contrasting methods have been used; a top-down method to estimate the damage to a specific structure using data from national or regional reports (Winter et al. 2016b) and a bottom-up method using itemised records of reconstruction (Klose et al. 2015) . Here again, the availability of the data and the data source will influence which method is most appropriate. Changes in price levels and upgrades to infrastructure after a disaster should be accounted for.

Indirect tangible impacts

Most indirect impacts of the failure of road structures stem from the decline in accessibility, connectivity and mobility due to the un-usability of a structure after a disaster. These indirect tangible impacts can be segregated into two main types of impacts. They are transport related impacts and impact on businesses. The literature reveals that these two types of impacts are assessed using fundamentally different concepts. Transport impacts, which can result in both economic and social impacts, are typically assessed based on transport engineering principles, whilst business impacts, which correspond to economic impacts, are measured based on basic economic modelling fundamentals. Therefore, the analysis of indirect impacts is treated under two main headings; transport impacts and business impacts.

Transport-related impacts

The most studied indirect impact of road infrastructure failure is the effect on transportation. This makes intuitive sense as the purpose of road infrastructure is to reduce the time and cost of transportation. Transport impacts arise when a section of the road is closed due to damage and alternative routes have to be used. The use of alternative routes will increase the time spent travelling as well as the cost of travel. The increase in travel time is one of the major factors considered when measuring transport-related impacts. Other factors that have been considered are extra fuel used, additional road maintenance costs, additional emissions and increased congestion during reconstruction activities.

Transport-related impacts have been assessed using two distinct approaches in the literature. Transport network analysis is based on network theory, and measures the impact on transportation through the functionality of the road system. Transport modelling, in contrast, is more descriptive in nature and uses transport demand functions to assess impacts. These two methods have typically been used separately and therefore will be analysed separately in this paper.

Transport network analysis

Transport network analysis is a branch of network theory that analyses a transport system from a top-down, graph theory perspective by considering the network as sets of nodes and links. The use of network theory to analyse transport systems can be advantageous in disaster scenarios, as it can be used in conjunction with geographical data of disasters. Network analysis has grown in popularity in recent times in the wake of advances in Geographic Information Systems (Ducruet and Lugo 2013). This method measures the transport impact as the reduction in the level of serviceability against the pre-disaster serviceability of the network. The pre-disaster serviceability of the network is assumed to be the optimal-level of service. The results of the transport network analysis are typically presented as a percentage or ratio of reduction in functionality.

Literature shows that either a topological approach (Bíl et al. 2015, Muriel-Villegas et al. 2016, Bono and Gutiérrez 2011, Aydin et al. 2018a, Aydin et al. 2018b) or a systems approach (Chang and Nojima 2001, Ho et al. 2012, Mudigonda, Ozbay and Bartin 2018, Utasse et al. 2016) could be used to measure the reduction in serviceability after a disaster event. The topological approach uses the number of links and nodes of a road system that are serviceable after a disaster to measure the network's serviceability. This method has limited data requirements and relies on a mathematically elegant, well elaborated and rigorous theory. However, these advantages in themselves make it difficult to incorporate any behavioural changes observed in times of disasters. System-based models, in contrast, use travel time or travel distance as measures of system performance. Such models are therefore highly data-driven despite overcoming the limitations of topological studies by allowing behavioural changes to be modelled.

The system-based approach allows for a broader spectrum of consequences to be measured and presented in a more intuitive manner (Mattsson and Jenelius 2015). The type of impacts measured in the systems approach are increase in average travel time and distance (Chang and Nojima 2001, Ho et al. 2012, Mudigonda et al. 2018). Topological approaches present results based on somewhat abstract performance measures, like network efficiency index (Aydin et al. 2018b, Bíl et al. 2015), connectivity reliability index (Muriel-Villegas et al. 2016) and Giant Connected Component (Aydin et al. 2018a). Abstract performance measures such as these lack comparability and would require some background knowledge for the results to be interpreted.

It can be observed that scholars have used a wide range of indicators to measure the serviceability of a network. One possible reason for this is that increasing the number of indicators can be thought to increase the accuracy of the calculations. However, no one specific indicator has been found to be significant in estimating the final serviceability of a network (Bíl et al. 2015, Muriel-Villegas et al. 2016).

The use of network theory can be helpful in a post-disaster scenario as it allows the researcher to assess the impacts of multiple disruptions to a road network, which can be common following a natural disaster. However, as the focus of network analysis is to understand the functionality of the network, monetizing the impacts may be challenging and has often been ignored in previous studies.

Transport modelling

Transport modelling tools are commonly used to estimate the number of people using a particular mode of transport from a bottom-up approach. Similar models are used to estimate transport-related impacts in post-disaster scenarios. A typical transport model is run in four stages: 1) trip generation; estimating the total number of trips generated, 2) distribution; allocation of these trips to different destinations, 3) modal split; selecting the specific mode of transport for each trip and 4) assignment; assigning the trips to the corresponding networks (de Dios Ortúzar and Willumsen 1994). In disaster impact analysis, the transport model is run in the same manner but attempts to account for commuter behaviour changes after a disaster.

Some researchers using transport models derive basic equations to manually calculate the travel demand in the conventional transport model (Wesemann et al. 1996, Negi et al. 2013, Pfurtscheller and Genovese 2016a). An increase in the use of transport modelling software can be observed in recent times; this has reduced the amount of time required for analysis (Xie and Levinson 2011, Shen and Aydin 2014, Mitsakis et al. 2014, Wen et al. 2014, Winter et al. 2016b). The use of transport modelling software gives the opportunity to analyse the effects of more than one disruption on the transport system as a whole. Conventional methods, in contrast, calculate the total cost of multiple disruptions by simple addition of separate models. Such simple additive methods may not account for the network-wide effects typically experienced with disruptions in road networks.

The use of transport modelling software comes with its disadvantages. The alternative routes in such models are limited to routes that are pre-set into the program and therefore, accounting for behavioural changes and community adaptation may be challenging. Transport modelling software packages have different features and generate different outputs. Therefore, making cross comparisons between these studies can be challenging. The reasons to choose a specific model are based on the specific software that was being used by authorities at that time (Wen et al. 2014, Xie and Levinson 2011) or based on recommendations of the relevant authorities (Winter et al. 2016b), while (Mitsakis et al. 2014) and (Shen and Aydin 2014) do not mention the rationale for choosing a specific software for their analysis. This highlights the fact that transport modelling needs to be conducted in a context-specific manner that accommodates the usability of the results of the analysis.

Researchers have used numerous indicators to estimate the total cost of delay in transport modelling techniques. These indicators are individual travel time (Wesemann et al. 1996, Negi et al. 2013, Wen et al. 2014, Winter et al. 2016b), additional fuel cost (Wesemann et al. 1996, Negi et al. 2013, Pfurtscheller and Genovese 2016a), additional travel fare (Negi et al. 2013, Pfurtscheller and Genovese 2016a), commercial vehicle travel time (Wesemann et al. 1996, Shen and Aydin 2014, Pfurtscheller and Genovese 2016a), additional emissions (Wen et al. 2014, Winter et al. 2016b), pavement maintenance and congestion costs (Wen et al. 2014, Pfurtscheller and Genovese 2016a) and accident costs (Winter et al. 2016b). Although the use of a wide range of indicators can increase the accuracy of the measurements, most of the results show that rerouting and delay costs account for the vast majority of total cost (Winter et al. 2016b, Wen et al. 2014, Negi et al. 2013).

Different methods for obtaining data for transport models can be seen in the literature. While some researchers labour to obtain the most accurate post-disaster data through real life counts, travel time runs and surveys (Wesemann et al. 1996, Negi et al. 2013, Mitsakis et al. 2014) others combine standard travel data with the post-disaster road network serviceability levels to obtain estimated indirect costs (Xie and Levinson 2011, Shen and Aydin 2014, Wen et al. 2014, Winter et al. 2016b). The latter method, although less resource intensive, can result in wide-ranging values based on the assumptions used. For example, (Xie and Levinson 2011) found that the daily indirect economic loss could vary between the lower bound of USD71,000 and an upper bound of USD220,000 depending on the different scenarios modelled.

A similar approach to transport modelling has been adopted by (Chan and Schofer 2015) to measure the impact of disruptions to rail transit systems due to disaster events in New York City. This model compares delivered vehicle miles to the planned vehicle miles during and after a disaster event, to measure the system output. The reduction in vehicle miles is then normalised and presented as Lost Service Days, which could be used for comparison across different events or different areas.

Summary

This section has critically reviewed literature pertaining to the transport-related impacts due to road failure, and is presented in Table 4-2. It is evident that two different approaches have been used for this purpose. The major difference in the two approaches is that the results of transport network analyses are abstract in nature and hence harder to interpret. The results of transport modelling, by contrast, can be presented using a monetary value and hence can be easier to interpret by practitioners. It also has the advantage of being able to be combined with other impact assessment techniques. This method therefore, can be useful in Cost-Benefit Analysis models.

Table 4-2 Comparison of transport impact measurement methods

Aspect	Network analysis	Transport modelling
Approach adopted	Top down	Bottom up
Number of disruptions	Allows for multiple disruptions to be assessed	Better suited for single disruption events
Monetizing impacts	Challenging	Widely used
Incorporating behavioural effects	Challenging	Straightforward
Scope of analysis	Wider	Narrower

Business impacts

Road failure can cause a variety of economic impacts by affecting the daily operations of businesses located close to the damaged infrastructure as well as longer term macroeconomic performance of the economy. The impacts to businesses can be due to disruptions to freight movement, decreased customer traffic and inability of employees to arrive for work and will impact a firm's revenues and costs. Business disruption impacts in this section do not consider increases in transport costs for businesses due to the damage to the road network. Such impacts are typically measured through transport modelling techniques as explained in the previous section.

The impacts on businesses are measured based on economic modelling techniques. The literature reveals that three distinct methods have been used to assess the impacts on businesses. These methods are Cost Survey, Input-Output analysis and Computable General Equilibrium.

Cost survey

The most common method to measure the impact of road failure on businesses is to obtain empirical data relating to business activities after the disaster. Researchers have obtained such data directly from businesses through questionnaires and surveys (Wesemann et al. 1996, Hansen and Sutter 1990, Willson 1998, Boarnet 1996) or through secondary sources such as press reports, which include interviews and statements from businesses (Pfurtscheller and Genovese 2016a). The majority of the previous research concentrated on obtaining information only from businesses that were directly affected by a disaster. However, (Boarnet 1996) also obtained information from businesses located 50 miles from the disaster zone, which was used as a control group for analysis.

Business impacts due to road failure can be assumed to affect transport-related industries more than other industries. This has prompted some scholars to measure business impact by focussing solely on the freight and passenger transport sectors (Wesemann et al. 1996, Hansen and Sutter 1990, Willson 1998), while others incorporate a wider array of businesses into their analysis (Boarnet 1996, Pfurtscheller and Genovese 2016a). Analysis of the literature shows that the biggest impacts are from route closures that caused shipping delays (Wesemann et al. 1996, Boarnet 1996). Interestingly, the decline in tourist arrivals accounted for the majority of the business impacts in an area relying heavily on tourism (Pfurtscheller and Genovese 2016a).

This shows that the type of industries that are severely affected would vary based on the economic structure in the disaster zone.

Based on the type of questions asked and the different information obtained from businesses, some scholars present results simply as a percentage change in the normal business levels (Wesemann et al. 1996, Hansen and Sutter 1990, Willson 1998) while others value them monetarily (Boarnet 1996, Pfurtscheller and Genovese 2016a). However, no clear positive or negative relationship of business levels could be identified. This was because the decline in revenue in one area may be compensated by an increase in revenue in another area located further away from the disaster zone (Hansen and Sutter 1990, Willson 1998). (Boarnet 1996) found that even firms located some distance away from a damaged highway can be negatively affected. This illustrates that business impacts can vary based on the high interdependencies of the businesses as well as the complexity of the transport network.

A major drawback in using a survey to measure the transport-related impacts on businesses is that respondents are given a free hand to distinguish between transport-related impacts and other non-transport-related disaster impacts. In such circumstances, the assumptions used by the respondents may vary significantly, and therefore, may not provide an accurate estimate across all respondents. For example, while one respondent may view structural damage to a loading dock that causes delays in goods movement as a transport-related impact, another may consider it as an impact to infrastructure.

Input-Output analysis

Input-Output (IO) analysis views the economy as a system wherein industries receive inputs from other industries, and produce outputs either for other industries or final consumers, and is represented through a commodity flow table. This focus on business interdependencies makes IO analysis well suited to measure the indirect impacts of a disaster on an economic system (Hammond et al. 2015). The natural disaster is typically conceptualised as a shock to the previously stable system and the impact to businesses is estimated through the final effect on demand in the system (Safarzyńska et al. 2013).

Although IO analysis allows for an external shock to the system to be modelled, modelling for the specific transport-related impacts could be a bit more complicated. To do this, scholars have typically combined a transport model with the IO table. (Sohn et al. 2004) estimated the damage to the transport network using disaster parameters and applied this to the IO model to calculate the transport-related impacts. (Gordon et al. 1998) used information obtained from businesses through surveys to estimate the transport-related impacts for the different sectors in the economy.

While one method relies heavily on the accuracy of the damage estimates of the transport network (Sohn et al. 2004), the other relies on responses of businesses. A simple aggregation of survey results overlayed on a network-based IO model may cause an over-estimation of the impacts (Gordon et al. 1998). The scope of the analysis also varies where (Sohn et al. 2004) estimated business impacts over a 25-year period for the entire USA while (Gordon et al. 1998) focused on a narrower region of the disaster for a period of one year.

Computable General Equilibrium models

Computable General Equilibrium (CGE) models are used in economics to analyse how changes in specific variables of the economy affect the economic system. It is assumed that consumers and producers make optimal decisions in response to changes in these variables. The model typically consists of blocks of equations, which represents key actors in the economy. Such analysis is usually derived from an IO table, and additional equations that make sure that the different blocks are consistent (Greenberg et al. 2007). A CGE model assumes that the economy is in equilibrium before the disaster and then compares the post-disaster equilibrium to the pre-disaster equilibrium to measure the effect of the event on the economy. As CGE models can incorporate price changes, input substitution and supply constraints, they address some of the deficiencies identified in IO models (Okuyama 2007).

Scholars have typically analysed the effect on businesses due to road network failure by analysing how the disaster would affect the transportation sector of an economy. While most studies have focused on the freight transport sector (Chen and Rose 2018, Shi and Wang 2013a, Xie et al. 2014), others have looked to incorporate passenger transport by analysing the impact on rail networks (Tatano and Tsuchiya 2008). The effect on the transport network has been analysed in two contrasting ways. This has been carried out through the estimation of damage to the network (Chen and Rose 2018, Xie et al. 2014) or through the use of a transport model (Shi and Wang 2013a, Tatano and Tsuchiya 2008).

Summary

This section has attempted to provide a brief summary of the literature relating to the assessment of business impacts due to road failure. It could be stated that cost surveys are a simple method to assess business-related impacts. This method could be appropriate for instances where the scope of analysis is temporally and spatially narrow. The accuracy of this method could be enhanced by the use of control groups such as businesses located further away from the disaster zone. Time series analysis to control for any non-disaster related variables can also be used to increase the validity of the results.

IO analysis is well suited to measure indirect system-wide impacts to businesses over the medium to long term, in highly interdependent industrial areas. However, the exact impacts due to transport disruptions are hard to model. In addition, the data and modelling that is required for IO analysis can result in over-analysis for areas that are not highly industrialised. Although IO analysis is considered a good economic model and is relatively easy to use compared to other economic techniques, the model itself has inherent short-comings, mainly due to its rigidity. Some of these challenges are the inability to incorporate price changes, substitution of inputs and explicit resource constraints (Rose 2004b), all of which can have a major influence in a post-disaster scenario (Safarzyńska et al. 2013).

CGE analysis takes on a very wide scope and hence is appropriate for indirect impact assessment at state or national level. It could be said that CGE analysis is better suited for the analysis of system-wide transportation disruptions rather than disruptions due to specific road infrastructure. Even though CGE models address most of the deficiencies of IO models, the flexibility and the focus on the long-run equilibrium of CGE models can lead to an underestimation of economic impacts (Rose and Liao 2005). CGE models are inherently broader in scope, and as the scope of analysis broadens, the measured economic impact of the shock may tend to decrease. One reason for this could be that the decline in revenue of a firm located within the disaster zone may get set-off against an increase in revenue of a firm located further away as economic transactions gets reallocated across the economy.

Further, CGE models are more complicated than IO models, and the extensive data requirements can present a major disadvantage for the empirical analysis of disasters. This is more critical where post-disaster behavioural changes tend to be irrational. A disaster event can cause a larger proportion of non-rational decisions to be made, thus altering one of the main fundamental assumptions of the model, which assumes that consumers and producers make optimal (rational) decisions in response to changes in economic variables. Non-rational decision making in post disaster situations occurs due to what has been referred to as "crisis of management" (Smith 1990). Crisis of management occurs due to vulnerability, latent and active errors which can occur due to the non-linear nature of activities associated with a post disaster recovery situation (Smith 2005).

The analysis of the methods used to measure business impacts of transport disruptions show that no one method is inherently superior to others. The type of method chosen by the researcher should vary according to the scope and focus of the project. A comparison of these three methods can be found in Table 4-3.

Table 4-3 Comparison of business impact measurement methods

Aspect	Cost survey	IO analysis	CGE model
Scope of analysis	Microeconomic	Macroeconomic	Macroeconomic
Time frame	Short – medium term	Medium – long term	Long term
Aggregation method	Simple aggregation	Systems approach	Systems approach
Geographical scope	Regional	State / National	National
Incorporating non-rational behaviour	Widely used	Challenging	Challenging

Direct intangible impacts

The direct intangible impacts of road structure failure can be identified as any direct social or environmental impact resulting from the disasters. These can typically be any deaths or injuries to people while travelling on the road and any environmental impacts due to the destruction of infrastructure.

Direct social impacts

The direct social impact of road failure includes any deaths or injuries to people while travelling on a road structure when the disaster hits. Deaths and injuries to humans due to disaster events is a commonly studied area of disaster management. There have been many scholars who have studied road-related deaths due to disasters such as floods (Coates 1999, Ashley and Ashley 2008, Diakakis and Deligiannakis 2013, FitzGerald et al. 2010, Yale et al. 2003), cyclones

(Rappaport 2000) and bushfires (Byard et al. 2012). Most of the literature is based on longitudinal studies which analyse disaster-related deaths over several years.

With reference to papers studying the direct social impact from a specific road failure event, (Negi et al. 2013) identified two people who lost their lives while travelling on the road. Though the loss of human lives is considered to be an intangible impact, the authors have attributed a monetary value to the lives lost based on the assistance payments for a deceased person by the Calamity Relief Fund.

It is evident that the highest number of flood fatalities in Australia is related to motor vehicle use and attempts to cross inundated bridges and roads (Coates 1999, FitzGerald et al. 2010). Hence it can be concluded that any research assessing the direct impacts of road damage due to hydrological disasters should focus on the human lives lost and injuries during the disaster.

Direct environmental impacts

In relation to environmental impacts, (Srinivas and Nakagawa 2008) identified potential impacts due to disasters. The impacts relevant to road failure are water contamination due to chemical run-off from roads, destruction of fauna and flora and disposal of debris. Some scholars have assessed specific environmental impacts due to disaster affected roads like sediment run-off from unpaved roads due to flooding (MacDonald and Coe 2008) and an increase in sediment run-off from roads affected by wildfires (Sosa-Pérez and MacDonald 2016). However, these papers focus only on a specific environmental impact rather than trying to incorporate a variety or at least the most important types of impacts for analysis.

Indirect intangible impacts

The indirect intangible impacts relate to impacts induced by the road failure, which occurs temporally and spatially distanced from the disaster event. These factors are considered intangible as they are not commonly traded in a market. These impacts could be broadly classified into social and environmental impacts and will be analysed separately in this section.

Indirect social impacts

The failure of transportation infrastructure is considered one of the most significant forms of impact to communities following a disaster. These impacts are caused by the lack of accessibility and mobility to communities (Ho Oh, Deshmukh and Hastak 2010). Some of these social impacts such as reduced access to schools, hospitals and recreational areas, play a major role in the recovery of the community and thus can be considered to be critical impacts of road failure.

Researchers have adopted two distinct approaches to assess the indirect social impacts of road failure. One group takes a statistical analysis approach to understand the proportion of people affected and how their mobility has been affected (Gordon et al. 1998, Adeagbo et al. 2016, Kontou, Murray-Tuite and Wernstedt 2016), while others have attempted to quantify impacts with the use of accessibility indices (Chang 2003b, Deshmukh et al. 2011). The statistical method is beneficial to get a basic idea of the social impacts and which segments of a society are affected. However, it will not reveal the level of impact or what specific types of impacts are significant. The surveys conducted by (Gordon et al. 1998) and (Kontou et al. 2016) had a broad focus as they tried to understand what types of commutes were affected after a disaster. In contrast, (Adeagbo et al. 2016) concentrated on non-work related travel but obtained data relating to different demographic segments of the community.

Differences in approaches that use accessibility indices can also be identified. (Chang 2003b) only considered the post-disaster rail network and analysed the changes through a system minimum distance ratio. (Deshmukh et al. 2011) have taken into account a wider range of community activities also comprising the level of assistance that a particular infrastructure offers to the community. A similar approach is adopted by (Oh, Deshmukh and Hastak 2012) to assess the criticality of a number of different infrastructure including roads and bridges. Even though information relating to demographics, duration of service failure, impact to daily activities etc. was obtained through primary sources, both (Deshmukh et al. 2011) and (Oh et al. 2012) have not calculated the exact social impact for the different activities identified. Instead, a Monte Carlo simulation has been carried out to illustrate potential social impacts due to different levels of serviceability of the infrastructure.

Accessibility indices can be seen to be a better measure of indirect social impacts as they show the magnitude of the reduction in accessibility due to road failure and provide a final measure that is comparable across different cases. For example (Chang 2003b) found that commuter accessibility was affected in varying proportions, immediately after the disaster, ranging from 0.1 to 0.5 across the regions under analysis. Six months after the event, all regions reached an accessibility ratio of 1. However, such a method will require more in-depth data and thus will need greater resources than a simple statistical data collection method.

Another major type of intangible impact could be the psychological impact on communities experiencing a disaster. Only a limited number of researchers have attempted to assess the impact that reduced accessibility has on psychological factors. (Morrice 2013) looked at the psychological impacts on disaster affected individuals based on the ability for them to return to their homes, while (Wang et al. 2012) analysed the impact of the distance from the epicentre on psychological effects on children. Although both these studies assessed the influence of accessibility, they do not try to capture specific psychological impacts related to road failure.

Indirect environmental impacts

The indirect environmental impacts caused by road failure will include incremental impacts on the natural environment that occur after the initial time of the disaster. Some environmental impacts that may occur includes extra resources used for reconstruction, air pollution, noise pollution and carbon emissions due to extra travel time during reconstruction (Bueno et al. 2015). Different types of environmental impacts are typically measured by multiple environmental indicators as the use of one specific metric would not be able to encompass all aspects of impacts. The indirect environmental impacts of road failure have been assessed only in a handful of studies and, in these instances, only the environmental impacts associated with the emissions of greenhouse gases have been analysed.

(Mackie et al. 2014) calculated the carbon footprint of the repair of bridges that were damaged due to earthquakes, using an input-output life cycle carbon assessment framework. This method measures the total carbon footprint of reconstruction for different bridges. Carbon emissions from onsite operations, material usage and transport of materials have been considered. Although this study focuses on the long-term environmental impacts, it only considers the global warming potential of reconstruction. Such a study on environmental impacts is incomplete as other environmental impacts such as noise pollution, destruction of ecosystems and air pollution due to rerouting are not considered.

In their assessment of indirect economic impacts, (Winter et al. 2016b) included carbon emissions from additional fuel consumption due to usage of alternative roads and congestion during the construction phase. However, these carbon emission figures were not presented as a carbon footprint but instead monetized using estimated abatement costs. Although such a method does not present the global warming potential explicitly, it gives an opportunity to compare the environmental impacts with the economic impacts.

Summary

It is evident from the literature that indirect intangible impacts are some of the least assessed impacts with regard to disaster-induced road failure. This holds true for both social and environmental indirect impacts. With regard to social impacts the psychological effects have been assessed the least. With increased public awareness on global warming, the use of carbon emissions as a standard metric to assess environmental impacts has increased. The increased use of carbon emission assessments could be seen in disaster impact literature as well. However, such a method only considers the global warming potential and excludes other environmental impacts, while a wider array of environmental indicators would add value to sustainability assessments (Munasinghe et al. 2016).

Summary of impacts and measurement methods

The review of literature helped identify an exhaustive list of impacts related to post-disaster road failure. The different methods used by scholars to measure these impacts were also identified. This list of impacts and the relevant measurement methods (Table 4-4) will be useful to academics and researchers studying disaster-induced road failure. It will also help government and road authorities involved in post-disaster road infrastructure decision making to identify important aspects of impacts and the different techniques available to measure each of them.

Table 4-4 Methods used to assess sustainability impacts of road failure

Method	Tools	Type of impacts analysed	References
Direct tangible			
Cost survey		Clean-up and disposal costs	Winter et al. (2016)
		Damage to infrastructure	Bíl et al. (2015), Klose et al. (2015), Klose et

			al. (2016), Winter et al. (2016)
		Damage to vehicles	Negi et al. (2013)
Cost modelling		Clean-up and disposal costs	Klose et al. (2015), Negi et al. (2013)
		Damage to infrastructure	Klose et al. (2015), Negi et al. (2013), Winter et al. (2016)
Indirect tangible			
Transport network analysis	System-based model	Increase in travel distance	Chang and Nojima (2001), Mudigonda et al. (2018)
		Increase in travel time	Ho et al. (2012)
	Topological model	Transport network efficiency	Bíl et al. (2015), (Aydin et al. 2018)
		Connectivity	Muriel-Villegas et al. (2016), (Aydin et al. 2018)
		Accessibility	Bono and Gutiérrez (2011), Utasse et al. (2016)
Transport modelling	Derived equations	Individual travel time	Negi et al. (2013), Wesemann et al. (1996)
		Additional fuel cost	Negi et al. (2013), Wesemann et al. (1996), Pfurtscheller and Genovese (2016)
		Additional travel fare	Negi et al. (2013), Pfurtscheller and Genovese (2016)
		Commercial vehicle travel time	Pfurtscheller and Genovese (2016), Wesemann et al. (1996)
		Pavement maintenance and congestion cost	Pfurtscheller and Genovese (2016)
		Loss of public transport service	Chan and Schofer (2015)
	Software	Individual travel time	Mitsakis et al. (2014),Wen et al. (2014), Winter et al. (2016)

		Commercial vehicle travel time	Shen and Aydin (2014), Mitsakis et al. (2014)
		Emissions	Wen et al. (2014), Winter et al. (2016)
		Pavement maintenance and congestion cost	Wen et al. (2014)
		Accident costs	Winter et al. (2016)
Cost survey	Questionnaires/ surveys	Business impact to transport sector	Hansen and Sutter (1990); Wesemann et al. (1996); Willson (1998)
		Business impact to multiple industry sectors	Boarnet (1996)
	Secondary data	Business impact to multiple industry sectors	Pfurtscheller and Genovese (2016)
Input-Output Analysis	Modelling the damage to transport network	Business impact to multiple industry sectors	Sohn et al. (2004)
	Business responses	Business impact to multiple industry sectors	Gordon et al. (1998)
Computable General Equilibrium models	Modelling the damage to transport network	Business impact to freight transport sector	(Chen and Rose 2018; Xie et al. 2014)
	Use of transport models	Business impact to freight transport sector	Shi and Wang (2013)
		Rail impacts on economy	Tatano and Tsuchiya (2008)
Direct intangible			
Numerical analysis of lives lost		Lives lost	Ashley and Ashley (2008), Byard et al. (2012), Coates (1999), Diakakis and Deligiannakis (2013), FitzGerald et al. (2010), Rappaport (2000), Yale et al. (2003)

Monetary valuation of lives lost		Lives lost	Negi et al. (2013)
Sediment production rate		Environmental impact	MacDonald and Coe (2008), Sosa-Pérez and MacDonald (2016)
Indirect intangible			
Statistical analysis		Social mobility	Adeagbo et al. (2016), Gordon et al. (1998), Kontou et al. (2016)
Accessibility index		Social mobility	Chang (2003), Deshmukh et al. (2011)
Criticality assessment		Social criticality	Oh et al. (2012)
Numerical analysis		Psychological	Morrice (2013), Wang et al. (2012)
Carbon footprint assessment	Life Cycle Carbon assessment	GHG impact of reconstruction	Mackie et al. (2014)
		GHG impact of re-routing	Winter et al. (2016)

Measurement of combined impacts

In this section, an analysis of the methods used to combine the different types of impacts is presented. The literature shows that there were numerous types of impacts identified and that most of the research focused on assessing only certain impact categories. The combined measurement of road failure impacts was considered important as it will help compare the various impacts on the community and economy in a post-disaster context.

The amalgamation of tangible impacts is considered to be straightforward as all types of impacts are measured in monetary values. However, it is evident that most scholars have not combined all tangible impacts to measure the total direct and indirect impacts of road failure. (Pfurtscheller and Genovese 2016a) measured the indirect tangible (business and transport) impacts and compared it against the direct impact in a Cost Benefit Analysis. They concluded that indirect impacts outweighed the direct impacts by a factor of 2. (Negi et al. 2013) found that indirect costs accounted for 92% of the total costs. In contrast, (Gordon et al. 1998) found that the indirect impacts were approximately only 25% of the direct impacts although they had not measured the transport-related impacts. Similarly, (Winter et al. 2016b) found that indirect costs were marginally lower than direct costs.

Research that amalgamates both tangible and intangible impacts has used a similar approach by converting intangible impacts to a monetary value. (Negi et al. 2013) accounted for the number of lives lost, by valuing each life based on the disaster relief payments for a deceased person. (Winter et al. 2016b) accounted for the cost of carbon emissions due to rerouting during the reconstruction phase. Both these studies showed that the social and environmental costs were negligible in comparison to the economic costs.

Valuing social and environmental impacts in monetary terms provides the opportunity to compare intangible impacts directly with tangible impacts. Such a method also allows for all impacts to be presented using a common measure. However, a major drawback of such valuation methods is that by assigning monetary values, environmental and social capital can be considered to be directly tradable with financial capital. For example, the monetary value given for one life lost by (Negi et al. 2013) was lower than the value of one damaged vehicle. Such a result can lead to the assumption that a vehicle is of more importance than a human life or more radically, that disaster impacts could be reduced by prioritising the minimisation of damage to vehicles rather than by saving human lives.

Discussion and future work

An analysis of the papers based on the year of publication shows that the methods used to assess impacts have not changed drastically within the last three decades. However, it can be seen that the use of software packages to carry out analysis has increased in recent times. Over the past decade, there has been an increase in the amount of literature focussing on the environmental impacts of disasters, whereas earlier research tended to focus mainly on the economic impacts.

The review demonstrates that the majority of research on post-disaster impacts focuses on earthquakes and floods, while research focusing on hurricanes, landslides and bushfires is sparse. The majority of the research has been conducted in the USA and focuses mainly on the impacts of earthquakes and hurricanes, while research conducted in European countries tends to focus on landslides and floods. A handful of research has been conducted in the Asia Pacific region, most of which focuses on earthquakes in Japan. Thus it can be understood that there is a gap in research focusing on bushfires and floods specifically from an Asia Pacific context. Future research could also focus on the sustainability impacts in developing countries, where very little research is available at present.

The review illustrates that a variety of methods have been used by scholars to measure the different types of impacts. However, no connection was found between the type of method used and the type of disaster analysed. The reason for this is that the economic, social and environmental impacts of road failure may not differ based on the type of disaster, although the severity of impacts may differ. The specific techniques and tools used by the researchers differ and tend to depend on the type of impact being assessed. Although researchers discuss the reliability and validity of the technique employed to collect and analyse data, no comparisons of results between studies using differing methods were identified. Future research could focus on such comparative studies, which would help both academics and practitioners in the field of disaster impact assessment.

Prior research has largely focused on the tangible impacts of a disaster. Researchers have adopted established economic and transport impact assessment techniques to assess such impacts. While such studies may help governments and aid organisations to better prepare for recovery programmes, it shows that comparatively less research has been conducted on measuring the environmental and indirect social impacts of a disaster. Research that assesses the social impacts of road failure tends to focus on the lives lost and typically measures and presents this separately from other types of impacts. It is also evident that there is a lack of research on the environmental impacts both direct and indirect. Research that has assessed indirect environmental impacts has focussed solely on calculating carbon emissions impacts, and it could be concluded that the assessment of wider environmental impacts could be beneficial in the future. Social and ecological vulnerability have been found to severely affect the resilience of disaster-affected communities (Adger et al. 2005) and thus highlights that future work to measure wider social and environmental impacts will add a lot of value to road structure decision making.

There are number of possible reasons why most research tends to measure only the tangible impacts, giving less focus to indirect social and environmental impacts of road failure.

- The intensity of a disaster is often perceived based on the size of the economic loss and the number of deaths caused by the event. Hence, measuring the economic impacts and the number of deaths may be given priority over other intangibles.

- The basic principles of economic loss assessment are very much agreed upon by academics. In contrast, there is debate on how to measure social and environmental impacts and if such impacts could be integrated with economic impacts. The main reason for this is that social and environmental impacts are generally considered external to an economic transaction. Hence, methodological and theoretical challenges may arise when trying to internalise such impacts.

- As all types of tangible impacts could be presented using one single measure i.e. monetary value, economic impact assessments are easily understood by the general public. This ease of understanding may have increased its usage in disaster damage assessment. This is in contrast to intangible impacts, which can have numerous different indicators and does not have a commonly accepted method of amalgamation. Therefore, intangible impacts are much harder to be combined and interpreted.

- Another finding of this review is that most research tends to focus on a narrow set of impact categories. This may be attributed to specific research interests of the scholars; objectives of the research proponent; and limitations in resources allocated for the project. This focus on specific impact categories has led to a gap in the research aimed at measuring the overall impacts of road failure.

Several scholars have investigated the divergence of reconstruction costs in ex-ante prediction studies against ex-post studies. However, no such assessments have been conducted on the indirect impacts after disasters. It can be presumed that the indirect impacts, like transport and business impacts, will change drastically in the event of a disaster. Such changes will be due to adaptation practices of communities and businesses. In this light, there is potential benefit from future research that will analyse differences in such indirect impacts predicted by ex-ante studies against impacts after a disaster takes place.

Assessment of the impacts in isolation has led to the belief that tangible impacts can be of more significance in contrast to other environmental and indirect social impacts. Future research must measure the total impacts of post disaster road failure, which includes a comprehensive set of social, environmental and economic parameters. A comprehensive assessment of impacts will provide the platform for academics and disaster management practitioners to understand which types of impacts will be the most significant and how the different impacts are interrelated. This will drive an understanding of how a reduction of one type of impact can affect other impact categories and how the total impact of a disaster could be minimised in the most efficient manner.

Much of the previous literature is cross-sectional in nature, covering a few significant disaster events, which tend to have drastically different characteristics. It is also evident that the literature is spread across several disciplines focusing on different types of impacts. This spread of research across disciplines has led to a lack of comparative analysis between research papers. However, the nature of such studies allow for a meta-analysis of a disaster event to be conducted. Researchers could review all work published on a specific disaster event, in order to combine the different types of impacts measured in those studies, in one meta-analysis.

In order to increase the accuracy of an overall impact assessment a few key points should be taken into consideration. Although different methods need to be used to calculate the different types of impacts, it is desirable to stick to one approach of measurement. All impacts need to be measured either using a top-down or bottom-up approach. This will not only lead to consistency throughout the study in terms of the basic methodology, but also increase comparability of the different types of impacts. Further, bottom-up, agent based approaches to modelling socio-economic impacts could be seen to be more relevant in disaster impact assessment as such models are adept at incorporating behavioural changes of people affected by a disaster. The use of bottom-up models could be said to be a better representation of the post-disaster socio-economic interactions, as behavioural changes are more likely to be less rational and optimal as opposed to the homogenous rational behaviour, which is a fundamental assumption in general equilibrium models.

A list of all potential impacts to be measured and the methods to assess each of them need to be agreed upon at the outset of the research. Such an approach will eliminate any double counting errors that may take place. For example, if the transport impact analysis includes some aspects of business impacts or social impacts, these should be excluded in the business impact and social impact assessments that will be carried out.

As most research projects have resource constraints, assessing all types of impacts may not be feasible. In such a situation, the study should focus on the most important aspects within a wide range of impact categories rather than only focusing on specific impact categories. Such an approach will lead to a more holistic outcome rather than a more accurate lower bound measurement with a narrow focus. A similar approach should be adopted when assessing a specific impact category where the focus should be on obtaining the most accurate data for the most important aspects. For example, researchers should strive to obtain more accurate and relevant data relating to rerouting and travel delay costs when assessing transport impacts, since these factors have been found to account for more than 90% of the total transport costs.

Conclusion

The aim of this paper was to analyse research conducted on the assessment of social, environmental and economic impacts of post-disaster road failure. The review demonstrates that research assessing post-disaster impacts of road structure failure covers a span of about three decades. The increase of such studies in recent years could be attributed to the increase in the occurrence of disasters during this time period. The review analysed the different methodologies used to assess various types of impacts and found that no common methodology has been adopted to measure a comprehensive set of social, environmental and economic impacts due to road failure in a post-disaster context. It is expected that future research could focus on a number of subject areas, especially assessing the indirect intangible impacts of disasters and disasters occurring in rural areas and developing nations. Measuring a comprehensive set of impact types due to road structure failure could assist in better decision making that would reduce the impact on disaster-affected communities and economies.

4.3 Context analysis for selection of methods

The analysis of the different methods to measure the diverse sustainability impacts showed that the selection would be highly dependent on the compatibility of the methods, so that a comprehensive integration was possible. The different methods were categorised into two broad groups based on the type of results that they provide. The results of one group of methods were model-dependent and abstract in nature, with the ability to interpret the results being based on the knowledge of the model itself. The other group of methods provided results in physical or monetary units, which were easier to interpret, even without in-depth knowledge of the model. Table 4-5 summarises these methods.

Table 4-5 Categorisation of methods based on model results

Impact category	Abstract results	Results in physical units
Direct tangible	Damage Index	Cost survey Cost modelling
Transport impacts	Topological transport network analysis	System-based transport network analysis Transport modelling
Business impacts	Input Output modelling	Cost survey General equilibrium models
Social impacts	Accessibility indices Social criticality	Statistical analysis
Environmental impacts		Life Cycle Assessment

Models that presented results using abstract parameters were less compatible with each other, while aggregating models that presented results in a less abstract manner were straight forward. As the objective of this research project was to measure a comprehensive set of impacts and to integrate them, it was vital to choose methods that were compatible and additive across categories. The representation of results in physical units also increased its ability to be converted to monetary values in the final integration stage.

However, the selection of the appropriate method could not simply be based on the compatibility of the methods. The review demonstrated that a comparison of the advantages and disadvantages of the existing models does not show that one specific model is better than all others. In addition to a comparison across methods, they needed to be analysed in relation to the scope of the project in order to select the most appropriate method. The main reason for this is the case-specific nature in the use of the models and because of the lack of standardised methods to report and compare results (Gaetani, Hoes and Hensen 2016). The advantages and disadvantages of each method that were identified were analysed and the most appropriate method for the project was identified based on its relevance and reliability to capture and represent the specific impacts. Sustainability impact assessment methods were also analysed at this stage to determine whether such tools could be used as is or modified for the purpose of the research. The different methods identified through the review were analysed in relation to the context of the given study in order to select the most appropriate method. The scope, sophistication and expected outputs of the framework played a vital role in the selection of the methods as explained in Section 6.2. The process of selecting the suitable methods was an iterative one, which helped in achieving the best outcomes for the project.

To improve the overall performance of the framework two aspects: model selection and model performance were evaluated. Model selection looks at the single best model while model combination builds a composite model by aggregating all available information (Xu and Golay 2008). For both these aspects model performance evaluation needed to be carried out. The complexity of a model can significantly affect its costs of development, ease of use, and the reliability of its output (Van Lienden and Lund 2004). The model selection framework proposed by Brooks and Tobias (1996) in their seminal work was used to analyse and select the most appropriate models to measure different impact categories. This framework has been used across many engineering disciplines in the last two decades to select appropriate models under complex environments (van der Zee 2019).

Different methods identified through the literature review were analysed based on four broad categories that need to be considered when selecting models. These four categories are: results of the model, future use of the model, verification and validation and resources required, which aids in the evaluation of the performance of models in a given context (Brooks and Tobias 1996). Specific criteria that helped in assessing the fitness of each model to the different categories were also used in order to assess the different models. The four categories and the relevant criteria for each category are explained in detail below.

Results of the model

Each method was assessed on the quality of the results it expected to generate. The quality of the results of each method depends on the accuracy and the extent to which they address the objectives of the study. This factor can be understood as the extent to which model results cover the experimental frame. This factor makes it harder for the assessment to be done until after the project has been completed, especially with regard to predictive models. The results also need to be understood easily to facilitate the wider use and acceptance of the method.

Future use of the model

This was an important factor to consider during the assessment of the methods as each method identified was to be brought together into the final framework. This meant that each selected method needed to be compatible with other selected methods, allowing them to be used in tandem. Models typically use either bottom-up or top-down approaches to generate results. It was important to select models that were all bottom-up or all top-down so that the different models could be combined without any overlap.

Verification and validation

The acceptance and implementation of the recommendations of the final framework developed to measure the SEE impacts would rely heavily on the different models that have been used within this framework. Therefore, the validity of these models was an important aspect to be considered. The model should not only generate the expected results but also needs to be realistic at the selection step. This category assesses how well a given method measured the real system comprehensively and the theoretical fit of the method, by assessing previous use of them in the literature.

Resources required

The time and cost constraints related to the project needed to be considered in selecting the most appropriate models. As no new model was developed from scratch, the resource requirement mainly focused on any modifications that were needed to be carried out on existing models and the data requirements involved. The time and cost of the resource requirements for each method was analysed.

The evaluation of the performance of a model should cover the impact of the model on all aspects of the project. The appropriateness of the models on the four categories identified earlier could be evaluated based on the various performance elements (Brooks and Tobias 1996). Out of 11 performance elements identified by Brooks and Tobias (1996), seven were chosen as applicable to the selection of methods for this research. These seven performance elements applicable to each of the four categories are:

Results of the model:

1. Does the model describe/predict the actual behaviour in adequate detail and scope?
2. Can the results be easily understood?

Future use of the model:

3. Is the method compatible (used in conjunction) with other methods?

Verification and validation

4. Does the method capture the actual behaviour of the system comprehensively?
5. Has the method been used in a similar context previously?

Resources required

6. The resource requirements to modify/apply the method (data requirements etc.).
7. Resource requirements to run and analyse the model (hardware and software, licensing etc.)

4.3.1 Ranking of the different methods

The different methods (and/or models) to measure a specific category of impact were then compared with each other. This was conducted by assigning a ranking to the models for the seven assessment criteria identified in the previous section. Such a process was adopted as it increased the transparency and replicability of the selection process. Given that the selection of the suitable method is very context-specific, a systematic semi-quantitative selection process added to the generalizability of the research.

The following tables show the rankings of each of the different methods that were given based on the quantitative analysis. The different methods that have been used in prior research were ranked according to the seven criteria. The different methods were compared against other methods that focused on measuring the same impacts. For example, the different methods that have been used to measure transport impacts were compared with each other and a ranking for each criterion was given to each method. Each of the methods was given a ranking, where a rank of 1 indicated that the respective method performed the best under a specific criterion in contrast to other methods. The rankings were based on the expected performance of the models against each of the seven performance elements identified earlier. A qualitative analysis is also presented explaining why a specific method was selected as the most suitable.

Direct tangible impacts

Table 4-6 Comparison of methods to measure direct tangible impacts

	Cost survey	Cost modelling
How well does the model describe/predict the actual behaviour in adequate detail and scope?	1	2
Can the results be easily understood?	1	2
How compatible is the method with other methods?	1	2
How well does it capture the actual behaviour of the system?	1	2
Has the method been used in a similar context previously?	2	1
The resource requirements to modify/apply the method.	2	1
Resource requirements to run and analyse the model.	2	1

Although cost survey was deemed to be a more reliable method to assess impacts, the high level of resources required to conduct a comprehensive cost survey was a major limiting factor. Given the immediate requirement of assessment in post-disaster context the cost modelling technique was considered as the most suitable method to assess the direct tangible impacts. However, the cost survey could be used much after the disaster event in order to obtain a more precise assessment or for the validation of the cost modelling technique that was carried out soon after an event.

Transport impacts

Table 4-7 Comparison of methods to measure transport related impacts

	Transport network analysis	Transport modelling
How well does the model describe/predict the actual behaviour in adequate detail and scope?	2	1
Can the results be easily understood?	2	1
How compatible is the method with other methods?	2	1
How well does it capture the actual behaviour of the system?	2	1
Has the method been used in a similar context previously?	2	1
The resource requirements to modify/apply the method.	2	1
Resource requirements to run and analyse the model.	1	2

The transport modelling was selected as the most appropriate method to assess the transport related impacts. This was mainly due to the compatibility with other methods and the ease of understanding the results of the model. The ease of understanding the results was an issue that was highlighted in the needs assessment interviews that were carried out.

Business impacts

Table 4-8 Comparison of methods to measure business related impacts

	Cost survey	I-O Analysis	CGE Modelling
How well does the model describe / predict the actual behaviour in adequate detail and scope?	1	2	3
Can the results be easily understood?	1	3	2
How compatible is the method with other methods?	1	2	3
How well does it capture the actual behaviour of the system?	1	2	3
Has the method been used in a similar context previously?	1	2	3
The resource requirements to modify / apply the method.	1	2	3
Resource requirements to run and analyse the model.	3	2	1

The cost survey method was identified as the most suitable to assess the impacts to businesses due to road infrastructure failure given the geographical focus of the project and the level of complexity of industries in the case study region. However, a major challenge with this method was the extra time and resources needed to conduct a cost survey soon after a disaster event. This challenge was overcome by modifying the cost survey to more of a cost modelling technique, which was similar to the method used to assess the direct tangible impacts. This method uses an approximation and probability values to estimate the level of impact to businesses in the region given the lack of connectivity and is termed as revenue loss estimates (Chang 2003a).

Social and environmental impacts

The socio-ecological impacts could be assessed through socio-environmental assessments after the event. Such methods are social surveys and post-event environmental footprint/impact assessments. However, since conducting such assessments is time and resource intensive, it may not be practical to conduct them soon after a disaster. The social impacts resulting from the damage to road structures are mainly accessibility and mobility related impacts. Such impacts could be measured through transport modelling techniques.

The major environmental impacts resulting from the un-usability of roads would be the extra emissions due to longer detours and the extra environmental impacts due to repair and reconstruction of the damaged bridges. The environmental impacts due to detours could be assessed using environmental economic principles, coupled with the transport modelling techniques. The environmental impacts of reconstruction could be estimated using streamlined Life Cycle Assessments. These methods overcome the challenge of the resource intensive methods that are traditionally used in environmental assessments and are better suited in rapid post-disaster impact assessments.

4.3.2 Selection of the appropriate methods

Table 4-9 summarises the selected methods to capture the different impact categories. The selection of a method as the most suitable, was based on the quantitative ranking and the qualitative assessment of appropriateness of the methods. The quantitative ranking was based on four categories, where each method was evaluated against seven performance elements. The qualitative analysis focused on the practicality of the use of the methods to measure the respective impacts in a post-disaster context. The availability of data, ease of collection in a post-disaster time period, the ability for practitioners to use such methods for decision making were all assessed within the qualitative analysis stage.

The selection of the specific methods that were to be used for the research project led to the identification of the data requirements. The identification of resource requirements in the earlier stage helped to identify the exact data requirements for each selected model. The required data was categorised according to the different impact categories. The list of the data types and the possible sources for this data was also identified during this stage and is presented in Chapter 7.

Table 4-9 Selected methods that best capture different impact categories

Impact category	Type of impact	Suitable method
Direct tangible	Cost of damage, clean-up cost	Cost modelling
Indirect tangible	Transport impacts	Transport modelling
Indirect tangible	Business impacts	Revenue disruption estimates
Direct intangible	Life loss	Survey
Direct intangible	Environmental damage	Rapid Environmental Assessment

Indirect intangible	Community accessibility	Transport modelling
Indirect intangible	Environmental impacts of detour	Transport modelling + environmental valuation
Indirect intangible	Environmental impacts of reconstruction	Streamlined Life Cycle Assessment

4.3.3 Analysis of integration techniques

An important component of measuring the social, environmental and economic impacts of a disaster is to integrate these three dimensions to one common platform. Such integration helps decision makers to compare the different types of impacts against each other and help in ranking different options based on a common score. These approaches are referred to as integrated assessment as they look to incorporate social, environmental and economic aspects, reflecting a triple bottom line (TBL) approach to sustainability (Pope et al. 2004).

Integrated assessment endeavours to combine categories of impacts, which cannot be aggregated in a straight-forward manner, by assigning weights to the different categories. The weighted categories are comparable with each other and could also be aggregated to obtain a total score. The different methods adopted to assign weights to the categories could be divided into three broad groups based on the fundamental principles adopted; monetary valuation, expert judgement and distance-to-target approaches (Balkema, Weijers and Lambert 1998). These three methods are analysed in the following section in order to select the most appropriate weighting and aggregation method for the developed framework.

Monetary valuation

Monetary valuation is related to the economic concept of externalities. Externalities are impacts to a third party stemming from an economic transaction, which is not accounted for by the agents involved in the transaction. Such instances lead to market failure and could be corrected by internalising the externality. Monetary valuation helps in the quantification of such externalities and is thus considered a vital aspect in welfare economics. Monetary valuation aids in decision-making and is a common practice in CBA of public projects where not only financial but wider economic, environmental and social impacts need to be considered (Pizzol et al. 2015). Monetary valuation of intangible impacts helps them to be compared against each other and other financial impacts that are typically represented in monetary units.

The interviews with authorities involved in reconstruction exemplified that only the financial cost of reconstruction is considered during post-disaster decision making. The need to internalise external costs stemming from SEE impacts for decision making processes was considered to be vital. If such impacts are not included in disaster cost assessment, it could lead to an incomplete and biased cost assessment (Markantonis et al. 2012). The advantages of monetary valuation for integration of impacts are manifold. An important advantage is that monetary valuation can be easily understood and interpreted by practitioners with different backgrounds. In addition, monetary valuation is extensively used in CBA of new infrastructure projects and hence the uptake of such a method would be much higher across infrastructure and governmental authorities. The monetary valuation of these impacts would provide an opportunity for decision makers to incorporate the wider sustainability related impacts together with the financial costs that are currently being considered for funding proposals and prioritisation of reconstruction projects.

A limitation of monetary valuation is that all socio-ecological impacts cannot be expressed in monetary terms, and even when quantified in this way may not accurately represent the intrinsic value of that impact. However, the objective of monetary valuation is not to provide an absolute cost of social and environmental capital, which is intrinsically invaluable, but to assign weights to different categories based on monetary preferences. For example, monetary valuation does not seek to provide a measure of the absolute value of human life, but rather the value that individuals are willing to pay for a small change in life expectancy or life quality (Pizzol et al. 2015).

Valuing impacts in monetary terms does not consider the equity impacts of decisions of how the benefits and costs are distributed across a population. By using broad-based monetary units to value all benefits and costs, equal weighting is given to all individuals across a population. However, this may not be realistic as some groups like the elderly and sick will be inherently impacted by a greater degree after a disaster. In addition, the costs and benefits may not be distributed fairly across the society, and generally the group that bears the benefit will not be the same as the group that bears the costs (Allenby and Rajan 2012).

Preferences between goods and services that have a tradable market are easy to obtain through the market price of that good. The market price shows how much people are willing to pay for that good at the current level of supply, and higher prices may indicate a higher valuation for a good. Market conditions can be simulated or values of related goods can be used to deduce the willingness to pay for a good that is not sold in a market (Ahlroth 2014). These monetary values estimate the willingness to pay for marginal changes in the availability of an intangible good either through revealed preferences or stated preferences of individuals.

The objective of monetary valuation is not to try and assign a price to social and environmental capital but only to assess the preferences given to different types of impact categories which are presented in dollar terms, which helps in decision making and funding processes. This understanding also clarifies a common misconception about monetary valuation where environmental and social capital can be considered to be directly tradable with financial capital. Another limitation of monetary valuation is the availability of relevant monetary values to be used in the decision making framework. As exact monetary values relevant to the geographical region and the time period may not be readily available, suitable values from different spatial and temporal contexts would need to be substituted.

Expert judgement

Expert judgement methods or Multiple Criteria Decision Analysis (MCDA) is an umbrella term used to describe a collection of formal approaches, which seek to take explicit account of multiple criteria to help make decisions in an objective manner (Belton and Stewart 2002). This method allows weightings to be assigned to the different types of impacts based on the opinions of experts in the field or the users of the framework. Different weightings are used to compare and contrast the effect the weighting process has on the final outcome. This is similar to monetary valuation methods which estimate willingness to pay, with the difference that monetary values are not included in the parameters (Ahlroth 2014). Although most MCDA approaches are based on the same fundamentals where values for alternatives are assigned for a number of dimensions, and then multiplied by weights in order to arrive at a total score, the approaches differ on how the values are assigned and aggregated (Huang, Keisler and Linkov 2011).

Multi-Attribute Utility Theory (MAUT) is an approach that assigns utility values to the different dimensions, based on preferences of decision makers, and then looks to optimise the total utility function to arrive at the best decision. MAUT facilitates rational choices and will be applicable in a scenario with one decision maker who is able to clearly express preferences over outcomes and clear trade-offs for specific levels of achievement across dimensions (Huang et al. 2011). This benefit in itself would be a disadvantage in that the ultimate outcome will be subjective and include preference bias of the decision maker.

The Analytic Hierarchy Process (AHP) uses pair-wise comparisons of criteria in order to rank the criteria based on personal judgments of the importance of one criteria over another, which makes it possible to compare both quantitative and qualitative data together (Saaty 1990). AHP is a good tool to be used when there are a high number of alternatives and multiple decision makers, although the value judgments used in the model can render it to be subjective.

Outranking is a MCDA method typically used to compare alternative options by assigning preference scores for the different dimensions of options. A range of possible scores for the different options is considered for each dimension, to develop preference functions across dimensions. An options score within a dimension will show how it compares against the other options (Murat, Kazan and Coskun 2015). Outranking is an approach that can be used for comparability of options hence does not necessarily identify the best options.

MCDA approaches are suitable for the aggregation and weighting of impacts in a specific case where it is important to consider expert or stakeholder preferences. As the results of an MCDA analysis will depend on the value judgements of the experts interviewed, the generalizability of the results will be low. This is critical in cases where the significance of the different impacts could vary based on geographical location. In such situations, opinions would need to be considered from a broad range of experts in order to come up with a more generalizable set of values. Another approach to overcome this challenge would be to conduct different MCDA value judgement interviews for each different area where the framework would be adopted.

Another obstacle in MCDA is that the method does not consider public opinion on the significance of the different aspects. As MCDA relies on “experts”, the values and preferences of the non-expert public, who may be the most affected by decisions made by the experts, are overlooked. With relation to this project, the importance of community involvement was also highlighted in the initial needs assessment interviews carried out during this research project. As such it is important to consider public preferences and values when assessing and valuing impacts.

Distance to target approaches

Another weighting method that could be used is the distance-to-target method where weights to different impact categories are given based on the current level of each impact and a target level. This method utilises a strict rule-based ethic, which is in contrast to monetary valuation and MCDA approaches (Pizzol et al. 2015). Distance-to-target relies on pre-defined optimal targets that are set for all indicators or impact categories. These targets could be policy targets, impact reduction targets or sustainability targets that are set by external authorities or for comparison of different alternatives against a pre-defined base case.

Distance-to-target approaches are widely used in environmental impact assessment where commonly accepted environmental targets are available. Carbon emissions targets, pollution reduction targets and reforestation targets are examples of such targets that can be used. The UNDP Sustainable Development Goals can also be used in sustainable development related projects. However, since the aim of this PhD research is to measure disaster related impacts, the distance-to-target approaches were not considered as a suitable method for integration.

4.3.4 Selection of appropriate integration approach

A summary of the integration approaches that were analysed are presented in the table below. A semi-quantitative and qualitative approach was adopted to select the most suitable method for integration of the different impact categories. The quantitative aspect was similar to that adopted to select the measurement methods as explained in section 4.3.1.

Table 4-10 Ranking of different integration methods

	Monetary valuation	Expert judgement	Distance to target
How well does the model describe/predict the actual behaviour in adequate detail and scope?	N/A	N/A	N/A
Can the results be easily understood?	1	2	3
How compatible is the method with other methods?	1	2	3
How well does it capture the actual behaviour of the system?	N/A	N/A	N/A
Has the method been used in a similar context previously?	1	2	3
The resource requirements to modify/apply the method.	1	2	3
Resource requirements to run and analyse the model.	2	1	3

The distance-to-target and monetary valuation is based on existing value judgements, while MCDA approaches rely on value judgements, which are case specific. The weightings used in the different approaches vary based on whose values are considered. Weightings in MCDA and distance-to-target rely on preferences of individuals (panels of experts, stakeholders or policy makers), while monetary valuation relies on preferences given to different impact categories by a wider group of potential stakeholders (Pizzol et al. 2015).

The most suitable approach to aggregate the impacts was selected after analysing the three different approaches explained above. This selection was based on the data obtained through the needs assessment interviews, context analysis of the different methods and the suitability of them to the context and scope of the project. As explained previously in this chapter, interviews showed that the assessment of the social, environmental and economic impacts in a post-disaster context should be carried out to so that value for money or cost – benefit of different options could be assessed and used in funding and risk assessment activities. The most suitable aggregation approach in this case was deemed to be monetary valuation.

The benefit of monetary valuation is that it is generally easy to understand for practitioners in different fields and with diverse technical knowledge, and it avoids abstract concepts that can be confusing to a layperson. The weights assigned through expert judgment are harder to be aggregated and even when carried out, could result in an abstract outcome, which will be challenging to be used in funding and budgetary level decision making processes. Further to this, quantification of impacts is understood more clearly when presented in monetary terms rather than very abstract concepts and hence the monetary valuation of impacts would be more widely incorporated in real-world situations. On a global scale, the monetary valuation of non-market goods and services has increased in damage assessments with the idea that such valuation methods could expand the potential to measure, value and restore all the impacts to the environment and society (National Research Council 2012).

Interdependencies among impact categories

One of the major objectives of this research was to understand how damage to bridges affects the sustainability and resilience of systems. To this end the framework aimed at integrating a comprehensive set of social, environmental and economic impacts in order to analyse how they influence overall sustainability and resilience of communities. However, one significant limitation with adopting a simple integration technique was that interdependencies across the various impact categories were overlooked. Understanding the interdependencies between subsystems and how such interdependencies affect the resiliency and sustainability of the entire system was out of scope for this PhD. As such, this research focused on the integration of a comprehensive set of sustainability impacts as a first step towards quantifying and aiding in post-disaster infrastructure decision making.

4.4 Summary

This chapter explains the analysis that was carried out of the different measurement and integration methods relevant to the research project. A review paper published during the candidature is presented in the first section of this chapter and summarises the methodological review that was carried out. The review showed that no one method is intrinsically advantageous over all others and that the selection of a method would depend on the context and objectives of the research project.

The selection of the specific methods that have been used by scholars to measure the different disaster impacts and to integrate them together to a common platform is discussed in the second half of this chapter. The selection was conducted by assessing the suitability of the methods against seven elements and by using a quantitative scoring mechanism. Such a method reduced the subjectivity of the selection process and could be used in future to select the most appropriate models for research projects. Monetary valuation was selected as the most appropriate integration method. This selection was based on the assessment of benefits and challenges of different methods and the results of the interviews carried out with practitioners and stakeholders in the post-disaster reconstruction processes.

5. END-USER NEEDS ASSESSMENT AND INTERVIEWS

5.1 Introduction

This chapter presents the results of interviews carried out as part of the research project. A needs assessment was identified to be a vital aspect of this research project as the final outcomes of the project were expected to include both academic and practical industry contributions. Although the initial requirement for the research had been identified by the BNHCRC, a more in-depth needs assessment was required for the purpose of the PhD research. The needs assessment was carried out by interviewing decision makers involved in the post-disaster reconstruction of road infrastructure in disaster prone regions in Australia. The interviews were carried out to understand how the post-disaster reconstruction decision making takes place in practice and to understand the requirements of practitioners so that a practical framework and toolkit could be developed to aid decision making. Incorporating end-user requirements to a theoretically sound framework was important as it would increase the acceptance of the framework and toolkit by practitioners. The interviews helped in achieving two research objectives pursued during this project: to develop a conceptual framework that can measure sustainability impacts of road structure failure and to develop a toolkit based on the framework that can aid in effective decision making. The interviews helped to increase the practicability of the research outcomes of the PhD.

This chapter is divided in to three parts, with the first two parts being research papers that were outcomes of the interviews. The first section is a conference paper presenting the results of interviews with decision makers in Queensland, which explains how decision making on post-disaster reconstruction takes place and the stakeholders' views on where and why improvements are required (Gajanayake et al. 2019). The next section is a journal paper based on a wider group of interviews, with a cross-case comparison of decision making processes in Queensland and Victoria. This paper explains the interrelationships between different factors influencing decision makers and identifies how a streamlined holistic approach to assessment of impacts can improve reconstruction outcomes. A cross-case comparison also increased the generalizability of the research outcomes to a broader range of practitioners and geographical regions. The final section of this chapter summarises the two research papers and describes the implications of the interviews on the development of the framework and tool.

5.2 Post-disaster decision making in road infrastructure recovery projects: an interview study with practitioners in Queensland

Gajanayake, A., Khan, T. and Zhang, G. (2019), *'Post-Disaster Decision Making in Road Infrastructure Recovery Projects–An Interview Study with Practitioners in Queensland'*, paper presented to Australian & New Zealand Disaster & Emergency Management Conference, Gold Coast, Queensland, Australia, 12 – 13 June 2019.

Abstract

The repair and reconstruction of road infrastructure plays a vital role in the recovery process after a disaster event and will be affected by the decision-making processes adopted by asset owners. The objective of this study is to understand how road asset owners assess and prioritise road reconstruction projects in order to identify how decision making could be improved in real-life post-disaster scenarios. This paper presents results of in-depth interviews with road infrastructure practitioners in Queensland, on decision making in a post-disaster context, using a case study based approach. A number of challenges were identified including the lack of a common decision making platform, the lack of focus on the socio-ecological impacts during decision making and the importance of community engagement during the reconstruction process.

Introduction

With the occurrence of natural disasters increasing in recent times the exposure and vulnerability of major infrastructure to such events has increased. The vulnerability of road infrastructure increases with the rise in the number and intensity of hydro-meteorological disasters. With multiple disasters occurring in the same area the importance of good decision making in repairing and reconstructing damaged assets becomes evident. Floods and storms are the most common type of disasters in Australia (Guha-Sapir et al. 2016) and the State of Queensland is one of the most vulnerable states to such events (Coates 1999).

Road structures play an important role in the recovery of disaster hit communities as it provides the means of access, which is vital in a post-disaster context. The rescue, recovery and reconstruction efforts will rely heavily on the accessibility to the disaster-zone and with the lack of serviceable roads and bridges, such efforts could be hindered (Gajanayake et al. 2018). It is thus evident that the reconstruction of road infrastructure after a disaster event is vital, so as to minimise the follow on impacts it may cause to the community and the economy.

The purpose of this paper is to examine how decision making with regard to post-disaster reconstruction of road infrastructure is carried out in a disaster-prone region in Queensland, Australia. The paper presents the factors influencing decision making and the methods and techniques used by practitioners in prioritising reconstruction projects based on information gathered through a series of semi-structured interviews.

Factors influencing road reconstruction decision making

The effectiveness of post-disaster reconstruction will depend on numerous factors while the availability of resources after an event is a major factor affecting the reconstruction processes (Chang et al. 2012). Other factors that influence the reconstruction activities are the influence of funding agencies on the decision making and prioritisation processes and the coordination between funding agencies, road authorities, central and local governments (Le Masurier et al. 2006).

(Lyons 2009) explains that post-disaster decision making is heavily influenced by economic and political actors, with less influence from grass root level. Therefore, reconstruction activities especially in rural areas tend to be centrally planned and managed with heavy influence from large actors and little focus on tapping into local knowledge (Peng et al. 2013). A disaster may lead to insufficient local capacity required for the rebuilding process and hence there can be potential for larger scale organisations to fill these local gaps (Haigh and Sutton 2012).

Post-disaster reconstruction activities are generally carried out based on disaster management and recovery plans, which have been specifically designed for this purpose. The lack of a clear disaster management plan has been found to delay the reconstruction activities due to lack of clarity in who needs to take responsibility (Pathirage et al. 2012) and unclear lines of authority (Lin Moe and Pathranarakul 2006). However, most regions or countries only develop such plans as a reactionary effort after a major disaster event and is specifically the case with areas which are not prone to major disasters (Palliyaguru and Amaratunga 2008). In addition to well-prepared disaster management plans and funding strategies a comprehensive method to prioritisation can improve reconstruction processes. Such prioritisation frameworks integrate technical factors of specific infrastructure and societal influences allowing for individual and system level assessment of structures (Liu, Scheepbouwer and Giovinazzi 2016).

Research methodology

The aim of the present study is to gain in-depth knowledge on how practitioners assess impacts and prioritise reconstruction projects in resource constrained post-disaster situations. Given the exploratory nature of the study, a qualitative approach was adopted, involving a thematic analysis of interviews carried out with practitioners in Queensland, Australia. Ethics approval for the research was obtained from the RMIT University Human Research Ethics Committee (SEHAPP 75-17).

Interview design

A semi structured interview technique was identified as most suitable for the purpose of the study. The questions were designed with a clear theme and fairly limited focus, but within the frame the questions were open ended in terms of structure. Particular themes were chosen for more rich description, focussed exploration and deeper understanding (Alvesson 2010).

Typically the responsibility of maintaining regional roads fall under the local authority or the regional roads authority, while funding for post-disaster reconstruction is facilitated by the reconstruction agency. A total of ten interviewees (Table 5-1) from these organisations were identified through previous research work carried out by the authors and were contacted directly by the research team.

Table 5-1 Respondents for the interviews

Organisation	Division	Number of respondents
Regional Council in Queensland	Infrastructure Works and Services	1
	Disaster Management	2
	Environment and Pest Management	1
	Economic Development	1
	Community Development and Engagement	2
Queensland Government	Engagement and Technical Services, Operations	1
	Program Delivery and Operations	2

The interview questions and a Participant Information Sheet were emailed to the respondents a week prior to the interview. The interviews were typically 30-60 minutes in length and were conducted face-to-face at a meeting room at the interviewee's office. The interviews were carried out during 2018 as one-off interviews, although the research team reached out to some interviewees afterwards to clarify issues.

Data analysis

The interviews were transcribed by the interviewer himself so that any emotional overtones and nuances captured in the interviews were not lost in the transcripts. The interviewer doing his own transcribing also helps in building familiarity with the data, which is useful for the analysis (Bazeley and Jackson 2013). The interviews were transcribed verbatim, which increased objectivity during the analysis by avoiding the researcher to be guided heavily by pre-existing ideas or jumping to conclusions without carefully having looked at and interpreting the interview material (Alvesson 2010).

The transcripts and notes were coded in order to capture the essence of the interviews. The in-vivo coding method, where coding words are selected from a phrase or word from the transcript itself, was used for generating the codes (Miles, Huberman and Saldana 2013). This method ensures that concepts do not diverge from what was described by the respondents and also prioritises and honours the participant's voice. An inductive coding approach was used to create the specific codes, where codes are determined progressively during data collection and analysis (Miles et al. 2013) while pre-determined codes were avoided so as to reduce interviewer bias in the coding process. The coding was used to generate pattern codes, which were used to form themes emanating from the interviews.

Results

The results obtained are presented in this section under five major themes, which eases understanding and the flow of ideas generated through the study. Some sections also include quotes taken from the interview transcripts. These quotes have been presented in order to draw attention to specific important ideas that were mentioned in the interviews.

The importance of social factors

A majority of the interviewees mentioned that social impacts were the most critical type of impact ahead of economic and environmental impacts and they considered it important to minimise such impacts. The idea that road infrastructure facilitates the smooth functioning of the community was echoed by most interviewees regardless of their professional background or department they represented.

"A bridge is not just a bridge, but a whole bunch of other implications [are associated with it]."

The objectives and deliverables of most of the departments and organisations interviewed were linked to social factors. This was especially evident with those interviewed from the Council. However, as no official documents were analysed by the authors as part of the study, it is not evident whether such social factors were highlighted purely due to the focus of the interview. It was observed that each department had aligned social factors with their departmental objectives in diverse manners. For example, infrastructure departments mentioned that the purpose of road infrastructure was to ease community impacts, while the environment division mentioned that the protection and enhancement of the natural environment was ultimately for the social wellbeing of the community.

A diverse set of impacts were identified by different interviewees as the most important type of social impact such as human health issues, access to facilities, inconvenience to communities and traffic related impacts. A very common social impact that was highlighted was that of isolation of people or households due to damaged roads. Isolation of communities was highlighted especially by interviewees working in more rural environments in contrast to those focusing on more urban settings. One interviewee from a regional council mentioned that isolation is one of the most critical factors that needs to be considered but is something that is overlooked by practitioners who work in urban areas.

"The more you think about it, everything affects the human social side of it".

Although social impacts were stated as the most important category, it was noted that methods to assess social impacts were lacking. The lack of such methods was seen in council and even in State decision making processes. It was agreed by the interviewees that a commonly accepted method to assess social impacts would be beneficial for infrastructure related decision making. It was also pointed out that although the measurement of social impacts were important, care should be taken to decide on the methods used to assess them and how the outcomes are interpreted by the decision makers.

Lack of focus on environmental impacts

The interviews highlighted that environmental impacts were the least analysed impact category. The reason for this was seen to be that social and economic impacts were considered to be more critical resulting in a lack of focus on the assessment of environmental impacts. A direct link between the natural environment and the socio-economic impacts were recognised by interviewees from the community and environment divisions, whereas reference to such links was not identified by engineers.

The environment, economic and community divisions within the council saw that the natural environment affects the socio-economic impacts of residents while the disaster management division was focussed more on how environmental factors influence vulnerability to natural hazards. There was seen to be an increase in the involvement of environmental practitioners in disaster management work within Councils and this could be attributed to the heightened awareness of the links between the natural environment and the socio-economic aspects.

"A lot of the environmental issues are actually at the root of social and economic issues as well."

The most important environmental impacts that could occur during the reconstruction process were identified as soil erosion, effects on water quality and sediment run-off. This was in contrast to other studies where the focus of environmental impacts was resource usage and greenhouse gas emissions during to the reconstruction phase (Padgett and Tapia 2013, Schweikert et al. 2018). Interestingly resource usage and greenhouse gas emissions were not highlighted by a single interviewee. The reason for this could be that the interviews were focused in a regional disaster-prone area, where a link between the natural environment and disasters are directly observable and take precedence over global environmental issues.

"Because an infrastructure solution may have a negative environmental [impact]… we need to talk together… [to] try and get a more holistic outcome with decision making."

The interviews exemplified that there were diverse opinions in thought on the best way to approach reconstruction in order to increase resilience. One group viewed the solutions from an engineering stance while others opined that purely technical solutions without socio-ecological considerations may aggravate the consequences due to the interdependence of infrastructure and the natural environment.

Post-disaster decision making processes

The interviews exemplified that there was no systematic method used to assess wider impacts of road infrastructure failure and to prioritise the reconstruction of assets. The only systematic processes that were utilised in post-disaster decision making were those used to estimate the reconstruction costs, which were stipulated by funding agencies. Such funding proposals tend to focus on the financial cost of reconstruction with minimal consideration given to wider socio-economic and environmental impacts.

Although wider impacts had not been assessed methodically, such impacts were not completely abandoned during decision making. Most decisions were made on "gut-feel" and the possible socio-economic impacts were considered based tacit knowledge of practitioners in past experiences and the intimate knowledge of the locality. It was highlighted that in a rural setting local knowledge may play a far more important role in identifying social impacts rather than a set system or method.

The interviewees did not seem to think that the decisions that were made in this manner could be completely flawed, but saw the need for a framework that could validate the current decision making processes. It was also highlighted that such a method could be used for numerous purposes including, as an evidence base for funding proposals, prioritisation of projects and the comparison of alternative reconstruction methods. Such ideas were seen across all organisations with the idea that a common tool, which can be used across different organisations, would be beneficial in State level disaster management.

"It's just really gut feel…. So we'll do it in our heads but if we were questioned later on, we have no record of how we made that decision."

Political aspect

Some interviewees were of the opinion that political aspects can influence post-disaster decision making and prioritisation. It was mentioned that there may be encouragement given to concentrate on specific areas during the reconstruction processes, purely from a political perspective. In instances where a follow up question was asked, there was hesitance to explain further stating "you know what I mean".

"In the real world sometimes it gets political, noisy wheels get the oil."

However, one interviewee stated that political factors actually may highlight other underlying socio-economic factors that may not have been identified, especially from State authorities. For example a bridge located close to a specific business entity may get political consideration, and it may well be that the business was a large contributor to the local economy, which was not immediately highlighted to state authorities.

Community engagement

Another aspect that came up in the interviews is the importance of community engagement during the recovery and reconstruction stages. It was highlighted that the residents were not too pleased with the way that the reconstruction took place and this increased the level of frustration among the community. It was pointed out that clarity and openness of communications would give the residents some peace of mind although it wouldn't necessarily speed up the recovery process.

"People say bloody Council haven't fixed that bridge yet. But they don't understand the NDRRA process and how complex that can be and time consuming."

The introduction of regulations that limit individual recovery actions could also exacerbate such frustration among the community. With limitations to clearing of debris in streams, clearing roads and using farm vehicles for transportation the community had to solely rely on the Council and State authorities to facilitate their recovery process. Some respondents were of the view that legislating such community recovery actions had an unintended consequence of reducing the resilience and adaptability of communities.

Interviewees commented that there were times when disagreements between communities and engineers involved in reconstruction work have ensued. Such disagreements mainly arose when experts who did not possess the necessary local knowledge were brought in and they were resistant to listen to the local farmers. Many interviewees were of the opinion that the residents had the local knowledge of the creeks and the geography and that such knowledge needed to be tapped into during the recovery process.

"But the farmers weren't saying this is how you build a bridge. They were saying, this is where we need a bridge and this is the order that we need them."

Discussion and conclusion

These interviews have shown that there are two schools of thought among practitioners on the most appropriate methods of disaster reconstruction: one being technical engineering solutions and the other by giving more consideration to socio-ecological issues. These two schools of thought can be categorized as engineering solutions and ecological solutions respectively (Raab 2017).

The results indicate that post-disaster decision making in the region studied is conducted utilising practitioners' tacit knowledge on the locality and past experiences. Such methods can be advantageous especially in more regional areas where standardized state level disaster recovery plans may not be appropriate. Further it was understood that the adoption of state level regulations intended to protect people can have unintended consequences that decrease resilience and recovery of communities in more rural regions. State level authorities can look at methods where recovery guidelines could be modified by local authorities to better suit the specific regions, which may increase the resilience of the communities.

Another finding is that more effort needs to be taken to engage with the community so as to bridge the gap between the people and the authorities. Interestingly it was found that community engagement was carried out during housing reconstruction in the same region (Okada et al. 2014) but not during the reconstruction of infrastructure. One reason for this may be that housing reconstruction is considered a societal issue while road reconstruction may be more an engineering problem. Distrust felt by the people towards authorities have been identified in post-disaster reconstruction efforts (Shaw and Goda 2004) while community acceptability of projects is perceived to be very important by decision makers in the public sector (Vu et al. 2018) indicating the importance of effective community engagement practices during reconstruction.

State level authorities could also look at how the soft sciences could be incorporated into the decision making process improving on the current processes which are predominantly engineering focussed. Such methods could help the organisations retain the tacit knowledge of the practitioners, which will ease decision making in the future, while increase community acceptability of reconstruction projects (Thanurjan, Indunil and Seneviratne 2009).

The present study set out to understand the decision making processes in road reconstruction activities in a disaster-prone area in regional Queensland. A number of challenges were identified including the lack of a common decision making platform that could be used across different agencies, the lack of focus on the socio-ecological impacts during decision making and the importance of community engagement during the reconstruction process.

5.3 Post-disaster reconstruction of road infrastructure: Decision making processes in an Australian context

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Abstract

The rehabilitation and reconstruction of damaged road infrastructure plays a vital role in the recovery of disaster affected regions. The methods and processes adopted by road asset owners during the reconstruction phase influences the longer term effects in disaster hit communities. While the decision making processes are intended to reduce impacts, mistakes at the decision making stage can lead to an increase in social and economic impacts in the longer term. It is thus imperative to understand how decision making takes place with regard to post-disaster reconstruction of road infrastructure. The objective of this paper is to understand how road asset owners assess and prioritise post-disaster reconstruction projects in order to identify how decision making could be improved in Australia and similar regions. The results of in-depth interviews conducted with road infrastructure practitioners in disaster affected regions are presented. The findings show that there is gap between the research community and

practitioners in the use of systematic methods to aid prioritisation and decision making. The interviews also showed that the consideration of only a limited set of engineering and financial elements can lead to unintended consequences that impede resilience. A causal loop diagram was developed to illustrate the interrelationship between factors identified and shows the importance of a systems thinking approach to infrastructure related decision making. These findings suggest that the development of more localised decision making tools can increase their adoption among practitioners.

Introduction

With increased climate change scenarios and higher population densities across the globe the adverse socio-economic effects of natural disasters have increased dramatically in recent years. Hydrological disasters such as floods and landslides account for the largest share of natural disaster occurrences globally since 2006 and the largest proportion of life loss and economic losses due to natural events (Guha-Sapir et al. 2016). Road structures such as bridges, culverts and flood-ways are designed to cross water-ways and can be severely damaged due to floods. The damage to such critical structures can render large portions of the road network inaccessible and cause knock-on effects. The humanitarian rescue and response efforts soon after a disaster rely heavily on the accessibility in and out of the disaster zone and these efforts could be hindered due to damaged road sections. In the longer term, damaged road infrastructure could exacerbate the socio-economic impacts of the disaster and can affect a wider spatial scale. It has been found that better connected areas tend to recover faster in contrast to areas which are less connected (Zhu et al. 2018). It is thus evident that Post-Disaster Reconstruction (PDR) of road infrastructure is a key aspect influencing the recovery of a community affected by a natural disaster.

Post-disaster reconstruction processes of road infrastructure typically differ from routine rehabilitation or new infrastructure projects given the expedited nature of reconstruction required (Le Masurier et al. 2006). PDR processes have been studied by several scholars and it has been found that the availability of resources after a disaster event can be a major influencing factor (Chang et al. 2012). Other factors that influence PDR are legislation (Rotimi et al. 2009), coordination between government agencies (Le Masurier et al. 2006) and stakeholder engagement processes adopted (Crawford et al. 2013).

PDR activities are generally carried out based on disaster management and recovery plans, which are specifically designed for this purpose. The lack of a clear disaster management plan can delay the reconstruction activities due to lack of clarity in responsibility and authority (Pathirage et al. 2012, Lin Moe and Pathranarakul 2006). However, it has been found that most regions or countries develop such plans as a reactionary effort after a major disaster event (Palliyaguru and Amaratunga 2008).

Even though road networks are considered to be essential public assets, its rehabilitation and reconstruction after a disaster can be delayed due to resource constraints. Financial constraints impact maintenance and replacement of transport infrastructure and have a major influence on how fast a damaged road structure could be brought back to pre-disaster service levels (Vanelslander, Roumboutsos and Pantelias 2018). Such constraints could be exacerbated in the event that a number of road structures are damaged or if back-to-back disasters occur in the same area. Under such circumstances the decisions made by the relevant authorities on how to allocate resources for reconstruction and to prioritise specific structures, will affect the recovery of the disaster affected region.

Researchers have proposed several different methods to overcome challenges faced during the PDR stage. The different methods that have been proposed could be categorised as; 1) Policy and legislation 2) Prioritisation and optimisation. Policy and legislation focuses on developing well prepared disaster recovery procedures that need to be implemented after a disaster occurs. These procedures can vary from being general guidelines to legislated regulations and are generally implemented through state or government authorities (Rotimi et al. 2009).

Prioritisation and optimisation methods accept that PDR can be severely hampered by various resource constraints and focus on aiding the practitioners to make the most effective decisions given these inherent challenges. Extensive research has been carried out on developing various models to assist in the optimisation of PDR of road infrastructure. Scholars have used different methods ranging from Analytic Hierarchy Process simulation, deterministic optimisation to stochastic optimisation based on concepts like reliability, robustness and resilience of the transport network for this purpose (Faturechi and Miller-Hooks 2014).

Although there has been an increased contribution in this area from both policy and theoretical aspects PDR tends to face major obstacles and challenges during implementation. This has resulted in delays in reconstruction, community back lash and even damage to reconstructed infrastructure in later disaster events. Most Australian guidelines on road infrastructure related PDR tend to pay more attention to the financial and engineering aspects, with less attention on wider socio-economic and ecological factors. This is in contrast to the academic scholarship where numerous models to aid PDR of transport infrastructure have been presented that considers the social and environmental aspects (Khaki et al. 2013, Dong, Frangopol and Saydam 2013, Tapia and Padgett 2016). The literature shows that PDR processes are heavily reliant on the expert judgements of the practitioners and the prevailing regulatory requirements (Chang et al. 2014, Palliyaguru, Amaratunga and Haigh 2010, Zhou and Wang 2015) . However, as most of these studies focus on reconstruction efforts in developing regions or the reconstruction of housing projects it is vital to understand how practitioners approach PDR of road infrastructure in order to identify any gaps between theory and practice, especially from an Australian perspective.

To understand this problem we examined how PDR of road infrastructure is carried out in practical scenarios by interviewing practitioners in disaster affected regions in Australia. The aim of the research was to investigate the methods adopted by practitioners involved in the decision making process of PDR. This paper builds on previous research carried out in interviewing practitioners to understand the decision making processes in a disaster-prone region in Queensland, Australia (Gajanayake et al. 2019). Practitioners involved in PDR of road infrastructure in Victoria were interviewed in order to conduct a comparative analysis. The states of Queensland and Victoria were selected for this study as they are two of the most disaster impacted states in Australia.

Methodology

Given the exploratory nature of this study a qualitative case study approach was adopted. This involved interviewing practitioners involved in PDR across two different geographical regions, which helped in a comparative analysis of the findings. Qualitative research is used to explore an area of interest where little is known, to obtain a holistic view of a complex system and to investigate social phenomena in the context that it takes place (Karlsson et al. 2007). Such research is constructionist and interpretivist in approach as the findings of the study are based on how ideas generated from the interviews are interpreted and constructed by the researcher (Mulowayi 2017). A multiple case-study approach increased the generalizability of the research findings beyond the immediate study area (Yin 2009).

Interview Design

In-depth interviews were chosen as the best method to obtain the relevant information as they are a pipeline to transmitting knowledge (Holstein and Gubrium 2004) and are intended to tap individual experiences that the researcher may not be aware of (Charmaz 2003). Exploratory interviews helped broaden and deepen the plan of research by facilitating new dimensions that were earlier not visited by the researchers and to develop ideas and research hypotheses rather than obtaining quantitative facts and statistics (Oppenheim 2000).

A low degree of structure for the format of the interviews was deemed to be suitable for the purpose of the study. This meant that it was easier to encounter new and unexpected views as the interviewer used a broad range of ideas, experiences and observations (Alvesson 2010). The questions were designed with a clear theme and fairly limited focus, with more open ended questions, which resulted in gaining deeper understanding and rich descriptions of the issues. The interview questions were designed to obtain information under three broad themes; current practices adopted in PDR, additional aspects that should be considered and how PDR processes could be improved in the future. The interview probed the different factors considered based on three the pillars of social, environmental and economic, which are considered in holistic decision making approaches.

Interview participants

The first stage of the project involved the interviewing of practitioners from disaster prone regions in Queensland, while a second round of interviews were conducted with practitioners in Victoria. These two states were selected for a comparative study as there were distinct differences in the disaster occurrences between them. Queensland is the most vulnerable State in Australia to disasters and experiences a high number of hydro-meteorological disasters, which can severely affect road infrastructure, while Victoria is prone to more climatological events like bushfires. This allowed for a comparative analysis across interviewees where one group experienced more disaster induced road infrastructure damage in contrast to the other. Participants were selected from both rural and urban organisations from within the two States in order to analyse any differences in practice and opinion based on the geographical setting.

A theoretical sampling technique was adopted to select the potential participants whose work aligned with the research objectives (Robson 2002). This allowed the selection of respondents with specific characteristics; those employed in organisations involved in post-disaster road reconstruction either directly through decision making processes or indirectly in vetting and stakeholder engagement processes. Typically the responsibility of PDR of roads fall under the local authority or the state roads authority, while funding for such projects is facilitated by the reconstruction agency. A total of eighteen interviewees (Table 5-2) from local government authorities, road authorities and reconstruction agencies in Queensland and Victoria were identified through previous research work carried out by the authors and were contacted directly by the research team. The snowball interview technique was implemented, where the interviewees were asked if they could recommend any other individuals or organisations relevant to the study. This helped the researchers to confirm that all the different types of organisations involved in PDR had been covered. The majority of the participants were civil engineers overlooking the transport infrastructure, while local government staff working in other divisions were also interviewed to obtain a more diverse opinion on reconstruction efforts.

Table 5-2 Interview participants

Participant	Organisational Sector	Work Division	Geographical Jurisdiction
P1	Local Government	Infrastructure Works and Services	Queensland
P2	Local Government	Disaster Management	Queensland
P3	Local Government	Economic Development	Queensland
P4	Local Government	Environment Management	Queensland
P5	Local Government	Environment Management	Queensland
P6	Local Government	Community Development	Queensland
P7	Local Government	Community Development	Queensland
P8	State Government	Reconstruction Operations	Queensland
P9	State Government	Transport operations	Queensland
P10	State Government	Transport operations	Queensland
P11	State Government	Transport Asset Services	Victoria
P12	Local Government	Infrastructure Projects	Victoria
P13	Local Government	Infrastructure Projects	Victoria
P14	Local Government	Construction (New Works)	Victoria
P15	Local Government	Asset Management	Victoria
P16	Local Government	Asset Services	Victoria
P17	Local Government	Asset Management	Victoria
P18	Local Government	Asset Management	Victoria

Interview process and analysis

The interview questions and a Participant Information Sheet were emailed to the participants a week prior to the interview. This enabled the respondents to get an overview of the project and also to prepare for the questions that would be discussed. The interviews were typically 30-60 minutes in length and were conducted face-to-face at a meeting room at the interviewee's office. The interviews were audio recorded, using the audio recording function of a smart phone, which was placed on the table. This was a non-intrusive method to record the interviews given the wide-spread use of mobile phones. Careful attention was given to conduct the interviews in a manner that created an atmosphere for the participants to respond with deep perspectives, which opened up new dimensions to be studied (Oppenheim 2000).

The interviews were analysed using qualitative data analysis principles in order to understand the underlying themes and the processes used by the different participants. Qualitative methods were chosen, as a detailed understanding of the process was needed and as information was required to determine the boundaries and characteristics of the issue being investigated (Bazeley and Jackson 2013). Data triangulation of the information obtained through the interviews was conducted using relevant institutional documents and systems. This helped in validating the information provided by the participants through more objective sources.

The analysis of the interviews took a two-step approach. The first group of interviews from Queensland were analysed with in-depth focus in order to understand the methods and practices used during PDR. These interviews helped the researchers identify the major factors that were considered, the techniques adopted on the ground and the subtleties that influenced the PDR processes. The analysis of the initial interviews helped in identifying the key issues that were highlighted by the respondents. The second group of interviews were used for comparative purposes and to increase the generalizability of the findings of the previous interviews.

Findings and discussion

This section presents the main findings in separate subsections and discusses their influence on PDR activities with reference to relevant literature. Specific quotations from the interviews have also been included in order to draw the reader's attention to important ideas that were mentioned in the interviews. The findings of the interviews are presented according to themes that emerged through the interviews and are different to the themes that were followed during the design phase.

Consistent use of tacit knowledge

The participants on the whole reported that there were no systematic processes which were followed for prioritisation of PDR. However, there was widespread use of tacit knowledge during the decision making and prioritisation works related to PDR. Such tacit knowledge of the practitioners played an important role in the decision making processes as no systematic methods had been utilized. The most vital aspects that were considered were the practitioners' past experiences and intimate knowledge of the locality. Participants used terms like "gut-feel", "ad-hoc decisions" and "grey-matter approach" to refer to this tacit knowledge.

One benefit of incorporating such tacit knowledge is that the decisions made were considered to be more suitable to the disaster zone. This could be more important in rural areas where state or federal level systems may not be as appropriate. Such measures have been found to benefit the recovery process rather than simply relying on central level, large scale actors (Lyons 2009, Peng et al. 2013)

"The guys in the field know how important a road is, [if we are asked how we made that decision] we'd be saying, well we made it on gut feel your honour, which isn't very good. But it's all there and it's all in the mind" Participant P1

Practitioners were of the view that communities in disaster-prone areas were much more resilient and adaptable due to generational experiences of living through multiple disaster events. It was considered important to tap into such local knowledge of how the water-ways behave during disaster events in order to re-build a more resilient bridge. This was considered vital in instances where professionals who were not from the locality were involved in PDR. The generational effects highlighted by the participants were related more to the knowledge of the locality in disaster times rather than experience in dealing with previous disasters from different regions. Practitioners in rural disaster prone areas stressed that some of the infrastructure designs that were done in the past may have been done with such intimate local knowledge in mind. Such decisions are seen to have a heavy influence on the impact to the community and the subsequent ease of recovery after a disaster.

The only systematic process that was utilised in post-disaster decision making was for obtaining funding of reconstruction projects, which were mostly stipulated by state agencies. Such funding proposals tend to focus on the financial cost of reconstruction with minimal consideration given to wider socio-economic and environmental impacts. Data related to road classifications and business types have also been used in such prioritisation processes although no systematic method was utilised to incorporate such information. The interviewees did not seem to think that the decisions that were made in this manner could be completely flawed, but saw the need for a framework that could validate the current decision making processes. It was also highlighted that such a method could be used for numerous purposes including, as an evidence base for funding proposals, prioritisation of projects and the comparison of alternative reconstruction methods.

The interviews showed that there was a mismatch between researchers and practitioners with regard to prioritisation of road infrastructure decision making. Although there have been many models and tools proposed by researchers to aid in road infrastructure reconstruction (Khaki et al. 2013, Gühnemann et al. 2012) no evidence for the use of such methods were identified. A possible reason for this could be that most of these methods have not been developed for an Australian context. Since the interviewees mentioned that local nuances were a vital aspect that needs to be considered, the development of such models needs to be localised and context specific as opposed to a more general model. Improving the contextual and scalability of such models may increase the adoption of them in practice.

Opinions on the immediate need of a systematic method to aid PDR, differed based on the disaster vulnerability of the regions that the participants worked in. Practitioners located in more disaster-prone areas saw an immediate requirement for the use of such systems, while those in less disaster-prone areas saw no pressing need to incorporate such tools. Councils that had experienced hydro-meteorological disasters seemed to see a high value in the use of such methods in road infrastructure decision making, confirming the high degree of damage to road structures due to such events. The practitioners expected probability of a disaster occurring explains why disaster management processes are mostly systematized in disaster-prone areas and especially after a major disaster event (Palliyaguru and Amaratunga 2008).

Roads viewed as social infrastructure

A majority of the participants were of the opinion that the primary role of road infrastructure was to facilitate the smooth functioning of the society. Most engineering professionals who were interviewed considered road infrastructure as part of the social infrastructure. This was in contrast to the general view among infrastructure engineers in Australia where transport infrastructure is typically classified as economic infrastructure (Infrastructure Australia 2019). Infrastructure like schools, hospitals and community buildings, which cannot be valued in economic terms, are typically considered as social infrastructure (Jefferies and McGeorge 2009). This dichotomy in views could be due to the objectives of the organisations that the engineers were employed in. The objectives of the infrastructure services departments in Councils were to ease connectivity purely from a social standpoint, with little or no mention of economic benefits. In general, therefore, it seems that the organisational outlook tends to flow through to the practitioners, and may take precedence during decision making procedures.

"Delay costs and then congestion related issues... [have] a number of health impacts and work life balance problems. You know if you're stuck in traffic for two hours, it's two hours less with your family." P12

A diverse set of impacts were identified by different interviewees as the most important type of social impact such as human health issues, access to facilities, inconvenience to communities and traffic related impacts. A very common social impact that was highlighted was that of isolation of people or households due to damaged roads. Isolation of communities was highlighted especially by interviewees working in more rural environments in contrast to those focusing on more urban settings. It was also highlighted that isolation is one of the most critical factors that needed to be considered but is something that is commonly overlooked by practitioners who work in urban areas. A typical reason for this could be that urban areas are better connected, with more alternative routes thus reducing the possibility of isolation when road networks are unusable.

Although social impacts were stated as the most important aspect influencing PDR, no systematic process was used to incorporate such factors in the decision making processes. Given this constraint practitioners have tended to use their tacit knowledge during reconstruction and prioritisation efforts. Some participants, particularly from the infrastructure divisions felt that the road hierarchies and classifications indirectly portrayed the underlying social factors, while others were cautious in relying purely on such quantifiable factors saying that *"need is not always counted by number"*.

Diverse perspectives on socio-ecological factors

Participants expressed a variety of perspectives on the importance and the types of socio-ecological factors influencing decision making. While social impacts were generally identified to be more important than environmental factors no clear distinctions were seen in the categorisation of them. The approach adopted by the researchers were to separate the types of impacts based on economic, social and environmental, which are the typical categorisations in sustainability literature. Participants differed in their opinions on what specific impacts fell into each category. A common view that was found across most participants was that financial factors like cost of reconstruction were confused with economic factors, while some economic factors like, the loss of business revenue were considered to be social factors. The implication of this confusion is potential dismissal of critical economic and social factors which need consideration to undertake a holistic analysis of post disaster recovery strategy and action.

Some participants explained that distinguishing impacts between economic and social could be misleading as economic impacts are within the social system. This portrayed the more contemporary approach of 'strong sustainability', where the economic system is considered to sit within the social system, which in turn is nested within the overarching environmental sphere (Sylva 2018). The nested approach is in contrast to the initial conceptualisation of sustainability being viewed as three interrelated but separate pillars. We could conclude that practitioners tend to understand this interdisciplinary nature of sustainability without being constrained by theoretical concepts.

"The more you think about it, everything affects the human social side of it. If they can't get their crops to market, yes it is economic, but at the end of the day it becomes [social]." Participant P2

A clear distinction was observed among participants on the most important environmental factors that need to be considered. Practitioners in more rural areas thought damage to the natural local environment during PDR to be significant, while practitioners in urban areas mentioned the use of recycled material and carbon emissions to be of significance. The most important environmental impacts that were highlighted in rural disaster-prone areas were soil erosion, effects on water quality and sediment run-off. These impacts were mentioned regardless of the background of the practitioners be they engineers or social workers. The reason for this could be that a link between the natural environment and disasters are directly observable in regional areas and take precedence over global environmental issues. This was in contrast to other studies where the focus of environmental impacts considered during PDR was resource usage and greenhouse gas emissions (Padgett and Tapia 2013, Schweikert et al. 2018), which was similar to the views posed by practitioners in more urban settings.

One interviewee mentioned that damage to heritage listed bridges is a significant environmental impact. Such a classification seemed peculiar at first, as heritage listed architecture would generally fall under the socio-cultural umbrella rather than environmental. However, a reason for this could be that heritage architecture comes under the purview of the Department of Environment in the State of Victoria, which was the jurisdiction of the particular participant. This exemplified that legislative separations could play a more influential role rather than more common academic separations in categorisation of impacts.

Political and legislative influence

A common theme that emerged from the interviews was that political factors played an influential role in the decision making process. It was mentioned that there may be encouragement given to concentrate on specific areas during the reconstruction processes, purely from a political perspective. In instances where follow up questions were asked, there was hesitance to explain further stating *"you know what I mean".* It was deduced that political factors could play a decisive role in post-disaster decision making, and was contrary to previous literature, where political and institutional factors have been identified as less important and more of an indirect factor (Pathirage et al. 2012).

Political influence was not always seen as a negative factor. Some participants mentioned that the political influence may indicate some underlying socio-economic factor that may not have been captured otherwise, while another mentioned that political influence was just another element of the tacit knowledge that is considered in the decision making process.

Participants from local councils noted that legislative and funding processes around PDR have a major influence on the type of reconstruction that is carried out. Most funding for reconstruction of infrastructure was available for 'like-for-like' re-building. This has resulted in many of the structures that were reconstructed after a disaster to be damaged in the next disaster event. It was noted that 'building-back-better' with more resilience built into the infrastructure can mitigate future impacts. However, most of the reconstruction did not include any mitigatory elements as funding for such elements were not available, even though the councils knew that such structures are *"not going to stand"* in the next flood event. Funding constraints have been found to negatively impact the resilience of structures due to non-optimal decision making processes in other similar industrial nations as well (Ćirilović et al. 2018). State level authorities mentioned that these issues have been identified and that measures have been taken to provide funding for more resilient PDR.

It was understood that increased regulations in recent times has had an impact on community level recovery processes and such regulations may be effectively *"legislating resilience away"* from the communities. Such regulations could reduce the adaptive capacity of communities while making them more reliant on Council or State authorities to facilitate recovery. The fact that legislation can have unintended consequences which can impede the resilience of rural disaster-prone communities is an aspect that policy makers should pay close attention to. This of special significance since disaster related regulations are designed to increase community continuity and resilience through institutionalising practices and processes (Britton and Clark 2000).

"Legislation tells people 'you are not smart enough… so don't even try, we'll tell you how to do it'. But then when a flood hits we try to tell people 'you should be able to look after yourself for three days' and we don't realise that we have disempowered people and it's the legislative approach that has done that." Participant P7

Requirements for holistic, systems thinking approach to decision making

The majority of participants mentioned that a more holistic approach to PDR decision making was needed moving away from the current practice of heavy reliance on financial factors. The participants were of the view that a commonly accepted methodology to incorporate wider socio-economic factors will be useful across most organisations. It was revealed that social, environmental and economic factors were considered during new infrastructure projects but was an area that was lacking during PDR.

Participants from local councils mentioned that there will be higher probability that a holistic approach will be adopted across other organisations if such a method was adopted by the State level authorities. Given the lack of use of PDR specific models in the Councils participants from less disaster affected areas were of the opinion that the current methods used during new infrastructure projects and renewal work will be suitable in post-disaster scenarios. This finding corroborates with similar work carried out in New Zealand where PDR is at times carried out in a similar fashion to routine maintenance work. However, it has been found that routine methods of work can be grossly inappropriate in disaster times (Le Masurier et al. 2006).

Many participants were of the opinion that if a range of practitioners from different disciplines worked together that they would be able to come up with more holistic and previously unexplored solutions to PDR issues. Infrastructure practitioners alluded that they *"selfishly focus on road assets"* during PDR although they do understand the importance of the environmental factors in play. This was a shortcoming that was constantly sighted by socio-environmental practitioners who were of the opinion that both these groups needed to work together if more resilient solutions are to be arrived at.

Some environmental practitioners suggested that the problems with regard to repeated damage to infrastructure could not be resolved from a purely *"engineering thought process"* but needed a more ecological approach. Issues were pointed out to where roads have been built very close to creek bends, the overlapping of road reserves with creek reserves, and an increase of river crossings over the years. This is especially important in a hydrological disaster context as engineering infrastructure can have can have unintended consequences on the socio-ecological systems and have knock-on effects during later disaster events (McCartney et al. 2019).

"If you've got the opportunity to reintroduce sinuosities to make it more a natural creek system instead of an engineered one… It's not in the infrastructure people's minds. It's a total different set of skills". Participant P4

This divergence in opinions could be due to the contrasting world views of engineers and ecologists (Raab 2017). The engineering profession is influenced from a high-modernist ideology (Scott 1998) and their main role is considered to be transforming natural capital, into human and built capital using technical competence (Mitchell, Carew and Clift 2004). The participants were of the view that engineers needed to pay more attention to the ecological aspects because if not "*the impacts of the flood events will continue to become more and more severe"*.

It was highlighted that there was disconnect between engineers and ecologists. It was noted that the engineering and environmental departments generally work very much in silos without looking at the bigger picture. Given that most of the PDR of infrastructure is driven by the engineering departments, engineering solutions have taken precedence over ecological solutions, and was seen as a major hurdle to adopting a more holistic decision making approach. It was understood that engineers had more faith that technology could reduce impacts, while ecologists believed that they also had unintended consequences that increased socio-ecological impacts. Most participants were of the view that these two streams of work need to work together in a holistic manner, which would bring about more effective and resilient outcomes in the future.

Similarly there have been instances of disagreements between the residents and the engineers that were contracted for PDR works. Due to high demand for construction work in post-disaster times, there had been many instances where engineers from outside the region were brought into fill this gap. Such workers are worried less about the socio-ecological aspects and are *"really just engineers, purely involved with the technical aspect"* of PDR. It was pointed out that there were instances where engineers did work closely with the local community during reconstruction. Such work helped to achieve more holistic outcomes as the engineers did not focus on solutions *"purely from an engineering perspective".*

"There was some resistance from them to listen to local farmers because, [they thought] 'who are you to tell me how to do my job, I'm an engineer what are your qualifications?' But the farmers weren't saying 'this is how you build a bridge'. They were saying 'this is where we need a bridge and this is the order that we need them.'" Participant P6

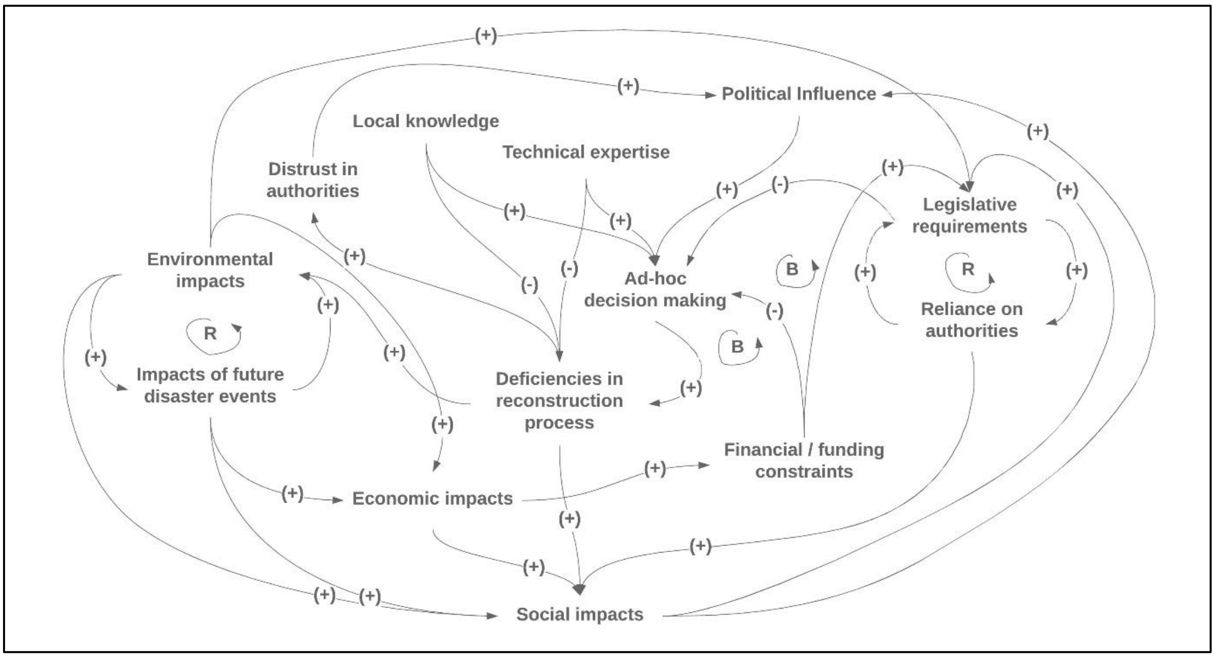
The findings show that systems thinking approach is needed in PDR efforts, which involve obtaining the views of a wide variety of stakeholders from different professional backgrounds as well as from communities and businesses. Such a holistic approach may create more resilient outcomes in infrastructure in disaster-prone areas and may also help to reverse negative public opinion where engineers are sometimes seen as part of the problem instead of the solution (Ainger and Fenner 2014).

Causal loop diagram of the system studied

Based on the responses of the interviewees a Causal loop diagram (CLD) was developed to identify the interrelationship between factors that influence PDR decision making (Rehman et al. 2019). CLDs are a corner stone of systems thinking approach and represent the dynamic system's causal structure (Schaffernicht 2010). A typical CLD consists of variables and causal links between the variables that identify feedback loops. The causal links are depicted with arrows showing the direction of causality and symbols to show their polarity. The polarity is presented with (+) or (-) signs representing the relationship of the two variables. Causal relationships between variables can be used to identify closed loops within the system. Closed loops with positive feedback are referred to as reinforcing loops, as a change of one variable propagates through the loop reinforcing the initial deviation. Balancing loops in contrast have negative feedback through the sub-system balancing the initial deviation.

Figure 5-1 is an illustration of the CLD developed following the analysis of the interview findings. The various factors influencing the PDR process and causal links between them were identified through the analysis of the participant responses. The numerous factors mentioned by all the participants were listed down and then grouped into clusters that are presented as variables in the CLD. The diagram was then used to identify feedback loops within the PDR process and to recommend intervention mechanisms at critical points that could increase resilience of the system. The development of a CLD was the initial step towards analysing the PDR process from a broader point of view so that more holistic intervention could be recommended. Such a method aims to move away from piecemeal solutions, which is typical in organisations that work according to operations silos, towards more sustainable solutions.

Figure 5-1 Causal loop diagram of PDR of transport infrastructure



It can be deduced from this CLD that there are many reinforcing loops within this system. One such reinforcing loop explains how increased legislation can cause a greater reliance on authorities (due to reduced community adaptation capabilities), which in turn increases legislative requirements. Another reinforcing loop was identified where negative environmental impacts can exacerbate impacts of future disaster events. As such environmental consideration during the reconstruction process is a vital aspect that needs to be considered in order to increase the resilience of the transportation system.

An important balancing loop within this system is where legislative or regulatory processes could be used to reduce ad-hoc decision making, which in turn will reduce deficiencies in the PDR process resulting in lower socio-ecological impacts in the future. However, if deficiencies in the PDR process are to be mitigated, socio-ecological factors need to be considered in addition to the techno-financial factors which are being considered currently. It is thus evident that post-disaster decision making processes needs a holistic, systems thinking approach, if more resilient and sustainable infrastructure networks are to be designed.

Conclusion

This study, through semi structured interviews with multiple stakeholders in local councils and state authorities, has identified the need for a holistic approach in post-disaster recovery situations. It is important to understand social, economic and environmental impacts in post-disaster recovery situations for example in the context of road infrastructure reconstruction. It has been identified that there is very limited use of any systematic techniques in the PDR process although such methods have been developed by many researchers.

A limited engineering and financial resource allocation approach seems to be the most straight forward choice when it comes to PDR strategy and implementation. This was mainly due to the heavy reliance on the engineering department during PDR, which can minimise collaboration across departments. Nevertheless this is not the most comprehensive and holistic approach as it tends to exclude social, environmental and economic factors from being considered. Reliance on narrow legislative and engineering processes that do not considered wider socio-ecological aspects may lead to unintended consequences that have the negative effect of reducing resilience. The use of holistic approaches can improve resilience not only of the engineering infrastructure but also of the community in the longer term. When multiple stakeholder views are taken into consideration, various angles relevant to reconstruction emerge, which may usually be ignored. Decisions made with a broader perspective may have an impact on various resource allocations (such as money and time) but can result in better quality outcomes in the longer run. Better quality outcomes include more resilient structures, less environmental impacts and community considerations embedded in recovery decision making and action.

The findings of the study can be used to develop targeted interventions aimed at reducing the socio-ecological impacts and increasing resilience during the PDR process. Further research could explore how best to incorporate the broader socio-ecological aspects during the PDR decision making processes. The results of this study indicate that consideration of local nuances with input from multiple stakeholders will be important in developing such a decision making framework. The adoption of holistic considerations, such as practices and decisions, which are based on multi stakeholder views and expectations, could be encouraged by State and Federal level agencies. Holistic views can be covered in funding proposals and in requirements for granting of funding. Tailor made, holistic considerations can be implemented in data and time constrained situations.

5.4 Implications of the interview results on the design of the framework and toolkit

The opinions and views of the stakeholders interviewed helped in designing the framework and toolkit developed through this research project. As the framework would be utilised not only for academic research purposes but also for practical decision making in post-disaster contexts, the views of potential end-users were deemed a vital aspect. The literature review and analysis of the methods discussed in Chapter 4 helped the framework to be theoretically rigorous, while the needs assessment interviews aided in the framework to be practical for decision making purposes. Three main areas of the framework were designed based on the interviews conducted. These areas were the scope of measurement, sophistication of the framework and the desired outputs of the framework.

5.4.1 Scope of the framework

The results and output of an analysis through a model depends on the scope and boundary of the model (Allenby 2014). As such, it was important to select a scope that was in line with the potential end-users of the final framework and tool. Three aspects relating to the scope of the framework were decided on based on the interview results. These were the types of impacts to be measured, the temporal focus and the geographical boundary to be considered.

The interviews revealed that the current reconstruction processes only considered limited financial and engineering aspects for decision making purposes. The majority of interviewees mentioned that the consideration of wider social and economic was vital and would assist in decision making processes in future disaster events. The assessment of environmental impacts was seen to be a "nice to have", and was not considered a vital aspect by some of the interviewees. Given such responses, the scope of analysis was selected to focus on the social and economic impacts, with the environmental impacts being included for a further analysis. The types of environmental impacts that were considered to be significant by practitioners in flood-prone areas were soil erosion, sediment run-off and damage to river beds. Such impacts to the environment are much harder to estimate given the time period required for the analysis.

The temporal requirement for the framework was discussed with the interview participants. All the participants mentioned that a method to estimate impacts due to the damage to road structures after a disaster event was a vital requirement. Such a time period was mentioned as there were no systematic methods to estimate impacts at that stage at the time. A systematic method used at that time could be used for the prioritisation of reconstruction projects as well as a validation method for funding proposals. A review of academic literature and government guidelines showed that there were numerous methods to estimate impacts before an event and to estimate sustainability impacts for new infrastructure projects. However, given the expedited nature of reconstruction required after a natural disaster, no such assessments had been carried out. Based on this input, the time period considered for analysis was selected as a short to medium term in a post-disaster context, focusing on the recovery and reconstruction phases. This was defined as the time period immediately after a disaster struck until the infrastructure was brought back to pre-disaster operational conditions.

The interviews exemplified that the geographical boundary of the framework needed to be focused on local government boundaries. This was mentioned by both local authorities as well as state road and reconstruction agencies. Desktop research also confirmed that such a boundary was realistic as the financial aid for reconstruction of bridges offered through the Natural Disaster Relief and Recovery Arrangements (NDRRA) was administered through the respective local government authority. The temporal and spatial boundaries were selected based on the boundaries of the public policy intervention during post-disaster reconstruction of road infrastructure (Merz et al. 2010).

5.4.2 Sophistication of the framework

It is important to build models of appropriate sophistication, and the models should be designed to operate at the level of sophistication that makes sense in the situation (Dowling et al. 2010). Highly sophisticated models that are not user-friendly and give abstract results that cannot be easily understood by users can be as ineffective as very easy-to-use models, which can have over-simplified results. Therefore, a delicate balance between sophistication and ease of use needed to be achieved. The interview participants opined that a relevant model needed to be easy to understand by personnel in different departments and authorities.

Another important aspect identified through the interviews was that the model needed to be flexible and scalable. A global model with a "one size fits all" assumption was not considered to be relevant as the level of damage and the type of impacts would vary based on the event and the geographical location. This meant that the assumptions and values used for the analysis needed to be visible to the users. One of the conclusions of the interview results was that although there are many models that have been developed by researchers to help in measuring impacts to aid in decision making, the use of such models was infrequent among practitioners. A major reason for this was that most models were not flexible enough to incorporate the local assumptions and values within them. The framework and toolkit developed through this research aimed at overcoming this limitation in order to increase its usability

5.4.3 Desired outputs

The desired output of the framework was decided based on end-user requirements. Most participants stated that the main requirement of an impact measurement framework was for it to be used as an aid in decision making purposes and to validate some of the decisions that are based purely on tacit knowledge. Participants mentioned that most decisions are made on gut-feel but a systematic method to validate such requirements was important.

The toolkit could also be used to assess the value for money of different options or the cost-benefit ratios for decisions taken. This could be done for the comparison of different options of reconstruction and for prioritisation of reconstruction, when multiple infrastructure assets were damaged. Such a model was also considered to be effective in the use of funding proposals to state or federal agencies. An important aspect in this regard was that the output needed to be easily understood by users. As such, care was taken to avoid the use of methods that would give out abstract results, which may not be easily comprehensible to a varied group of users.

The final framework was designed with these goals in mind. However, the theoretical and fundamental principles of sustainability assessment were not compromised so as to attain the identified end-user needs. Rather, the project aimed at working out the most suitable method for the given situation, keeping in mind that there is no one optimal solution to wicked problems but technically, politically and socially feasible solutions (Allenby 2014).

5.5 Summary

This chapter presented the interviews conducted with road infrastructure decision makers who were identified as the potential direct end-users of the outcomes of this research. The first two sections of this chapter explains how decision making takes place in disaster prone regions and what factors are considered in such instances. The interviews showed that there was no systematic method to measure wider socio-economic impacts, and that the use of such processes would optimise post-disaster reconstruction projects. The interviews also helped in scoping the framework that was developed in order to increase its practicability. The useability of the project outcomes was improved by obtaining the views of the end-users and designing the framework and toolkit to cater to their requirements. Chapter 6 presents the process followed in developing the framework.

6. DEVELOPMENT OF AN INTEGRATED FRAMEWORK AND TOOLKIT

6.1 Introduction

This chapter explains how the final framework to measure social, environmental and economic impacts of disaster induced road structure failure was developed. The framework was developed by taking into consideration both academic scholarship as well as current practices in the industry. The analysis and selection of the appropriate measurement methods explained in chapter 4 was the basis of the theoretical foundations of the framework, while the current industry practices and end-user requirements were considered by interviewing practitioners working in the road infrastructure area.

This chapter is broken down into three broad areas. Firstly, the theoretical underpinning of the framework is explained so that readers can understand the methodology and assumptions behind amalgamation of the diverse impact measurement methods. This is followed by an explanation of how each of the selected measurement methods is used, the data requirements and analytical skills required to assess the impacts. The final section explains a toolkit that was developed to demonstrate the application of this framework. The toolkit is based on the conceptual framework developed, and focuses on measuring the sustainability impacts of the failure of a bridge. Although the specific data and assumptions for the toolkit has been selected to assess the impacts of damage to a road bridge, the framework can be modified and used to assess impacts of any other type of road infrastructure. Such infrastructure can be culverts, flood-ways, over passes, tunnels or even stretches of road networks.

6.2 Objectives and framework development processes

The objective of developing a framework to measure sustainability impacts of road network failure was to present a theoretically founded mechanism that can be used by both academics and practitioners. It was intended to be a framed process and not separate individual processes. The literature review and end-user interviews found that the use of systematic methods to measure impacts in post-disaster decision making has been limited to academic scholarship. One of the main objectives of this PhD was to bridge this gap between the advancement of the academic research and the use of such models for decision making in a practical sense. Catering research to achieve both academic and practical outcomes is often a delicate matter, and was one of the major challenges encountered in this research. However, many steps have been taken to address these issues, which include in-depth analysis of literature and validation of the model that was developed.

The process followed to develop this framework could be broken down to three steps: 1) building on prior knowledge, 2) processing and linking 3) translation and synthesis (Loughran 2012). Prior knowledge includes the information, ideas, beliefs and attitudes that decision makers and academics have before development of the framework. Building on this prior knowledge that practitioners had was crucial, as the framework was designed to be used in collaboration with other tools and practices within organisations. The prior knowledge that was gathered included both academic as well as knowledge of practice. The relevant knowledge of practice was identified through the in-depth interviews that were carried out, while the necessary theoretical ideas and techniques from academia where gathered through the analysis of the literature. The approach of analysing both fields of knowledge helped in fostering a more collaborative outcome, which was necessary to bridge the gap between academics and practitioners.

The processing stage aimed at using the information to apply it a different but relevant situation in the decision making process. The processing helped in organising the information so that it could be retrieved and used for the specific purpose of the framework. Through the end-user interviews it was identified that there were many techniques that were being used in the different divisions and authorities that could be applied to the given framework. These different levels of knowledge, both from practice and academia, were linked in a coherent manner. This step focussed on analysing how different models and ideas could be linked together in the final framework.

Translation occurs when ideas and information presented in one way are processed and then used in another form. It requires cognitive manipulation as the ideas and information being worked with need to be well understood in order for them to be applied in a different way in a different setting. This step involved modifying the different techniques and models to best suit the analysis of impacts of disaster induced bridge failure. Finally all the different techniques were brought together to make up the coherent whole of the final framework. Synthesising was important as it brought together the different techniques together and joined them so that each of the elements interacts in such a way as to build on one another.

6.3 Fundamental assumptions of the framework

The analysis of measurement methods demonstrated that there are diverse approaches and techniques to measure the different types of impacts. As the framework aimed at amalgamating different types of impact measurement methods, the compatibility of the methods was a vital aspect in selecting the appropriate method. The selected methods needed to be appropriate to the scope, sophistication and the expected outputs that end-users required, which were highlighted in section 5.4. Table 6-1 shows the expected outcomes of the framework and the most relevant principles within different modelling approaches that will help attain them. These expected outcomes and the modelling principles needed to attain them were considered in the selection of the appropriate measurement methods as explained in Section 4.3. The process of selecting the suitable methods was an iterative process, which helped in achieving the best outcomes for the project.

Table 6-1 Principles adopted for framework

Expected outcomes	Modelling principles / approaches
Scalability	Microeconomic (bottom-up) modelling
Incorporating behavioural change	Agent-based techniques
Allows for aggregation	Use of complementary methods
Flexibility	Ability to select required impact categories
Ability to be used in Cost Benefit Analysis	Monetary weighting

6.3.1 Scalability

The interviews showed that one of the most important aspects for end-users was that the framework needed to be scalable both on a temporal and spatial scale. Bottom-up modelling approaches help attain this scalability as they are more suitable to measure localised impacts and can be expanded to cover larger geographical scales if needed. Given that the geographical scope selected for the framework was local government regions, bottom-up approaches were the most suitable. On the aspect of temporal scalability, microeconomic approaches are more suitable to cover short-term impacts and could also be easily extrapolated to increase the time frame of measurement. As such, methods that used microeconomic, bottom-up approaches to modelling impacts were well suited to attain the criteria of scalability.

6.3.2 Behavioural change

Natural disasters and their impacts on road networks can cause major changes in travel patterns in the communities affected. Such behavioural changes are in stark contrast to changes in travel patterns that are observed when routine road closures due to maintenance or construction of road infrastructure take place (Zhu and Levinson 2012). Given the possibility of such changes in behavioural patterns affecting post-disaster transport decisions of communities, it was vital to select methods that could incorporate such changes. Agent-based techniques allow for such behavioural changes to be modelled, as such models are less reliant on pre-determined assumptions on behaviour (Dia 2002). Agent-based techniques attempt to study the collective behaviour of individuals as more than rational decision makers who have a limited view of their environments and react only according to pre-established rules, which will be more relevant in disaster affected zones.

6.3.3 Aggregation

As the framework incorporates diverse models designed to measure different types of impacts, their results could vary. The selected methods needed to be compatible with each other, which allowed for aggregation so that the final results of the framework could be easily interpreted by users. As such the compatibility of the techniques was an important aspect that was considered in their selection.

6.3.4 Flexibility

End-user interviews indicated that the framework needed to be flexible enough to enable relevant modifications when being used in real life disaster impact assessments. This was considered important as the impacts would vary based on the severity of the event, the type of event and the area affected. Accordingly, a one-size-fits-all model was not considered suitable.

End-user requirements for the ability to select the different impact categories that will be measured and the ability for it to be localised meant that the final toolkit developed on the framework provided the option for users to select the impact categories that were important in different disaster situations.

6.3.5 Compatibility

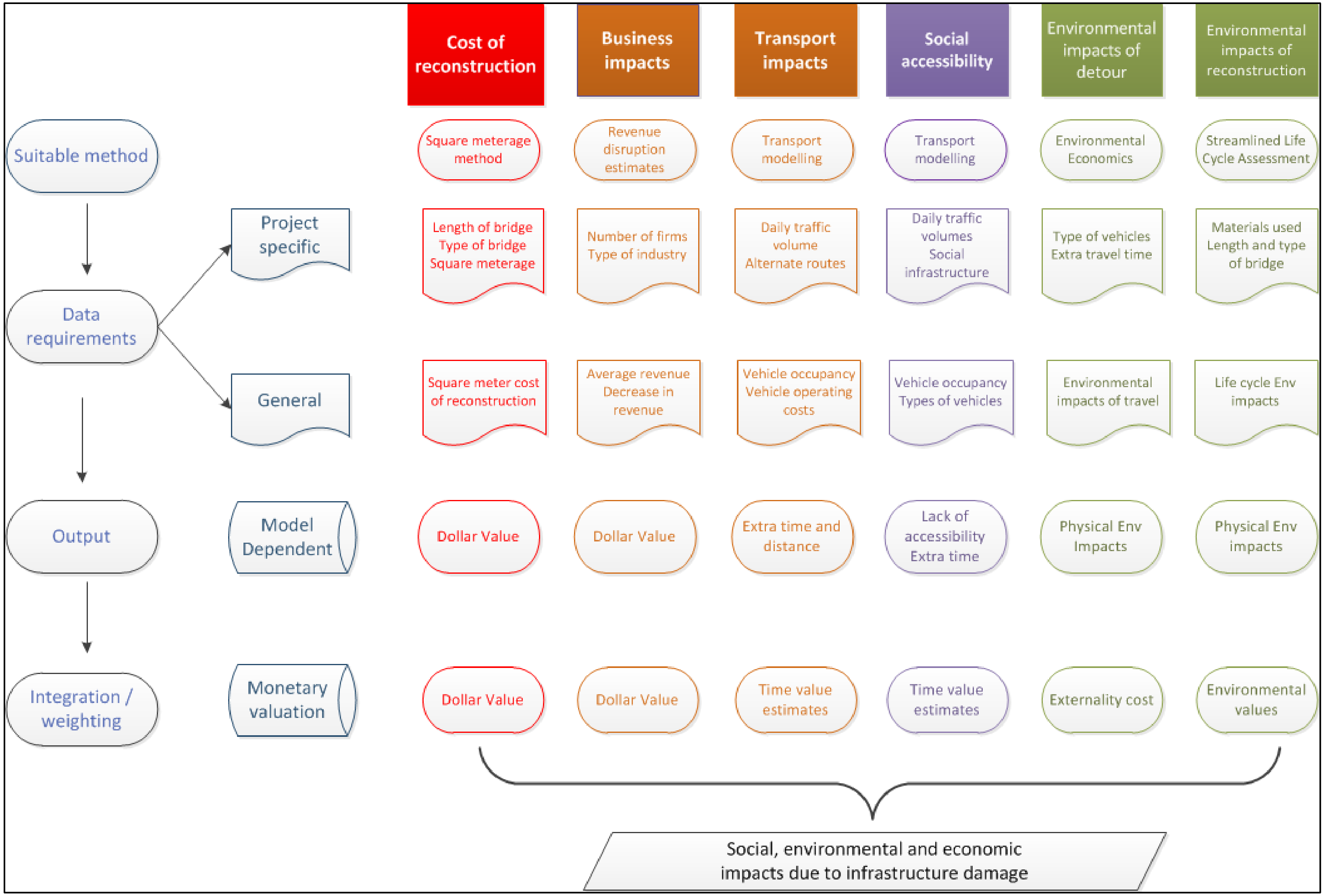
The majority of end-users mentioned that if the model were to be used widely, it needed to be used in conjunction with Cost Benefit Analysis and Value for Money assessments. Cost Benefit Analysis assesses the total private and external benefits of a project against its total costs to determine whether a project is socially beneficial, while Value for Money is a measure of the utility of the money spent on a project by assessing the efficiency and effectiveness of a given project (Cruz and Marques 2013). Both these methods rely on monetary estimates for their implementation. Such an option would increase the objectivity of the framework and can be used in conjunction with other techniques used currently for funding purposes. As the current methods rely purely on financial and technical parameters, the use of monetary valuation was considered to be compatible with them. A monetary valuation of impacts would make the assessment more objective and also increase its use across a wider group of decision makers.

6.4 Outline of the framework

This section explains how the selected methods have been brought together in a theoretically founded framework that can be used to measure social, environmental and economic impacts of road failure due to disasters. A detailed explanation of the selected methods, the fundamental assumptions behind them and their data requirements are explained in this section. Figure 6-1 illustrates the outline and process of the framework that was developed.

The framework presents a systematic method that can be used by researchers and practitioners to assess the sustainability impacts of road failure. It has been developed as a method of rapid assessment, giving the ability for it to be used soon after a disaster event. Given the context-specific nature of the usage of the framework, some of the equations and data used for the framework were modified to suit the case study region. However, this does not limit the usage of the framework in other regions or to assess impacts of varied transportation infrastructure. In order to increase the generalizability and spread of use across different jurisdictions, the different methods have been explained in detail. As the framework was tested through the assessment of damage to bridges in Lockyer Valley, Queensland, the data requirements and the framework itself was modified to suit the requirements of the case study region.

Figure 6-1 Outline of the framework



6.4.1 Direct tangible impacts

The direct tangible impacts of road structure failure were identified as the cost of damage to the bridge and the clean-up costs associated with it. The cost of damage can be estimated by using the cost of repair and reconstruction of the bridge as a proxy value to the damage to the bridge. These costs are estimated using a cost modelling approach. Cost modelling identifies specific items that need to be repaired or replaced and attributes monetary values to these items by using current market prices obtained from construction cost data bases or proxy costs. The accuracy of the cost modelling approach could be improved by incorporating the most relevant cost estimates that are available. The different methods and indices that can be used in a cost modelling approach are explained below. It should be noted that the focus of this framework is not to estimate the cost of reconstruction, as there are many academic and industry best practices that have been developed specifically for the estimation of reconstruction costs. However, for completeness of the measurement of all types of impacts, the estimation mechanisms for the cost of reconstruction are included in the framework.

Methods of reconstruction cost estimation

Engineering cost estimates can be categorised into three major types based on the time of estimation and level of details available for the estimation process (Holm et al. 2005). Conceptual cost estimates or approximate cost estimates are designed at a very early stage of the project, when detailed documentation and data is not available, and are typically used for feasibility assessment and budgetary and funding allocations (Seeley 1996). Semi-detailed and detailed estimates are with the use of detailed unit costs based on engineering drawings, prepared when parts of the project have been completely designed or fully designed and thus are expected to be more reliable estimates.

In a post-disaster context, time would be a critical factor, and decisions would need to be made in a shorter time period. Hence the use of conceptual cost estimates would be the most useful, even though such a method would compromise the accuracy of the estimate. For the purpose of this research, conceptual cost estimation methods were analysed as the cost of reconstruction would need to be estimated soon after a disaster when detailed project documentation would not be available. A number of approximate cost estimation methods could be used to estimate the costs.

Rough-order-of magnitude (ROM) cost estimates

ROM cost estimates, also known as construction costs per square metre are used to estimate the cost of construction based on historical cost data and are presented as square metre rates. Such square metre rates are calculated by local authorities or construction firms using their own historical costs, while similar costs are published in cost reference books for regions or countries.

Assemblies (elemental) cost estimates

Assemblies cost estimation uses unit cost rates for different elements of an infrastructure asset and can be carried out after a basic material selection has been done. The overall project cost is estimated by aggregating the costs of the different elements.

Cost indices

The costs of a project could also be estimated based on the cost of a similar project completed in a different geographical region and/or in a previous time period. Such cost indices would then have to be normalised to arrive at a more accurate figure applicable to the project under consideration.

Comparative estimates

Comparative estimates take the known costs of a similar construction project as a base and then make adjustments to this base cost to arrive at an approximate value. Comparative estimates are more useful for comparing alternative proposals in the conceptual stage of a project (Seeley 1996). Comparative estimates could also be combined with other methods such as elemental estimates and cost indices to arrive at a more reliable value.

The use of the specific method to estimate the cost of reconstruction will depend on the data availability at the time of assessment. It can be concluded that ROM cost estimates and elemental cost estimates would be more appropriate as they would provide more relevant and reliable estimates.

6.4.2 Indirect tangible impacts

Most indirect impacts of the failure of road structures stem from the decline in accessibility, connectivity and mobility due to the un-usability of a structure after a disaster. These indirect tangible impacts can be segregated into two main types of impacts. They are transport related impacts and impact on businesses. These two types of impacts are assessed using fundamentally different concepts: transport impacts are assessed based on transport engineering, whilst business impacts are measured based on basic economic modelling fundamentals. Therefore, the analysis of indirect impacts is treated under two main headings: transport impacts and business impacts.

Transport impacts

The major transport related impacts due to road structure failure are the costs of delay to users of the road. These delay costs can arise due to the un-usability of a road structure after a disaster and will continue until the structure is repaired or reconstructed and brought to normal operational conditions. Transport modelling was identified as the most suitable method to measure the transport related impacts in chapter 5.

Transport modelling could be carried out using software or by using equations to estimate traffic volumes. The use of software can be less time consuming if a model has been developed for the specific region under analysis. The Queensland Department of Transport and Main Roads uses the Brisbane Strategic Transport Model (BTSM) for transport modelling purposes, but its use has been predominantly for the Greater Brisbane region. As the case study area of this project was in regional Queensland, the BTSM could not be used and the transport model needed to be built using manual equations.

A typical transport model is run in four stages; trip generation, trip distribution, modal split and assignment (de Dios Ortuzar and Willumsen 2011). The trip generation phase aims to predict the total number of trips within the study zone. Such a prediction could be carried out in a number of ways such as travel surveys to households or estimations based on socio-economic properties of the given area. These studies will provide a basic idea of the amount of trips made within a geographical area. Trip distribution looks to estimate the purpose and/or the destination of the trips generated in the previous stage, while the next stage selects the specific modes of transport chosen for each trip. The final stage assigns the trips to the corresponding networks and provides the basis for the required analysis.

The typical four-stage model is only a point of reference, and some approaches estimate the trip frequency, destination and travel mode simultaneously or have estimated modal split before trip distribution (de Dios Ortuzar and Willumsen 2011). As the collection of data to perform the typical four-stage transport model can be costly and timely, simplified transport demand models using traffic count data can be used. Such models tend to be more suited to situations where transport modelling needs to be carried out in a short time frame with limited budgets and resources and have been used in post-disaster transport impact assessment (Negi et al. 2013, Pfurtscheller and Genovese 2016a).

Given the time constraints after a disaster and the inability to run surveys among residents affected due to road closures, transport modelling with the use of traffic count data was deemed the most appropriate. The following data requirements were identified to conduct a comprehensive transport modelling analysis.

- Average Daily Traffic (ADT)
- Alternative routes
- Incremental time and distance on alternative routes

Business related impacts

Road failure can cause numerous impacts on businesses in the disaster zone, due to disruptions to goods movement, decreased customer traffic and inability of employees to arrive for work, which could impact both revenues and costs of a firm. Business disruption impacts in this section do not consider increases in transport costs as they are included in the transport modelling step where the specific impact of freight is calculated. The focus here will be in on the secondary effects to the business stemming from the transportation disruptions.

The impacts on the business could be estimated by applying revenue loss estimates for different businesses that would be affected by road closures. The revenue disruption will depend on the types of businesses, as well as their proximity to the relevant structure. The total business impact in the region could be estimated by discounting the average earnings by an estimated reduction in revenue directly due to the disaster (Pfurtscheller and Genovese 2016a). The following equation was developed to assess the total impacts on business revenue.

$$\text{Daily reduction in business revenue} = \sum_{i=1}^{n} B_i * R_i * \frac{C_i}{100}$$

Where, B_i is the number of businesses of industry type *i*, R_i is the average daily revenue for a business type *i*, and C_i is the percentage of estimated loss of revenue. As the average daily earnings and the reduction in earnings would vary according to the type of industry the business operates in, the business entities needed to be categorised according to industry sectors.

6.4.3 Direct intangible impacts

Direct social impacts

The major direct social impact of road structure failure due to flooding is the injuries and lives lost during the event for people travelling on that specific road. As the focus of this research is purely on the impacts of road failure, the wider injuries and life loss due to the flooding events are excluded from the analysis. The most appropriate method to measure the social impact would be to quantify the number of individuals who were injured and killed during the event.

The valuing of lives is a contentious topic among scholars with polarising opinions on whether or not human life should be given monetary value. However, in most Cost Benefit Analyses or Value for Money assessments, human life and impacts to human life are assigned monetary values. Such values are used for decision making purposes where the decisions could affect humans. The direct social impacts relevant to this framework are the injuries and lives lost due to the damage to the road infrastructure, which can be assumed to have no influence on decision making processes in the post-disaster time period. As such the assessment of the direct social impacts would be relevant only when a total impact assessment of the structure or event is carried out. Although not specifically relevant to decision making processes, the framework did consider the impact on human life and how it could be incorporated in a holistic impact assessment.

A common method used to value social impacts is to use the Value of a Statistical Life (VSL) for a life lost. VSL is the amount that a group of people are willing to pay for fatal risk reduction in the expectation of saving one life (Miller 2000) and has been used to value the social impacts of lives lost on roads due to disasters (Dong et al. 2014b). Costs of injuries could also be valued using Value of a Statistical Life Year, which is based on VSL for a certain region (Abelson 2003).

Another method to value life loss and injuries after a disaster is to use the value of compensation paid for deaths or injuries by the Government to survivors (Negi et al. 2013). However, as compensation paid may differ from disaster to disaster the value used may vary drastically and hence be a challenge to be used in comparative analyses. However, if VSL figures are not available using compensation values may be a second option.

Direct environmental impacts

Potential direct environmental impacts of disaster induced road damage are water contamination due to chemical run-off from roads, destruction of natural habitat and natural life and the disposal of debris (Srinivas and Nakagawa 2008). A post-disaster environmental impact assessment would need to be carried out in order to estimate the total environmental impacts. The environmental impacts would vary drastically based on the type of infrastructure damaged, the type of disaster, the severity of the event and the environmental surroundings. Given the short time frame required for the analysis, a comprehensive environmental assessment may not feasible. In such an instance, a rapid environmental assessment would be the most appropriate to assess the environmental impacts.

A rapid environmental assessment could consider whether the structure is located in close proximity to any ecologically sensitive areas and how such areas have been affected. The environmental impact of debris disposal would be straight-forward to assess if the quantity, type of waste and method of disposal is known. The environmental impact of the disposal of debris could be estimated using a streamlined Life Cycle Assessment method (Birgisdottir and Christensen 2005).

6.4.4 Indirect intangible impacts

Indirect social impacts

The indirect social impacts could be divided into two main categories; 1) mobility related impacts and 2) psychological impacts. Mobility related impacts were measured using the percentage reduction in accessibility and mobility of the residents living in the area. The difference between the indirect tangible transport impacts and the indirect intangible transport impacts is that the tangible impacts include financial or economic costs associated with extra travel time and distance, while intangible impacts are impacts that cannot be assigned a monetary value based on market transaction costs. Such intangible social impacts relevant to this section include reduced access to schools, hospitals, markets, recreational activities, time spent away from home and extra travel time and delay to communities. These mobility related impacts could be estimated through the transport modelling technique explained earlier and are amalgamated using the extra time spent due to damage to structures. The extra time then could be valued monetarily according to environmental economics principles, which is common in CBA and transport infrastructure planning procedures.

The psychological impacts, although an important factor, were not considered in this research as it was deemed to be outside the scope of the researchers' knowledge and expertise to assess such impacts.

Indirect environmental impacts

The indirect environmental impacts could be broadly categorised into two: environmental impacts due to rerouting during reconstruction and the environmental impacts due to reconstruction. The indirect environmental impacts due to rerouting could be estimated through transport modelling techniques together with relevant environmental indicators for transport.

Environmental impacts of transport

As transport modelling has been carried out to assess the transport related impacts during reconstruction, this could be extended to estimate the environmental impacts associated with the detouring. Such extensions of transport modelling in post-disaster detouring scenarios have been used to estimate carbon emission impacts of detouring during the reconstruction phase (Dong, Frangopol and Saydam 2014a, Winter et al. 2016c). The environmental impacts of detours due to the damage of the bridge could include carbon emissions and air pollution from extra fuel burnt, soil and water pollution from vehicle run-off and noise pollution.

These environmental impacts could also be quantified monetarily using environmental economics principles, which gives an opportunity for the environmental impacts to be aggregated and compared with other social and economic impacts (Winter et al. 2016c). The method that was chosen in the development of the framework is to use a comprehensive set of environmental indicators not limited to carbon emissions and then to value it in monetary terms. This method requires the collection of data regarding the environmental impacts of transport of different types of vehicles and monetary values for these environmental impacts, preferably in an Australian context.

Environmental impacts of reconstruction

The reconstruction process of a damaged bridge could have the following environmental impacts:

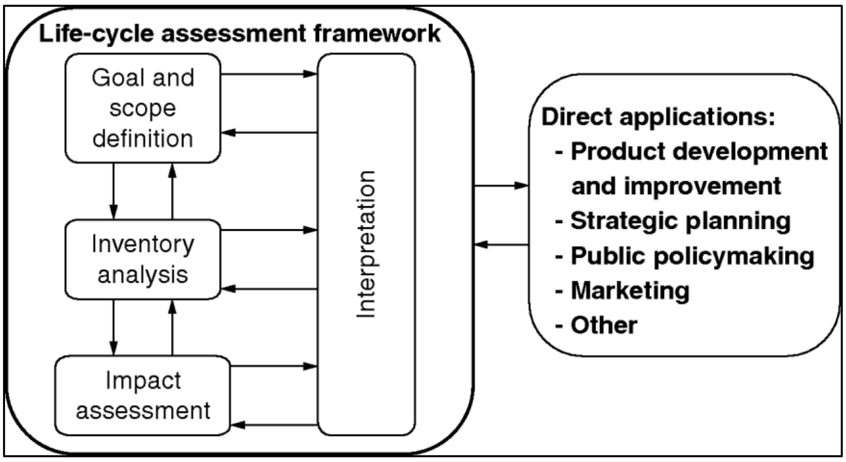
- Waste disposal
- Resource consumption
- Green House Gas emissions
- Soil, water and air pollution
- Destruction of fauna and flora
- Soil erosion and sedimentation

The environmental impacts occurring during the reconstruction process could be estimated using a Life Cycle Assessment (LCA) approach, which is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or process through its life cycle (International Organization for Standardization 2006). LCA studies have been conducted previously to assess environmental impacts of road structures (Du et al. 2014, Pang et al. 2015, Zhang, Wu and Wang 2016) and also to estimate impacts of natural disasters on bridges (Itoh, Wada and Liu 2005).

LCA can be conducted either with the use of licensed LCA software or by using public data bases. Licensed LCA software is the most common method used as it overcomes the challenges of the limited amount of publicly available data and the tedious modelling work required in the other method (Boulenger 2011). LCA addresses the potential environmental impact of a product or process, and cannot be used to predict the absolute or precise impacts due to the uncertainty in the modelling of environmental impacts and that some possible impacts are future impacts. Due to this reason, the reference units of the environmental impacts are expressed as potential impacts (International Organization for Standardization 2006).

There are four phases of an LCA study; goal and scope definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA) and the interpretation phase. The first phase details the scope of the study including the intended use of the study and the level of detail required. The LCI phase involves the collection and quantification of the inputs and outputs of a product or process based on the goals of the study. This data is then assessed through the LCIA phase where additional information is used to understand and evaluate the magnitude and significance of the potential environmental impacts. In the final stage, the results of the LCI or the LCIA or both are summarised and interpreted as a basis for decision making. These four phases have been explained in detail below with relevance to the LCA study for the case study bridges.

Figure 6-2 LCA framework



Source: (International Organization for Standardization 2006)

Goal and scope definition

The goal of the LCA study is to assess the environmental impacts of the reconstruction process of a bridge damaged by flooding events. The function studied through the LCA is construction of the bridge and the relevant functional unit would be construction of a bridge with the same technical specifications of the two case study bridges. The system boundary to be considered would be the incremental processes and material required to reconstruct the bridge to its original pre-disaster serviceable level. This would include any demolition and disposal of the old bridge and the materials and processes required for the construction of the new bridge. The operations, maintenance and disposal of the new bridge would be out of the scope of the study. Given that the LCA needs to be carried out within a short time frame, a simplified method known as Streamlined LCA was selected (Weitz et al. 1999).

Life Cycle Inventory analysis (LCI)

The data required for the LCI is typically primary data related to the study area to improve the reliability of the study. The LCI data required to conduct an LCA of bridge reconstruction are detailed below.

- Type and quantity of waste generated during the demolition of the damaged bridge
- Types and quantities of materials used for construction
- Methods used to transport the materials to the site
- Machinery and methods used on-site
- Resources (electricity, fuel, water etc.) used on-site
- Amount of waste and effluent generated during the construction

The following table shows the possible methods and sources that could be used to gather the required information to conduct a detailed LCI.

Table 6-2 Information requirements for a LCA study

Required information	Data sources
Type and quantity of waste due to demolition of the damaged bridge	Project reports Historical records
Types and quantities of materials used for construction	Bills of Quantities Tender documents
Methods used to transport the materials to the site	Construction plan
Machinery and methods used on-site	Construction plan
Resources used on-site	Machine specifications Purchase records
Waste generated during the construction	Project reports

However, accurate primary data related to the inputs and outputs listed above may not be available since the LCA of the reconstruction of the bridge needs to be carried out at a very early stage where detailed information may be lacking. If an LCA is to be carried out during early stages of the process where detailed information is lacking an approximate LCA could be carried out (Sousa, Wallace and Eisenhard 2000). One method to streamline the LCA is to use surrogate data where selected processes within an LCA are replaced with apparently similar processes based on physical, chemical, or functional similarity to the datasets being replaced (Weitz et al. 1999). Surrogate data refers to source data that is sufficiently similar to the process, material, or product for which target data does not exist and that is used to represent the target data (Canals et al. 2011).

The lack of sufficient onsite data and the difficulties in predicting the specific methods and machinery used in construction are some of the biggest challenges when conducting an LCA for bridges (Du et al. 2014). As a result, the vast majority of bridge LCA studies has used surrogate data to a certain extent.

The main types of material used for construction (concrete, steel, asphalt and reinforcement) have been found to account for the major portion of the environmental impacts of bridge construction (Hammervold, Reenaas and Brattebø 2011, Du and Karoumi 2014, Du et al. 2014). Therefore, a streamlined LCA study should focus on the environmental impacts caused by the material used during reconstruction. This could be carried out by estimating the types and quantities of the different types of materials that will be used for the construction and then applying the environmental impact indicators as explained in the LCIA phase below.

However, data relating to the quantities of materials used for the reconstruction was not available as the construction had been outsourced by the Council to a private company. Although the specific companies were contacted, obtaining the necessary data was not possible. As a result, a different method for a streamlined LCA was carried out for the estimation of the environmental impacts of reconstruction.

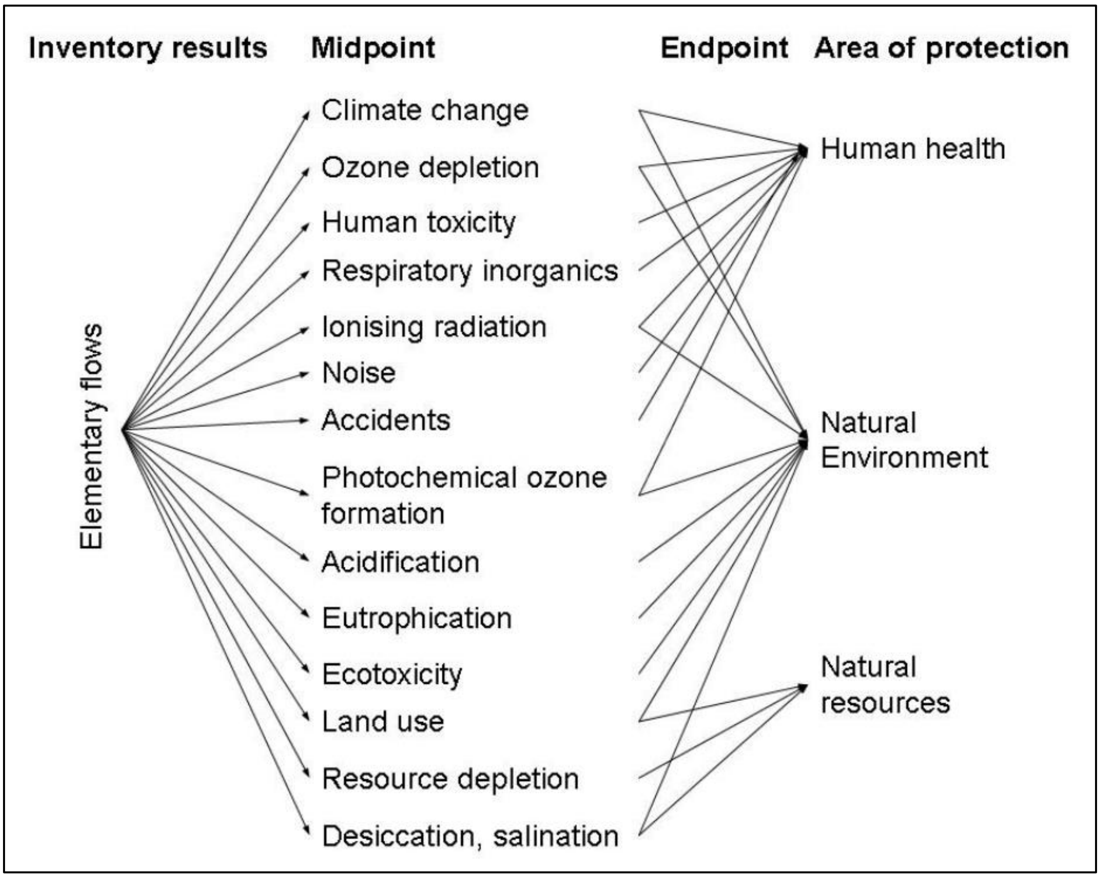
Given that the only details available were the length and the type of the bridge at the initial stage, the environmental impacts of reconstruction were estimated using surrogate data for square metre rates of the construction of a similar bridge. This technique is similar to the method used to estimate the financial cost of reconstruction based on a square meter reconstruction cost that was explained previously. To estimate the environmental impacts on a square metre rate, previous LCA studies on the construction of a similar bridge was assessed and then used as the surrogate figures.

Life Cycle Impact Assessment (LCIA)

The impact assessment phase of LCA involves connecting the inventory data obtained from the LCI phase with specific environmental impact categories and indicators (International Organization for Standardization 2006). This step helps in understanding the follow-on impacts, and provides information on the interpretation phase. The LCIA typically goes through four steps: selection of impact categories, characterisation, normalisation and weighting (European Commission - Joint Research Centre 2010).

The first step is to define the environmental impacts relevant to the study. The elementary flows from the LCI (emissions, resource consumption etc.) are assigned to impact categories according to each substance's potential to contribute to environmental problems. The impact categories typically assessed are detailed in the figure below.

Figure 6-3 Mid-point and end-point impact categories in LCA



Source: (International Organization for Standardization 2006)

As the environmental impacts would be estimated through a streamlined LCA based on surrogate data obtained from a previous LCA study, the environmental impacts and indicators for the LCIA stage would depend on those selected in the surrogate study. This can be a challenge if a detailed LCIA has not been carried out or if data relating to the LCIA stage is not clearly spelled out in the surrogate study.

The characterisation step involves the quantitative modelling of the elementary flows from the LCI. The result is expressed as an impact score in a unit common to all contributions within the impact category by applying characterisation factors. For example, kg of CO2- equivalents is the unit to measure greenhouse gases contributing to the impact category 'Climate Change'. The mid-point impact categories and the units of measurement are explained in detail below.

Table 6-3 Explanation of impact categories

Impact category	Reference unit	Explanation	Potential sources
Agricultural Land Occupation	m2 × year	The extent of agricultural land continuously used for human-controlled purpose	Industrial processes
Global Warming Potential (climate change)	kg CO2 eq	The impact of human induced global warming potential through Green House Gases to the atmosphere.	Fossil fuel combustion; electricity generation, transport and production processes
Fossil Fuel Depletion	kg oil eq	Depletion of fossil fuel stock considered a physical non-renewable resource	Fossil fuel combustion; electricity generation, transport and production processes
Freshwater Ecotoxicity	kg 1,4-DB eq	Impacts to individual species due to toxic substances released to aquatic environments	Waste disposal and production processes
Freshwater Eutrophication Potential	kg P eq	Release of nutrients to aquatic environments	Waste disposal, fuel combustion in electricity, transport and production processes
Human Toxicity Potential	Kg 1,4-DB eq	Adverse effects of chemicals on human health, including both carcinogenic and non-carcinogenic impacts	Waste disposal and production processes
Ionizing Radiation Potential	kg U235 eq	Impacts due to the release of radioactive substances to the air and water	Upstream processes related to construction
Marine Ecotoxicity	kg 1,4-DB eq	Impacts to individual species due to toxic substances released to marine environments	Waste disposal and production processes

Marine Eutrophication Potential	kg N eq	Release of nutrients to marine environment	Waste disposal, fuel combustion in electricity, transport and production processes
Metal Depletion	kg Fe eq	Depletion of metal stock considered a physical, non-renewable resource	Production processes
Natural Land Transformation	m2 x year	The extent of natural land continuously used for human controlled purpose	Industrial processes
Ozone-layer Depletion Potential	kg CFC-11 eq	Reduction in concentrations of ozone in the ozone layer due to the release of when ozone depleting substances to air.	Release of CFC, HCFRC and halons in refrigerants, solvents and fire extinguisher agents
Particulate Matter Formation Potential	kg PM10 eq	Release of PM that gives rise to secondary aerosols through atmospheric reactions	Electricity generation, industrial sources and transportation
Photochemical Oxidant Formation Potential	kg NMVOC	Impacts from increases in ozone concentrations in the troposphere	Incomplete combustion of fossil fuels
Terrestrial Acidification Potential	kg SO2 eq	Impact of acidic substances released to the air and subsequently deposited on land	Any fossil fuel consuming process
Terrestrial Ecotoxicity Potential	kg 1,4-DB eq	Impacts to individual species due to toxic substances released to land	Waste disposal and production processes
Urban Land Occupation	m2 × year	The extent of urban land continuously used for human controlled purpose	Industrial processes
Water Depletion	m3	Quantity of water that is no longer available for other uses because it has evaporated, transpired, been incorporated into products and crops, or consumed by man or livestock	Production processes

The potential environmental impacts measured through the LCIA relate to all possible impacts that could occur throughout the whole life cycle of the process considered. This includes environmental impacts from the extraction of raw material, production and processing of the materials, transport of materials to the site and the on-site construction process. Hence some environmental impact categories, such as urban land occupation and ionizing radiation potential, which initially may seem irrelevant to the reconstruction of a bridge need to be considered as these impacts may have occurred at the raw material extraction, processing or transport stages and not necessarily during the construction phase.

Normalisation and weighting

Normalisation and weighting are two optional steps that facilitate comparisons and aggregation of the potential environmental impacts identified in the LCIA process. The mid-point characterisation impacts could be normalised based on three end-points: human health, natural environment and natural resources, which facilitates comparisons across impact categories. Normalisation of the LCIA results was not carried out as showing the results of the different environmental impacts was considered to be less abstract and easier to comprehend for non-technical users. Further, midpoint impact assessment is generally carried-out in a bottom-up manner, which eases the aggregation of impacts (Pizzol et al. 2015). As a bottom-up approach was used to measure and aggregate other socio-economic impacts in this research the mid-point assessment of environmental impacts complemented such approaches.

The weighting phase aims at solving the incomparability of the different environmental impacts that are measured in varied biophysical units and ranks the different mid-point or end-point results using specific weights for each result. Weighting the different impacts by using monetary valuation allows for a direct comparison between the impacts, which eases the aggregation and comparison of the different impact categories as well as for integration with other social and economic impacts identified in this research project (Pizzol et al. 2017).

One of the methods to do this is known as the shadow price method. It uses the highest acceptable costs for mitigation measures as a weighting factor and has been used in valuing impacts of LCA studies (Pizzol et al. 2015) The advantage of using shadow prices is that different environmental impacts are translated into external costs that can be compared with each other and with internal production costs. However, the use of shadow prices can lead to certain intrinsic values being underappreciated during the total cost analysis (van Harmelen et al. 2007).

Different methods have been used for monetary valuation in LCA studies, and the methods typically vary depending on how the priority or weighting is assessed. The observed preference or market price method values an impact based on the market price if a market for it exists. The depletion of resources could be valued using the market prices of such goods if markets do exist. Such impacts are not considered externalities as the effect of the depletion of the resource will be included in the market price of the resource and therefore the costs of depletion have been internalised (De Bruyn et al. 2010).

When market prices are not available, revealed preference and stated preference approaches are used to obtain monetary values. Both these methods assess the willingness to pay for the avoidance of a negative environmental impact. The revealed preference approach uses prices in surrogate markets to assess the willingness to pay, while stated preference approaches determine willingness to pay using surveys that ask respondents preferences to hypothetical markets or trade-off situations (Pizzol et al. 2015). The observed preference or market price was identified as the most appropriate method for the valuation of resource depletion, the revealed preference approach of hedonic prices for the valuation of acidification, eutrophication and nuisance, while stated preference methods were appropriate for other impact categories (Pizzol et al. 2015).

The best method to obtain the monetary values relevant to the study is to conduct valuation studies in the study area. However, it was not possible or efficient to conduct such original valuation studies given the limited time and resources available for the PhD research. Budget and time constraints are common in most research projects, and hence the appropriate method to value impacts is the use of benefit transfer. Benefit transfer uses existing data from valuation studies to estimate environmental values for the area under study. Benefit transfer is helpful to estimate monetary values of projects where specific valuation studies to estimate values of nonmarket ecosystem services cannot be conducted due to time or budget constraints (Richardson et al. 2015).

Benefit transfer is commonly used by policy and decision making authorities as primary data collection for an original study is not practical given the short time horizons available (Iovanna and Griffiths 2006). Benefit transfer has the potential to provide approximate monetary values for resources in cases where such valuation would have been not possible. The approximate values obtained from benefit transfer is considered adequate for decision making processes where more precise values are not likely to change the conclusions of the analysis (Richardson et al. 2015).

The word “benefit” in benefit transfer refers to the benefit of an ecosystem service to a certain population that cannot be valued through a typical market. The value of the environmental impacts that needs to be measured in this case refers to costs as opposed to benefits. For example, in ecosystem service valuation, the monetary value will be calculated for the potential benefit of avoiding a certain level of pollution. However, when estimating values for pollutants that have been identified within an LCA study, the negative impact of that pollutant on society and the environment could be considered. The non-market costs of undesirable and negative impacts are referred to as shadow prices for a pollutant (Färe, Grosskopf and Weber 2006). In the valuation of the environmental impacts derived through the LCA both shadow prices and eco-system service values could be used. The values obtained from either of these two methods will result in a negative value as the impacts estimated through the LCA cause harmful impacts on humans and the environment.

In conducting benefit transfer specific criteria needs to be followed in order to increase the validity and the reliability of the results (Richardson et al. 2015). One main criterion that needs to be considered is that the commodity values need to be identical at the original study site and the policy site that they are applied to. Unit value transfers, where the shadow price obtained from an original study refers to the same unit of environmental impact as considered in the LCA, were used in order to reduce any discrepancies. Another important aspect to consider is the differences in the populations of the study site and the policy site. In order to reduce the applicability of the shadow prices to Australia, shadow prices from other industrialised nations were used, when values specific to Australia were not available. The temporal component of transfers was also considered when choosing the original literature to conduct benefit transfer, as some studies can be too old to make a reliable estimate through a transfer. Hence, the most recent studies were chosen and inflation rates used to value the estimates in 2012 prices, which was the year of analysis for the research.

Proposed streamlined LCA

The most suitable method to assess the environmental impacts due to reconstruction is to estimate potential impacts from materials used and the reconstruction process, which will be case specific. Although the lack of data prevented such a study from being carried out, this thesis proposes a streamlined method that could be used in future research. The proposed toolkit that was developed based on this framework uses the following method to estimate the environmental impacts of reconstruction.

Streamlined LCAs are carried out at a fairly high level to identify and qualitatively rank the most important aspects, and not so much for a detailed quantitative assessment (Allenby and Rajan 2012). Streamlined LCA provides the necessary information for internal validation of projects and can be used in engineering projects effectively to assess the environmental impacts (Jonker and Harmsen 2012) and will provide a rough measure of the environmental impact when imminent post-disaster decisions are made where less-than-perfect results are better than no results at all (Bala et al. 2010).

The functional unit for the proposed streamlined LCA would be the reconstruction process of a damaged bridge until it is brought to its original pre-disaster serviceable level. The boundary for a proposed streamlined LCA should be the incremental processes and material required for this reconstruction process. This would include any demolition and disposal of the old bridge and the materials and processes required for the construction of the new bridge. The additional environmental impacts due to detours during the reconstruction can be estimated through the transport impact analysis as explained in 7.3.5.

The most significant environmental impacts relevant to the scope of the proposed streamlined LCA were identified to be the material used for the reconstruction and the ecological impacts to the stream and its surrounds due to the reconstruction process. The estimation of the ecological impacts during the reconstruction process would be more challenging than estimation of impacts due to material use. However, since the impacts to the stream can have significant effects on the vulnerability of the bridge and the wider socio-ecological system in future rain events, a rough estimation of such impacts were considered a vital element.

The environmental impacts from material usage could be estimated using the following equation.

$$Environmental\ impact\ of\ material\ use = \sum_{i,j=1}^{n} M_i * E_{ij} * V_j$$

Where, M_i is the quantity of material i used, E_{ij} is the environmental impact of impact category j for material i and V_j is the monetary value of one unit of environmental impact category j.

The environmental impacts from the reconstruction process could be estimated using similar equations. When estimating the environmental impacts during the construction process, more focus should be given to the significant impact categories relevant to the region of analysis. Such impacts with relevance to the reconstruction of bridges could include soil erosion, sediment run-off and negative impacts to water quality.

6.4.5 Integration of the different impacts

The integration of the different types of impacts helped in the practical use of the framework in decision making. This was one aspect that was highlighted in the end-user interviews. In addition, the results obtained needed to be easily understood and allowed for use in conjunction with the financial analysis techniques that were being used. In order to achieve these outcomes, a monetary weighting of the different impacts was carried out. The monetary valuation of the impacts allowed for each type of impact to be aggregated in a seamless manner without the need for subjective expert opinions being used. Estimating social and environmental impacts using monetary values is considered a practical method for use in policy decision making, as it allows the impacts to be compared with economic services and manufactured capital (Costanza et al. 1997).

As monetary weighting was selected as the most suitable option to integrate the different impacts, the representative functional units used to measure the impact categories were selected based on the ease of converting them to monetary values. For example, physical socio-ecological impacts of transportation were not calculated, as the total external costs of transport were available per kilometre travelled. This approach reduced the number of steps required in the calculation process in the instance where relevant monetary values were available. However, if monetary values for such functional units were not available, a step-by-step approach to value the different impacts was adopted.

6.5 Toolkit to test framework

The framework that was explained in Section 6.4 was used to develop an interactive platform that can be used by end-users to measure sustainability impacts to aid in post-disaster decision making. The initial step was to develop an Excel-based toolkit that can be used to test the validity of the framework in measuring impacts. It also gave the opportunity for end-users to understand the real-life applications of the framework and to provide feedback on its useability. The toolkit was used to measure impacts in a disaster affected region in Queensland, in a case study based approach. The toolkit has been developed with the specific objective of measuring impacts of damage and closure to road bridges. The program structure, analytical elements and the data base was created by the author. This toolkit could be developed further with the aid of software developers for it to be more user-friendly and to be available to be used on a web-based platform. Such steps will increase the adoption of the toolkit across diverse authorities. The different working tabs in the toolkit are explained below.

6.5.1 Contents page

The first sheet gives a brief introduction to the toolkit by explaining the different worksheets, how it should be used, and methodology and key assumptions used. This section is designed for the user to get a basic idea of the toolkit and how it can be used in a step-by-step process.

Figure 6-4 Contents page of the toolkit

Framework and Toolkit to measure SEE impacts of Bridge Failure
Contents Page

Model Framework	Description
Project Specific Data	This sheet allows users to enter the project specific data that will be used for calculations. The data needs to be entered manually by the user. These data requirements were formulated based on minimum amount of data generally available to end-users. If users have more detailed and specific data for these items, they could be included in this sheet. In such instances the underlying equations in the Calculations and the Reporting Sheet would need to be modified.
Calculations	The calculations sheet includes some predetermined calculations needed to combine and/or convert values in the Project Specific Data and Reference Database so that they could be easily used to calculate the final assessment of the impacts.
Reporting Sheet	This sheet reports the final summary of the different impact categories. The final reporting sheet combines the different types of impacts and reports them in monetary values. The impacts are categorised as economic, social and environmental and includes damage to the bridge, transport impacts, business impacts, lives lost and environmental impacts of detours. The techniques used to calculate these impacts are explained below.
Reference Data Base	The reference database contains standard data which is used for the calculation of the impacts. This data has been sourced mainly from Australian Government reports and websites. The standard data saved in this sample framework has been sourced with specific reference to Lockyer Valley region in Queensland as the framework was tested in this area. However the users have the freedom to add more relevant data, based on the location of the project and to update the database if and when updated data is available for use.
User defined data base	This sheet includes some predetermined calculations needed to combine and/or convert values in the Project Specific Data and Reference Database so that they could be easily used to calculate the final assessment of the impacts.
Methodology and key assumptions	
Damage to the bridge	The damage to the bridge can be included directly by the user if estimated costs of reconstruction are available. If not the the reconstruction cost could be estimated using the standard costs based on square meterage values. More relevant or up-to-date standard costs could be used by adding such values to the Reference Database and modifying the equations. The final damage cost is estimated by discounting (subtracting) any costs that have been incurred for upgrades that were not part of the initial bridge when it was damaged.
Transport impacts	Transport impacts refer to additional time and costs incurred by road users due to the delays and detours during the reconstruction period. This includes both economic and social impacts. The economic impacts are increased vehicle operating costs and freight delay costs, while the social impacts are the increased delay times for individual road users. The transport impacts will vary based on the number and types of vehicles using the road, the additional time and distance on detour roads and the duration of the reconstruction period.
Business impacts	The business impacts estimates the reduction in revenue to business entities located in the vicinity of the damaged structure. User discretion is required when interpreting these values as they are based on subjective data regarding the average turnover of businesses and the percentage reduction in turnover which are entered by the user.
Environmental cost of detour	The environmental impacts of vehicle detours during the reconstruction period are calculated by multiplying the total incremental distance travelled by the total environmental externality cost of the different types of vehicles.
Environmental cost of reconstruction	The environmental costs of reconstruction are estimated using a Streamlined Life Cycle Analysis approach.
Total impact	The different types of impacts are converted to monetary values and presented. A conversion to monetary values helps in Cost Benefit Analysis or Value for Money assessments that were identified as a user requirement through the initial interviews.

:Notes
. Please note that this is a pilot version of the framework that needs to be validated before being used for practical decision making purposes
. The layout of the framework is not final and needs to be improved to make it more user-friendly and adaptable to end-users

6.5.2 Project specific data

The next section is designed to allow users to enter the project specific data that will be used for calculations. The data needs to be entered manually by the user. These data requirements were formulated based on a minimum amount of data generally available to end-users. If users have more detailed and specific data for these items, they could be included in this sheet. In such instances, the underlying equations in the Calculations and the Reporting Sheet would need to be modified.

Figure 6-5 Project specific data sheet

	B	C	D	E	F
1	Type of Input	Value	Unit	Source	Notes
2	Estimated cost of reconstruction	2,500,000.00	AUD		
3	Length of Bridge	0.09	Km		
4	Square area of bridge deck	450	Square m		
5	Clean up costs	2,000.00	AUD		
6	Damage to vehicles	4,000.00	AUD		
7	Net disaster relief payments to LGA	200,000.00	AUD		
8	AADT	958	No. of vehicles		
9	%HV	8.7	% of AADT		
10	Distance on alt route	2.086	km		
11	Time on alt route	2.62	mins		
12	Duration of road closure	150	days		
13	Duration of road closure (Heavy vehicles)	630	days		
14	Number of nano-businesses impacted	1			
15	Number of small businesses impacted	2			
16	Estimated reduction in revenue (nano)	30%			Daily reduction in revenue
17	Estimated reduction in revenue (small)	5%			Daily reduction in revenue
18	Lives lost	0			
19	Quantity of demolition waste	450	Tonnes		

6.5.3 Calculations

The calculations sheet includes some predetermined calculations needed to combine and/or convert values in the Project Specific Data and Reference Database so that they could be easily used to calculate the final assessment of the impacts.

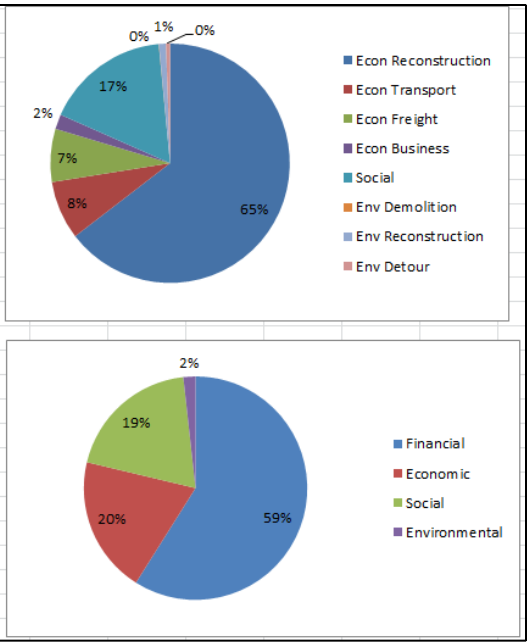
6.5.4 Reporting sheet

This sheet reports the final summary of the different impact categories. The final reporting sheet combines the different types of impacts and reports them in monetary values. The impacts are categorised as economic, social and environmental, and include damage to the bridge, transport impacts, business impacts, lives lost and environmental impacts of detours. The techniques used to calculate these impacts are explained below.

Figure 6-6 Reporting sheet

Impact	Cost ($)	% of Total
Direct financial	1,302,000.00	58.95%
Transport impacts	816,543.34	36.97%
Business Impacts	51,200.00	2.32%
Environmental cost of detour	14,036.04	0.64%
External cost of reconstruction	23,734.86	1.07%
Environmental cost of demolition	1,021.50	0.05%
Total impacts	**2,208,535.75**	

Impact	Cost ($)	% of Total
Financial	1,302,000.00	58.95%
Economic	436,809.72	19.78%
Social	430,933.62	19.51%
Environmental	38,792.40	1.76%
	2,208,535.75	



6.5.5 Reference database

The reference database (Appendix A) contains standard data that is used for the calculation of the impacts. This data has been sourced mainly from Australian Government reports and websites. The standard data saved in this sample framework has been sourced with specific reference to the Lockyer Valley region in Queensland as the framework was tested in this area. However, users have the freedom to add more relevant data, based on the location of the project and to update the database if and when updated data is available for use. The reference database also presents the users over 200 detailed data points relating the measurement of SEE impacts. The data base is categorised according to different data groups and unique names, making it easier for users to select the most appropriate data point to be used in calculations.

In addition, a user defined database includes some predetermined calculations needed to combine and/or convert values in the Project Specific Data and Reference Database so that they could be easily used to calculate the final assessment of the impacts.

6.6 Summary

Based on the analysis of previous literature and an end-user needs assessment a framework to measure the sustainability impacts of road structure failure was developed. This framework is intended to add to academic knowledge in the area by providing scholars a systematic method that can be used to measure a comprehensive set of impacts. An Excel based toolkit has been developed based on the fundamental principles of the framework. This toolkit is intended to test the validity of the framework and be used by practitioners to aid in post-disaster decision making processes. The toolkit was developed to be flexible and scalable so that it could be used in varied disaster situations, in different geographical locations and by a diverse group of practitioners. The next chapter explains how this toolkit was used to measure the impacts in disaster affected regions.

7. CASE STUDY

7.1 Introduction

The relevance of the developed framework and the practical use of the toolkit were tested through a real-life application in a disaster impacted region. This chapter explains how the toolkit was modified for the use in measuring sustainability impacts due to damage to bridges. One of the criteria in developing the toolkit was to allow for modifications so that it could be catered to local conditions and requirements. This was valuable when measuring the impacts in the case study region as the equations in the toolkit needed to be modified to suit the data available in the location. The toolkit was designed to overcome challenges in data collection and other resource constraints that would be practical issues faced during post-disaster decision making.

This chapter provides an explanation of the case study region for the reader to get an idea of the setting and the importance of measuring wider socio-economic impacts due to road damage. The data collection process is explained with information provided on where specific data was obtained from. The final section gives a detailed explanation on how the different types of impacts were measured.

7.1.1 Case study location

The area selected for the case study was the Lockyer Valley Regional Council, situated in South East Queensland, Australia. The Lockyer valley is situated in a flood plain and is a major catchment for the Brisbane area. The Lockyer Valley region experienced major flooding due to tropical cyclones in 2011 and then again in 2013, with heavy damage occurring to road infrastructure. The 2010-11 events saw close to 80% of the road network being damaged while 43 out of the 46 bridges maintained by the Lockyer Valley Regional Council (LVRC) were damaged in subsequent floods in 2013 (Lokuge and Setunge 2013).

The Lockyer Valley region was selected for the case study as it is a regional area that had experienced repetitive flooding events, which had caused major impacts to road infrastructure. As most of the previous work measuring wider impacts of damage to road infrastructure has concentrated on urban areas, this research project focussed on a more regional area. Impacts were presumed to differ between urban and regional areas as there is generally a lack of alternative routes in regional areas and because reconstruction may take longer in regional areas as opposed to more urban settings. Impacts in regional areas will also be spatially narrow, thus making it easier to measure.

Two bridges that were damaged during the 2013 floods were selected to conduct the case study. The two bridges were selected after consultation with the Infrastructure Works and Services Department of the LVRC based on the importance of the locations and the availability of data specific to those structures. Both bridges were completely damaged during the 2013 floods and were reconstructed.

The Thistlethwaite Bridge is situated on the Grantham Winwill Road, a major arterial road servicing a productive vegetable cropping district and the Stanbroke Meat Processing Plant, the region's largest employer. The Clarke Bridge is located in a more rural setting and provides access to the Thornton State School. The two bridges are located in two diverse areas in the Council, with the Thistlethwaite Bridge located in a more densely populated, economically vital area while the Clarke Bridge is located in a more rural setting. Both bridges were timber bridges and were replaced by concrete structures after they were damaged in the floods.

Figure 7-1 Thistlethwaite Bridge after the 2011 floods

Figure 7-2 The damaged Thistlethwaite Bridge after the 2013 floods

Figure 7-3 The damaged Clarke Bridge after the 2011 floods

7.2 Data collection

7.2.1 Data requirements

Following the selection of the specific methods to assess the various types of impacts, the data requirements for those methods were listed. The requirements were obtained by conducting an analysis of the literature that had used the specific methods for prior assessment. The following table shows the data requirements identified.

7.2.2 Data collection process

The data collection was carried out in two distinct methods. The site specific data related to the two case study areas were collected by personally contacting the officers of the Lockyer Valley Regional Council, Queensland Reconstruction Authority and the Department of Transport and Main Roads, Queensland. The information obtained from these organisations was mainly sourced from their documented historical records, while interviews were used to obtain more generic information about the activities and the surroundings of the case study areas.

The majority of the statistical data was obtained from publicly available data sources through a desktop search. The sources included data sets, government reports, publicly accessible data bases and academic publications.

Table 7-1 Data requirements and data sources

Category	Potential impacts	Data requirement	Method	Source
Economic	Damage to infrastructure	Cost of reconstruction	Interviews, Data sets	QRA, TMR, Qld Gov, LVRC
		cost of additional mitigation	Interviews, Data sets	QRA, TMR, Qld Gov, LVRC
		Depreciation / discounting rate	Interviews, Data sets, calculation	QRA, TMR, Qld Gov, LVRC
	Clean-up, emergency relief costs	Total cost paid	Interviews, Data sets	QRA, Disaster Assist, LVRC
	Disaster relief	Direct payments made	Interviews, Data sets	QRA, Qld Govt, Disaster Assist
	Transport impacts	Possible alternate routes	Calculations	Google maps
		Distance and time on normal route	Calculations	Google maps
		Distance and time on alternate route	Calculations	Google maps
		Duration and extent of disruption	Interviews, Public data	LVRC, TMR
		Traffic volume	Data sets	TMR, LVRC
		Type of vehicle used	Data sets	ABS, ATAP
		Fuel usage	Data sets	ABS, ATAP
		Average occupancy	Data sets	ATAP
		Fuel prices (pre and post)	Data sets	ATAP
		Vehicle operating cost	Data sets	BITRE
		Freight delay costs	Data sets	BITRE

		Delay costs for occupants	Data sets	BITRE, ABS, ATAP
	Business impact	Average weekly earnings	Data sets	Chamber of Commerce, ABS
		% reduction in earnings	Calculations, Literature	
		Number of days affected	Public data	
	Personal income	Avg daily income	Weekly earnings, income LGA level	ABS
		Days away from work	Estimations	
		Days away from home	Public data, estimations	
		Cost of accommodation	Estimations	
Social	Lives lost	Number of deaths on the road	Interviews, data sets	LVRC
		Disaster relief paid	Interviews	Disaster Assist, LVRC
		Value of statistical life	Data sets	Office of Best Practice Regulation, BITRE
		Value of statistical Life Year	Data sets	Office of Best Practice Regulation, BITRE
	Injury	Cost of injury	Data sets	BITRE
	Extra travel time	Congestion cost, health cost of air pollution	Data sets	BITRE
		Private travel cost	Data sets	TIC, ATAP
Environmental	Environmental impact of detour	External costs of transport	Literature	
	Environmental impact of reconstruction	Life cycle impacts of bridge construction	Literature	
		Monetary values of environmental impacts	Literature	Environmental Valuation Reference Inventory
		Quantity of C&D waste	Estimations	

7.3 Results

The data collected for the two case studies were used to estimate the social, environmental and economic impacts due to the damage and subsequent reconstruction of the bridge. The following sections explain in detail how sustainability impacts could be estimated given a constraint on data availability and time to conduct an assessment soon after a disaster.

7.3.1 Direct tangible impacts

Direct tangible impacts are those impacts that occur due to direct damage to the specific road structure, and will include costs such as road clean-up, debris disposal, damage to infrastructure and damage to vehicles on the road at the time of the disaster (Merz et al. 2010). As there were no vehicles affected while crossing the bridge during the floods, the analysis mainly focused on the costs of immediate clean-up and recovery and damage to the structure.

Estimated cost of bridge reconstruction

The estimation of the reconstruction costs was not a major focus of this study as there is comprehensive literature focussing on detailed construction cost estimations. The purpose of this section is to provide a brief description of how reconstruction costs of bridges could be estimated in a post-disaster context in Australia. Such a description added to the holistic approach taken in this research project. The cost of bridge reconstruction was estimated based on conceptual estimation techniques as highlighted in 6.4.1. Square metre costs to estimate the cost of reconstruction is the accepted method of the Australian Government Natural Disaster Relief and Recovery Arrangements (NDRRA) at the initial stage of project funding. Therefore it was deemed suitable to use a square metreage method to estimate the reconstruction costs soon after the disaster event.

Construction costs were estimated for both the Thistlethwaite and Clarke bridges based on initial estimated square metre areas of the proposed new bridges. This data was obtained from the Lockyer Valley Regional Council through a schedule of quantities for the two bridges. A detailed cost estimation using a Bill of Quantities (BOQ) could not be carried out as the Council did not have the required data since the construction of both the bridges was contracted to private companies. Efforts to obtain data from both the construction companies were unfruitful. The cost estimation was conducted using the rough-order-of-magnitude or square meter cost estimate method. The square metre rates for the estimation were obtained from two different sources, which allowed for comparisons and are explained in detail below.

Estimates using Rawlinson Australian Construction Handbook unit rates

The Rawlinson Australian Construction Handbook is a widely recognised source in the construction sector and is used to estimate costs of construction projects in Australia (Islam et al. 2014). This handbook provides cost estimates for various types of construction work based on local average cost data and provides information necessary for cost benefit studies (Rawlinsons 2013). The Rawlinson cost estimates have been used to estimate damage indices for buildings affected by natural disasters (Blong 2003), life cycle cost estimates (Lu, El Hanandeh and Gilbert 2017) and rehabilitation costs of community buildings (Mohseni 2012).

(Rawlinsons 2013) provides construction costs per square metre and elemental costs for bridge works, as well as cost indices for metropolitan and regional areas in Australia. The handbook recommends the use of square metre costs for initial feasibility studies, as they would provide no more than a rough guide to the probable cost (Rawlinsons 2013). The regional cost indices are an indication of the cost adjustment factor to be used in order to estimate a more reliable cost for construction in country towns.

The square metre costs most relevant for the Thistlethwaite Bridge were identified as the composite price of a two lane 11metre wide reinforced concrete single span bridge for Brisbane, while for the Clarke Bridge it was a single-lane overpass 7 metres wide. The composite price was presented within a range of $1,680 and $1,800 per square metre for the two-lane bridge, while for the single-lane bridge it was $1,720 and $1,820. As this cost excluded approach works, abutments and piling, it was decided to use the upper limit of this cost range for estimation purposes.

This cost was then multiplied by the regional price indices in order to reflect a more accurate cost of bridge construction in the Lockyer Valley region. The regional cost index for Toowoomba of 103, which was the closest city for which cost indices were available, was used for this purpose. The cost of construction of a two-lane bridge was estimated to be $1,854 per square metre while for a single-lane bridge it was estimated at $1,874.6 per square metre. The approximate cost estimate for the two case study bridges using this value is presented in Table 7-2 below.

Table 7-2 Estimated reconstruction costs using Rawlinson estimates

Bridge	Square metres	Estimated reconstruction cost ($)
Thistlethwaite Bridge	450	834,300.00
Clarke Bridge	159.6	299,186.16

Estimates using Transport Infrastructure Council (TIC) unit rates

The Bureau of Infrastructure, Transport and Regional Economics (BITRE) estimated the cost of bridge construction using state and territory supplied historical cost data for the whole of Australia (Transport and Infrastructure Council 2015). These cost estimates are categorised according to road classes based on the Austroads functional road classification definitions. However, as the LVRC road classification was different to that of the classification provided by (Transport and Infrastructure Council 2015), the required unit prices were obtained by using the following table of classifications.

Table 7-3 Comparison of road classifications

Bridge	Classification by LVRC	Related classification by TIC
Thistlethwaite	Rural arterial	Class 2: Principal rural arterial
Clarkes	Rural access	Class 3: Main rural arterial

Table 7-4 shows the relevant square metre cost estimates obtained from (Transport and Infrastructure Council 2015).

Table 7-4 Unit costs provided by TIC

	Unit	Class 2	Class 3
Average project cost (Excluding land acquisition)	$m / lane km	3.72	2.7
	$/lane m	3720	2700
Average bridge cost	$/sq. m	4150	3880

Source: TIC 2015, *Infrastructure benchmarking report*, Transport and Infrastructure Council, Australia

Based on the above cost estimates and the square metre rates obtained from the schedule of quantities, the cost of reconstruction for the two bridges were calculated and are shown in Table 7-5.

Table 7-5 Estimated reconstruction costs using TIC unit rates

	Unit	Thistlethwaite	Class 2 $	Clarke	Class 3 $
Average project cost (Excluding land acquisition)	$/lane m	90	334,800	38	102,600
Average bridge cost	$/sq. m	40	1,867,500	159.6	619,248
Total			2,202,300		721,848

Comparison between Rawlinson and TIC unit rates

The average bridge cost according to the (Transport and Infrastructure Council 2015) values show a drastic difference in contrast to the cost values presented in (Rawlinsons 2013). The bridge cost per square metre as per (Rawlinsons 2013) is 55% lower for Class 2 roads when compared with the (Transport and Infrastructure Council 2015) values, while for Class 3 roads it is 52% lower. The reason for this disparity could be due to the following reasons:

- (Rawlinsons 2013) values exclude the costs for approach works, abutments and piling, which could add up to a significant portion of the total cost of the bridge.
- (Rawlinsons 2013) estimates are for single span bridges, whereas the (Transport and Infrastructure Council 2015) values are an average for all bridges including multiple span bridges.

Council cost estimates

The LVRC also carries out cost estimation for the reconstruction processes for funding and budgetary purposes during the planning stages of construction. At the initial stage, councils applying for funding from the Queensland State Government are required to estimate the cost of the project using the square metre method for the relevant area of the bridge deck. The LVRC uses their own unit rates for this initial estimation based on historical costs and quotations received from contractors in previous years.

The cost estimates for the two case study bridges based on the LVRC estimates were obtained from Council and is presented in Table 7-6 below.

Table 7-6 Council estimates of reconstruction costs

	Thistlethwaite Bridge	Clarke Bridge
Estimated cost of construction ($)	3,502,707.90	1,265,829.00

Direct tangible impact due to damage to the bridge

The purpose of measuring the cost of reconstruction of damaged bridge is to estimate the cost of the damage to the original structure due to the disaster. When the damage to a structure is not very extreme and the structure could be brought to its original pre-disaster service level through repairs, the cost of repair would indicate the financial cost of damage to the structure due to the disaster. However, if a structure needs to be completely demolished and constructed newly, the total reconstruction cost would be reflective of the direct cost of damage due to the disaster. In the instance where a structure is reconstructed newly, the post-disaster reconstruction work may include upgrades to the structure, which did not exist at the time it was destroyed.

In the case of the Thistlethwaite Bridge, the structure that was damaged by the flooding in 2013 was a timber bridge, while it was replaced by a better designed concrete structure. Therefore in order to estimate a more accurate cost of damage due to the floods the cost of a timber bridge needs to be measured. As the financial cost of constructing the original timber bridge was not available, prior literature was analysed to estimate the cost differences between timber and concrete bridges. The cost of construction of short span timber bridges has been found to be 25-30% less than similar concrete bridges (Tazarv, Carnahan and Wehbe 2019, Behr, Cundy and Goodspeed 1990). Using this figure, it can be concluded that the direct cost of damage to the original timber bridge would have been approximately 75% of the reconstruction cost of the concrete bridge.

Another factor that needs to be considered is that the above cost is for a new build, which may include upgrades to the asset that was not part of the asset when the bridge was damaged and (Stephenson et al. 2013) argue that it is important to use the depreciated value of the asset at the time of the disaster rather than the reconstruction cost when assessing damage to infrastructure. They propose to use a percentage of the replacement or repair cost as an estimate of the depreciated value of the asset. However, as data relating to the date of construction or depreciated values of the bridge at the time of the disaster were not available, further discounting of the direct costs was not carried out.

Costs of road clean-up and disposal of debris

Interviews with council staff elicited that road clean-up and debris disposal after the flood event was carried out by council staff, residents and volunteers from outside the locality. However, data relating to costs involved or the associated amount of man-hours for the clean-up where not available and as a result the analysis has left out any potential costs incurred due to immediate clean up and recovery efforts. Further as the recovery effort included all flooded areas even if such data was available it would have been challenging to isolate the costs for the two specific bridges under consideration.

No accurate estimate for the immediate recovery phase could be ascertained as previous literature has shown that the recovery costs could vary drastically when compared with the total direct impacts. (Winter et al. 2016b) found that the clean-up and recovery phase for two different cases were 19% and 67% of the total direct tangible impacts.

7.3.2 Indirect tangible impacts

Most indirect impacts of the failure of road structures stem from the decline in accessibility, connectivity and mobility due to the un-usability of a structure after a disaster. These indirect tangible impacts can be segregated into two main types of impacts. They are transport related impacts and impact on businesses. The literature reveals that these two types of impacts are assessed using fundamentally different concepts. Transport impacts are assessed based on transport engineering, whilst business impacts are measured based on basic economic modelling fundamentals. Therefore, the analysis of indirect impacts is treated under two main headings; transport impacts and business impacts.

Transport impacts

As discussed in Chapter 6, a transport model was developed to measure the transport related impacts of road infrastructure failure. The model was developed in a sequential method similar to a four-stage transport model. Traffic count data obtained from the council was used for the trip generation phase as collecting data and deriving transport demand models was impractical in post disaster scenarios.

Estimating number of trips

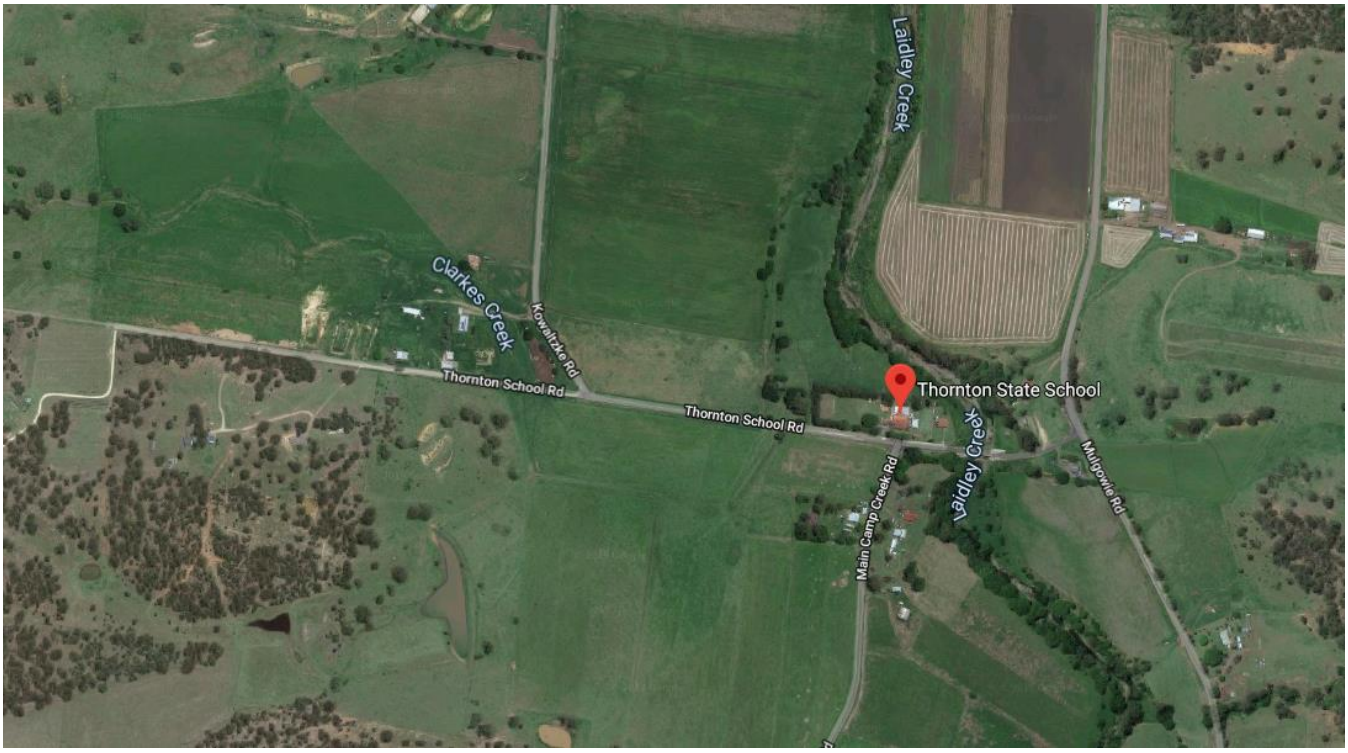
The total number of trips using the bridges was estimated using real life traffic counts, which were obtained from the LVRC Infrastructure Services team and the Department of Transport and Main Roads (TMR), Queensland. The two-way Average Annual Daily Traffic (AADT) volumes for the Grantham-Winwill Road, on which the Thistlethwaite Bridge is located, was provided by the LVRC and was a good estimate to the number of vehicles using the bridge on a daily basis. The AADT was 958, while the percentage of heavy vehicles was 8.7% of the total AADT.

However, traffic count data for Clarke Bridge on the Thornton School Road was not available, and further calculations were carried out to estimate the number of vehicles using the bridge on a daily basis. The Clarke Bridge crossed the Laidley Creek on Thornton State School Road (Figure 7-4). It provided access from Mulgowie Road to Thornton State School and three other properties on Thornton School Road and approximately 25 other properties on Main Camp Creek Road. Thornton State School had an enrolment of 39 students for 2013 with a full-time staff of nine in addition to visiting staff (Queensland Government 2014). The following assumptions were made to estimate the vehicles per day (VPD) for the Clarke Bridge.

- The school staff would use the bridge twice a day
- All the students would be dropped and picked up in a vehicle, and these vehicles would use the bridge four times a day.
- The number of ride-sharing users was assumed to be 25% of all students.

- The residents on Thornton School Road would use the bridge twice a day.
- 50% of the residents on Main Camp Creek Road would use the bridge twice a day.
- The number of trips on non-school days was assumed to be only the residents' travel.
- The number of school days in a year was assumed to be 200.
- The percentage of heavy vehicles using the bridge was estimated to be 4.4%, which was half of the heavy vehicle percentage on the Thistlethwaite Bridge.

Figure 7-4 Map indicating the location of Clarke Bridge



Trips on school days = trips by school staff + trips by parents + trips by residents

= No. of staff x 2 trips + No. of students x 4 trips + No. of residents x 2 trips

= 9 x 2 + (39 x .75) x 4 + [(3 x 2) + (25 x .50 x 2)]

= 166

Trips on non-school days = No. of residents x 2 trips

= (3 + [25 x .50]) x 2

= 31

Total yearly trips = trips on school days x no. of school days per year + trips on non-school days x no. of non-school days per year

= 166 x 200 days + 31 x 165 days
= 38,315

VPD = Total yearly trips / 365 days

$= 104.97 \approx 105$

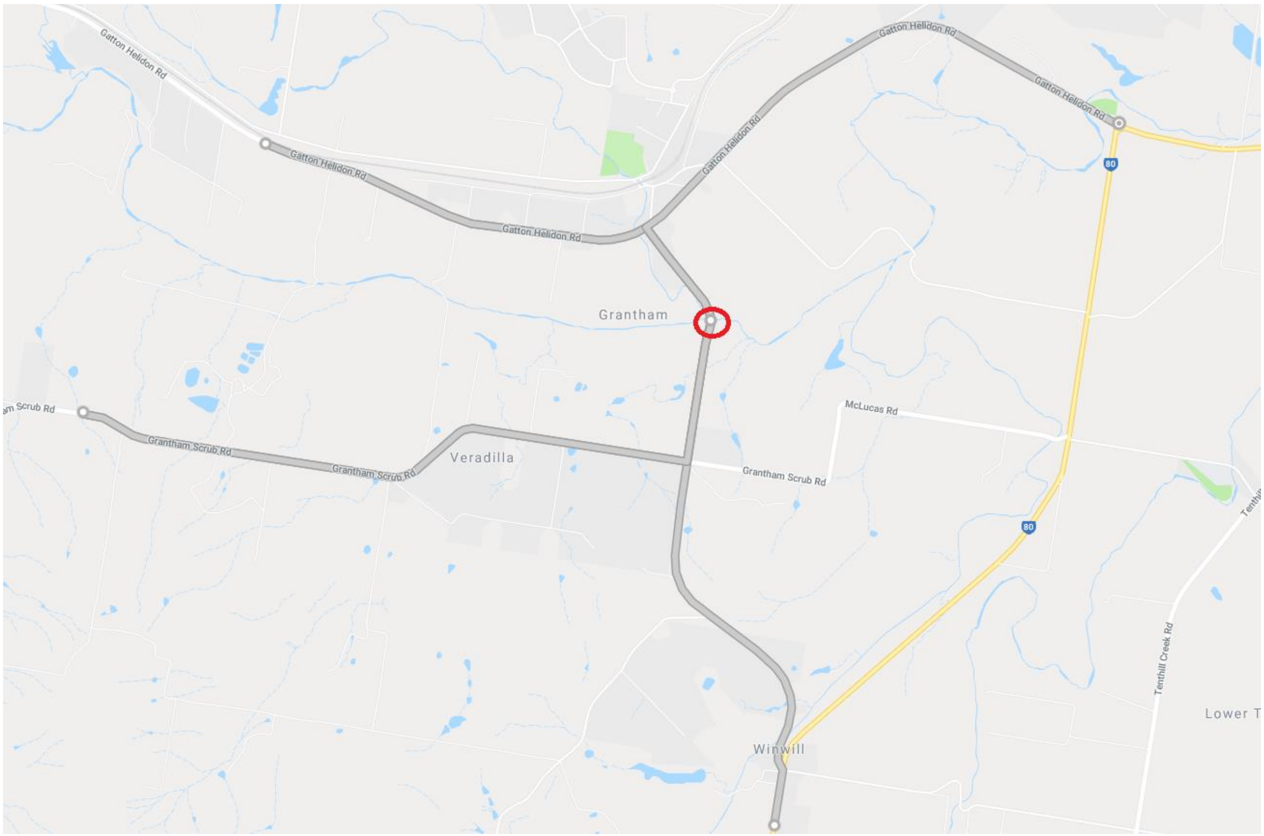
% of heavy vehicles 4.4%

Estimating Trip Distribution

The next step in the transport modelling process is to determine where each of the trips generated in the previous step would end. As the purpose of the modelling in this research was to estimate the diversion routes and the resulting delays, the potential trips using the bridge needed to be assigned to other diversion rotes (Negi et al. 2013). The potential diversion routes for the two bridges were identified by going through the diversion route maps provided by Council and using the Google Maps routing function.

The Thistlethwaite Bridge is located on the Grantham – Winwill Road, which is a connector road with a north-south link and an east-west link. The north-south link connects the Gatton-Helidon Road to State Route 80, Gatton – Clifton Road, while the east-west link connects the Grantham Scrub Road to the Gatton - Helidon Road as shown in Figure 7-5.

Figure 7-5 Map showing the alternative links on the Thistlethwaite Bridge



The total daily trips were differentiated as trips on the east-west link and the north-south link based on the AADT values obtained for the Grantham Scrub Road and the south end of the Grantham Winwill Road. The AADT values for these two roads were 361 and 590 respectively, which when added up corresponds very close to the AADT value at the Thistlethwaite Bridge of 958. The total trips on the Thistlethwaite Bridge were then distributed across the two links based on the following calculations.

% of trips on East-west link = AADT Grantham Scrub Road / AADT Grantham Winwill Road

$$= 361 / (361+590) = 38\%$$

% of trips on north-south link = AADT Grantham Winwill Road (South) / AADT Grantham Winwill Rd

$$= 590 / (361 + 590) = 62\%$$

The Clarke Bridge is located on the Thornton School Road, in between Main Camp Creek Road and Mulgowie Road. It was assumed that all traffic using the Clarke Bridge would head in the Northern direction as Thornton School Road, Main Camp Creek Road and Mulgowie Road all were dead ends running toward the South.

Estimating time and distance on diversion routes

Previous literature has used different methods to estimate incremental time and distance due to road closure. (Wesemann et al. 1996) used a transport demand model already in use in the area and then double-checked the times generated by the system by timing actual drive times measured by the researcher. In contrast, (Pfurtscheller and Genovese 2016a) used the routing function of Google Maps to estimate the incremental time and distance. Given the practicality of the approach used by (Pfurtscheller and Genovese 2016a), this research too calculated the incremental time and distance through Google Maps. The times generated by this method for the alternative routes of the Thistlethwaite Bridge were double-checked by noting down times of real drive times. The actual timing obtained was in line with those obtained from Google Maps. It was also noted that given that the study was set in a regional area the effect of congestion on drive times were negligible and hence was not considered for the analysis.

It was also important to calculate only the extra time and distance travelled due to the closure of the bridges and not simply the time and distance on the alternative route. Therefore the time and distance on the normal route using the bridge was deducted from the time and distance of the alternative route, which provided the incremental increase in time and distance of travelling when the bridge was unserviceable. These values are provided in the table below.

Table 7-7 Incremental times and distances on the alternative routes

	Thistlethwaite – North South link	Thistlethwaite – East West link	Clarke Bridge
Incremental time	3 mins	2 mins	5 mins
Incremental distance	2.2 km	1.9 km	3.6 km

Given the trip distributions calculated in the previous section an average incremental time and distance was calculated using the following equations.

Average incremental time T = $\sum_{i=1}^{n} t_i * \frac{R_i}{100}$

Average incremental distance = $\sum_{i=1}^{n} d_i * \frac{R_i}{100}$

Where t_i is the incremental time (minutes) on route i, d_i is the incremental distance (km) on route i and R_i is the percentage of trips on route i.

The average incremental time and distance for the Thistlethwaite Bridge was calculated to be 2.62 minutes and 2.086 km. The average time and distance on the Clarke Bridge was 5 minutes and 3.6 km as there was only one alternative route.

Estimating total transport impacts

The total transport related impacts of the closure of the bridges is made up of two separate cost categories; total cost of delay and the increased operating cost due to using a longer route. Monetary values were assigned to both these impacts using transport economics principles.

The different types of vehicles that use the two case study bridges needed to be estimated in order to calculate the total transport impacts. As the traffic count data available to the local council included only estimations of vehicles per day and the percentage of heavy vehicles, further calculations were carried out to categorise these traffic counts to more detailed vehicle types. This estimation was carried out using the total number of registered vehicles in the Lockyer valley regional council.

Increased Vehicle Operating Costs (VOC)

Vehicle Operating Costs refer to the variable costs of driving a vehicle. VOC typically include fuel and lubricant usage, wear and tear of tyres and maintenance and repairs associated with running the vehicle (Ozbay et al. 2007). Each type of vehicle would have different VOCs and they would also differ depending on the speed travelled, quality of the road and other external variables. The total VOCs for the case study area was calculated as per the following equation.

Total VOC = $\sum_{i=1}^{n} N_i * D_i * VOC_i$

Where N_i is the number of vehicles of type I, D_i is the average incremental distance and VOC_i is the Vehicle Operating Cost per km for vehicle type i.

The estimation of the total VOC will depend heavily on how the total traffic volume numbers are categorised into different vehicle categories. As the number of vehicles using the bridge was broken down into Light Vehicles and Heavy Vehicles, average VOC per km for Light Vehicles and Heavy vehicles was used to estimate the increase in VOC due to bridge closure.

The passenger vehicle operating cost was obtained from (BITRE 2017) which was $16.58 per 100km travelled. This cost included the cost of fuel, lubricants, additives, vehicle parts and servicing of running an additional 100km and excluded fixed vehicle costs such as time-dependent depreciation, insurance and registration fees, financing and parking costs, which are not directly affected (Kumarage and Weerawardana 2013). Heavy vehicle operating costs were calculated using the average operating costs of 2 and 3-axle rigid trucks, heavy truck trailers and 6-axle articulated trucks obtained from (BITRE 2011), which were the most widely used trucks registered in the Lockyer Valley Region. As such the heavy vehicle operating cost was calculated to be $144.45 per 100km.

Table 7-8 Total Vehicle Operating Costs per day

	Thistlethwaite Bridge	Clarke Bridge
Light Vehicle Operating Cost ($/day)	302.51	59.91
Heavy Vehicle Operating Cost ($/day)	251.40	24.05
Total VOC ($/day)	553.91	83.96

Travel delay

As the reconstruction of a section of road takes place, traffic on that route will experience delays. These delays can be a result of slower speeds if the road is partially closed, or detour delays if the road is completely closed for vehicular traffic during the period of construction. In both of the cases analysed, the bridges were completely closed for traffic during the reconstruction period and hence the travel delays were calculated based on potential detour routes.

Travel time delay could be straightforwardly measured and presented in total minutes or hours by estimating the delay on a diversion route and the number of vehicles typically using that route. Transport economists have also used the value of travel time in order to convert the delay time into a monetary unit, which can be used for Cost Benefit Analysis (CBA) purposes. Using such travel time values for commercial and freight vehicles is common as the increased time spent traveling will increase the costs of the businesses, and will be part of the indirect tangible impacts. However, valuing personal time can be more challenging as different people will value their time differently. Furthermore, personal travel time, even though valued monetarily, can be argued to be a social cost rather than an economic cost. The travel delay for commercial vehicles and private vehicles were calculated separately as shown below.

Freight Delay Cost

The freight delay cost can be calculated by estimating the additional distance travelled by the vehicles, the time cost per vehicle and the number of vehicles typically using that link in a given time period (Kumarage and Weerawardana 2013). The freight delay cost was calculated using the following equations.

$$DC_F = T * \left(\sum_{i=1}^{n} VT_i * N_i \right)$$

Where, DC_F is the delay cost to freight vehicles, T is the average incremental time, VT_i is the time value per vehicle type i and N_i is the number of vehicles of type i travelling per day.

The time value per vehicle type was calculated using the following equation.

$$VT_i = FT_i + (O_i * OT_i)$$

Where FT_i is the freight travel time value for vehicle type i, O_i is the average occupancy for vehicle type i and OT_i is the time value per occupant travelling on vehicle type i.

The time value per freight vehicle (in hours) was calculated for three different classes of freight carrying vehicles using and time values obtained from (Transport and Infrastructure Council 2016).

Table 7-9 Time values used for calculations

	Heavy rigid trucks	Articulated trucks	Light rigid trucks and light commercial vehicles
Freight travel time value ($/vehicle per hour)	7.22	19.8	0.78
Average occupancy (persons / vehicle)	1	1	1.3
Time value per occupant ($ / person)	26.19	26.81	25.41
Time value per vehicle ($/ vehicle per hour)	33.41	46.61	33.81

The total freight delay cost was $ 02.56 per day for the Thistlethwaite Bridge and $94.55 per day for the Clarke Bridge.

Personal Delay

Personal delays to travellers were estimated based on the incremental time that passenger vehicles were estimated to take due to the reconstruction of a bridge. The personal delay cost of bridge closure was calculated using the following equation.

$$DC_P = T * \left(\sum_{i=1}^{n} VT_i * N_i \right)$$

Where DC_P is the delay cost to passenger vehicles, T is the average incremental time, VT_i is the passenger time value per trip type i and N_i is the number of vehicles of trip type i travelling per day.

The passenger time value per type trip was calculated using the following equation.

$$VT_i = \sum_{i=1}^{n} O_i * OT_i$$

Where O_i is the average occupancy for trip type i and OT_i is the time value per occupant per trip type i.

The time value per passenger vehicle was segregated into two based on the use of the vehicle either for business related travel or personal use. Business related travel included travel to and from work and use of the vehicle that is chargeable to business expense or for which an allowance is received. Business related travel has been classified as a social cost as the delay due to the diversion will affect the person travelling more than it impacting the business. However, extra vehicle operating costs due to longer routes were classified as a business/economic impact and were addressed in the previous section under Vehicle Operating Costs.

The time value per vehicle by type of use was calculated based on the following data obtained from (Transport and Infrastructure Council 2016).

Table 7-10 Time values for passenger cars

	Occupancy rate per vehicle (persons per vehicle)	Time value per occupant ($/person per hour)
Personal use	1.7	14.99
Business related use	1.3	48.63

The use of passenger vehicles for business and personal use was calculated using the Survey of Motor Vehicle Use prepared by the Australian Bureau of Statistics. Based on these values it was estimated that 53% of the passenger trips were for personal purposes, while 47% was for business related travel. The number of trips to and from work was considered as business related travel and valued using the time value per occupant of $48.63/person per hour. The total passenger delay cost of diversions was calculated to be $1,180.64 per day for the Thistlethwaite Bridge and $258.58 per day for the Clarke Bridge.

Increase in crash costs

The increased travel required due to a regular route being unusable can increase the risks or accidents. This is especially the case where alternative routes do not have the same capacity and the quality of the road that is damaged. Thus as more drivers use such alternative routes, the risk of accidents can increase, which may result in injuries to passengers. These social impacts also need to be considered when estimating the indirect effects during reconstruction of the bridge. The increase in crash cost per day can be calculated using the following equation;

CC = $N + D + CC_{VKT}$

Where, CC is the crash cost per day, N is the number of vehicles per day and CC_{VKT} is the crash cost per vehicle Kilometre travelled.

Total transport impacts

The total transport impacts per day where calculated by adding the different categories of impacts as shown in the equation below.

Daily transport impacts = $Total\ VOC + DC_F + DC_P + CC$

Table 7-11 Breakdown of total transport impacts per day of bridge closure

	Thistlethwaite Bridge ($)		Clarke Bridge ($)	
Passenger delay cost business travel	808.81		177.14	
Passenger delay cost personal travel	371.83		81.44	
Total delay cost per day		1,180.64		258.58
Freight delay cost light vehicles	365.46		80.04	
Freight delay cost heavy vehicles	137.10		14.50	
Total freight delay cost		502.56		94.55
Light Vehicle Operating Cost	302.51		59.91	
Heavy Vehicle Operating Cost	251.40		24.05	
Total Increase in Vehicle Operating Cost		553.91		83.96
Increase in crash costs		161.07		30.47
Total transport impacts		2,398.18		467.56

The results show that the passenger vehicle delay cost accounts for more than 50% of the total transport impacts in both case study areas, while the passenger delay of people travelling for business purposes costs account for 35% of the total transport impacts.

Duration of road closure

The daily transport impacts were then multiplied by the number days of road closure to obtain the total transport impacts. In the first version of the toolkit, the duration of road closure was estimated to be the time from the date of the disaster to the date that the new bridge was re-opened. However, during the validation interviews it was learned that the Thistlethwaite Bridge load limited and used by light vehicles for close to a year and a half after the disaster. As a result, this was factored into the toolkit and the equations. This improvement to the tool allows for users to compare the socio-economic impacts of partial closure of a bridge against full closure.

Business impacts

The closure of roads could impact businesses in the area due to increased freight costs and changes to customer visits. The most common impact to businesses would be increased freight costs due to longer trips as roads are closed for reconstruction processes. This specific business impact was estimated through transport modelling in the previous section. Another freight related impact is the loss of sales due to the inability to get produce to the market as access routes may be unserviceable. Such impacts are very challenging to estimate as the impacts would vary based on the types of industries affected. As both the bridges were not the only access routes available it was assumed that no businesses were affected by the inability to transport goods to market on time. However, it should be noted that since the economy of the region is predominantly agriculture based, the closure of some specific routes may have had an impact on farmers, where goods were not transported to market in a timely manner and thus causing considerable damages to the local economy.

The closure of roads can also affect the number of customers patronising the businesses in the area. Based on the exact location of the business and the type of industry, some business entities may see a decrease in customers, while other businesses may experience an increase in customers. Generally it could be assumed that businesses located close to the area of road closure would see a decrease in customers as accessibility to the premises will reduce. Such adverse impacts would be more for 'convenience' businesses that depend on traffic flow like restaurants, coffee shops and petrol stations (Matthews, Allouche and Sterling 2015).

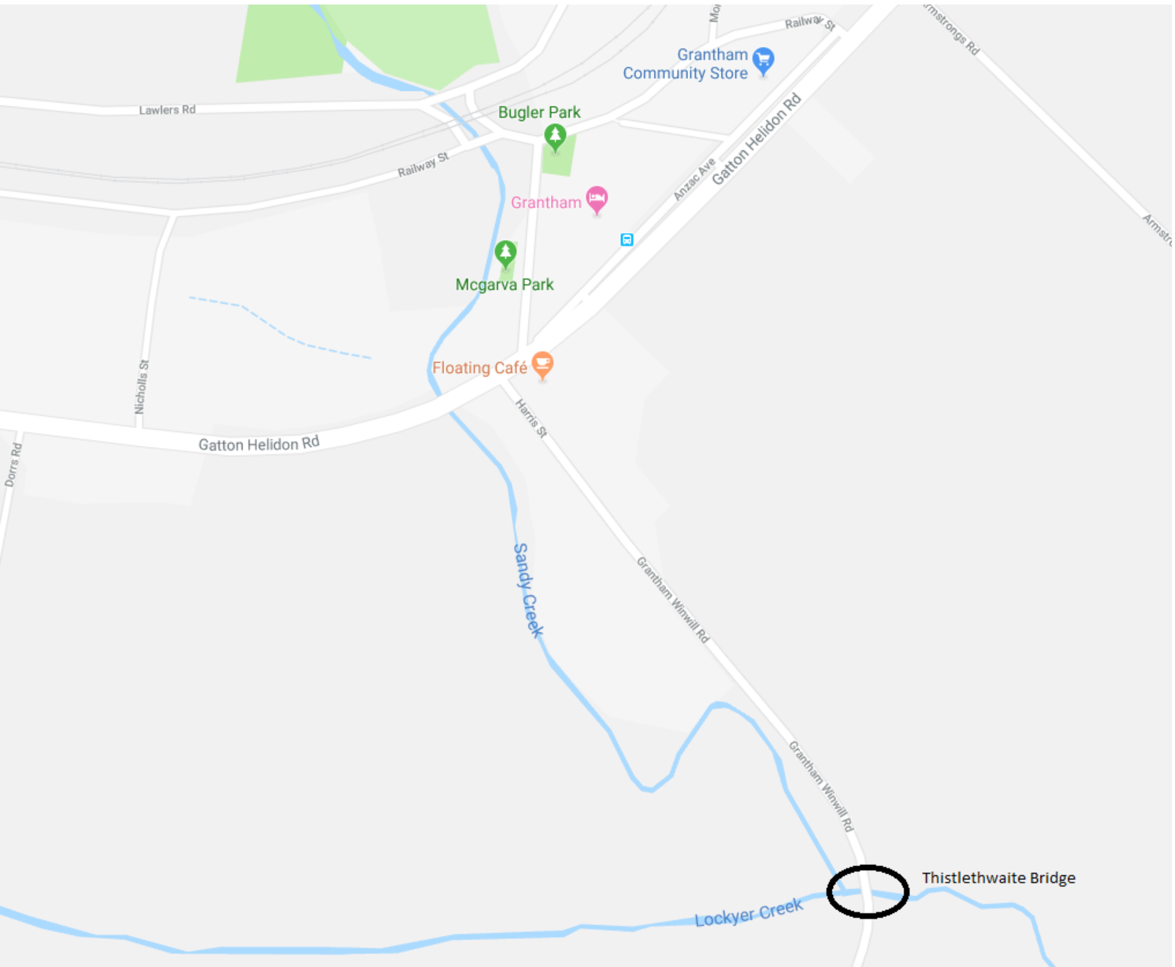
The decrease in business revenue could be estimated based on the following equation.

$$\text{Daily reduction in business revenue} = \sum_{i=1}^{n} B_i * R_i * \frac{C_i}{100}$$

Where, B_i is the number of businesses of industry type i, R_i is the average daily revenue for a business type i, and C_i is the percentage of estimated loss of revenue.

Three businesses were identified that may have been affected by the closure of the Thistlethwaite Bridge (Figure 7-6). As there were no businesses which rely on customer traffic located in proximity to the Clarke Bridge, the business impacts from the damage to the bridge is assumed to be zero.

Figure 7-6 Map of the area showing the businesses affected



The reduction in customers for the businesses was assumed based on the location of the premises. The Floating Café is located on Harris Street, which connects directly to the Thistlethwaite Bridge and hence it was assumed that customers travelling along the affected road who would have typically patronised the business were lost customers. The Grantham Community store and Grantham Fuels were located off the Gatton Helidon road and it was assumed that the business impact due to the closure of the Thistlethwaite Bridge was minimal.

The average annual turnover for The Floating Café was assumed to be $48,000 while for the other two businesses it was assumed to be $368,000 each, which was the mean annual turnover for micro sole trader businesses and small business entities for 2013 (Australian Government 2016). A summary of the estimated business impacts are provided in Table 7-12.

Table 7-12 Estimated impacts to business revenue

Business name	Industry	Location	Routes patronising the business	Reduction in revenue
Floating Café	Restaurant	Harris Street, leading to Thistlethwaite Bridge	North – South link East – West link	30%
Grantham Community Store	Retail	Off Gatton Helidon Road	East – West link	5%
Grantham Fuels	Fuel	Off Gatton Helidon Road	East – West link	5%

The estimated values were used to calculate the total reduction in revenue for the three businesses located in proximity to the Thistlethwaite Bridge. The total reduction in turnover was calculated to be $140.27 per day for the three business entities. This was equivalent to a reduction of 6.5% of cumulative turnover of the three businesses.

7.3.3 Direct intangible impacts

Direct Social impacts

The major direct social impact of road structure failure due to flooding is the injuries and lives lost during the event. As the focus of this research is purely on the impacts of road failure, the wider injuries and life loss due to the flooding events are excluded from the analysis. The most appropriate method to measure the social impact would be to quantify the number of individuals who were injured and killed during the event.

The social impacts of lives lost and injuries could be valued using Value of Statistical Life (VSL) and Value of Statistical Life Year (VSLY) estimates for Australia. The VSL was estimated to be $4.2 million, while the VSLY was estimated at $182,000 per year in 2014 (Office of Best Practice Regulation 2014). The monetary value of the number of lives lost can be calculated by multiplying the number of deaths by the VSL. The costs for specific injuries could also be estimated through similar VSL studies which provide estimates for specific injuries (Abelson 2003).

The use of VSL and VSLY estimates in decision making processes should be used to understand how different options would affect the health and wellbeing of individuals in a community. In relation to post-disaster reconstruction, VSL estimates could be used to understand how different reconstruction options compare against each other on human health and wellbeing aspects. Using VSL estimates to measure the total cost of disasters can be problematic and are generally avoided in disaster impact analysis.

Direct environmental impacts

Potential direct environmental impacts of disaster induced road damage are water contamination due to chemical run-off from roads, destruction of natural habitat and natural life and the disposal of debris (Srinivas and Nakagawa 2008). The direct environmental impacts could not be measured as it was infeasible to conduct a post-event environmental assessment.

7.3.4 Indirect social impacts

The indirect social impacts due to the reduction in mobility and accessibility was assessed through the transport modelling exercise. The total delays for passengers were calculated using the following equation and is presented in delay hours.

Total delay per day= $T * \left(\sum_{i=1}^{n} O_i * N_i \right)$

Where T is the average incremental time on the alternative route, O_i is the average occupancy per vehicle type i and N_i is the number of vehicles of type i.

Table 7-13 Total delay per day

	Thistlethwaite	Clarke
Personal trips (Hours)	16.3	5.7
Business related trips (Hours)	16.6	3.8
Total delay (Hours)	32.9	9.5

These indirect social impacts were estimated on the assumption that all daily trips that were conducted prior to the disaster will be carried out after the event. However, there can be instances where some trips are coupled in order to reduce the travel time or cancelled altogether due to the inconvenience caused due to the diversion routes.

7.3.5 Indirect Environmental impacts

As indirect environmental impacts could be categorised into to two separate areas, two distinct methods were used to measure them. The first method used an environmental economics valuation method to assess the impacts occurring due to extra travel on detour routes during the reconstruction process, while a Life Cycle Assessment (LCA) approach was used to assess the environmental impacts of the reconstruction of the damaged bridges.

Environmental impacts due to detour

The environmental costs of detours were estimated using externality costs of transport for Australia published by (Austroads 2014). External costs are not directly borne by the vehicle user but refer to wider environmental costs incurred as a result of the use of vehicles (Kumarage and Weerawardana 2013). (Austroads 2014) uses road externality costs published for 27 countries in the EU region and converted them to reflect costs more suited for Australia based on Australian data for adjustment factors such as vehicle occupancy, population density and purchasing power parity. The report provides externality costs in Australian dollars (as at June 2013) for passenger vehicles and commercial vehicle kilometres travelled. The environmental impacts considered are air pollution, greenhouse gas emissions, noise pollution, soil and water pollution, biodiversity, nature and landscape and upstream and downstream costs.

The total environmental costs were calculated as follows;

Daily environmental cost = $\sum_{i=1}^{n} N_i * D_i * E_i$

Where N_i is the number of vehicles of type i, D_i is the average incremental distance in km and E_i is the total environmental cost per km for vehicle type i.

Table 7-14 Environmental costs of detours

	Thistlethwaite Bridge	Clarke Bridge
Environmental cost of passenger vehicles	20.50	4.06
Environmental cost of LCV	2.82	0.56
Environmental cost of HCV	15.13	1.45
Total environmental cost ($ per day)	38.45	6.07

Environmental impacts of reconstruction

Life Cycle Assessment (LCA)

An LCA was considered to be the most appropriate method to assess the environmental impacts of reconstruction. Large amounts of data such as material consumption, energy consumption and emissions factors, are required to conduct a detailed LCA (Zhang et al. 2016), which can be challenging given the timing of the study. The scope of the LCA would be cradle to gate considering direct and indirect emissions of the project. A cradle to gate approach will assess the environmental impacts of materials, transport of materials to site and construction phases, while maintenance and disposal phases will be excluded from the analysis. The reason for this decision is that the incremental environmental impacts due to the disaster will only be due to the construction of the bridge as maintenance and disposal of the previous bridge would have been relevant even before the disaster.

Primary data relating to the material and energy consumption of the construction process is vital for conducting an LCA and is generally conducted after the completion of the project. Since the focus of the study was to estimate the environmental impacts at a very early stage, a streamlined LCA was carried out to estimate the life cycle impacts of the construction of the bridges. With the minimal data availability at the initial stage of the project, the most appropriate method was to obtain the life cycle environmental impacts of a similar project and to use those values as a proxy. For this purpose a literature survey was carried out to identify LCA's of bridges so that a standard value could be used for a comparative estimation.

Literature on the LCA of concrete bridges showed that most of the studies focused on bridges that were more than 100 metres in length (Du et al. 2014, Boulenger 2011, Itoh and Kitagawa 2003, Penadés-Plà et al. 2017). Two LCA studies of concrete bridges were found where the bridge assessed was similar in length to the two case study bridges. However the method of construction were different in the two studies, one being a box girder bridge (Hammervold et al. 2011), while the other was a T girder bridge (Penadés-Plà et al. 2018). As the two case study bridges were T-girder bridges it was decided to use the environmental data from (Penadés-Plà et al. 2018) for the purpose of this research.

The following environmental impacts for building a T-girder bridge 12 metres wide was estimated for a functional unit of 1 metre of bridge (Penadés-Plà et al. 2018). These values were adjusted to obtain the relevant environmental impacts of materials, transport and construction for 1 square metre so that it could be used to estimate the environmental impacts of the two case study bridges.

Table 7-15 Environmental impacts of reconstruction in physical units

Impact	Acronym	Reference Unit	Units per m2	Thistlethwaite	Clarke
Agricultural Land Occupation	ALO	m2 × year	6.86	3,088.13	1,095.26
Global Warming Potential	GWP	kg CO2 eq	175.53	78,990.00	28,015.12
Fossil Fuel Depletion	FD	kg oil eq	30.70	13,814.25	4,899.45
Freshwater Ecotoxicity	FEPT	kg 1,4-DB eq	3.26	1,465.50	519.76
Freshwater Eutrophication Potential	FEP	kg P eq	0.07	31.13	11.04
Human Toxicity Potential	HTP	Kg 1,4-DB eq	124.46	56,006.25	19,863.55
Ionizing Radiation Potential	IRP	kg U235 eq	21.97	9,887.25	3,506.68
Marine Ecotoxicity	MEPT	kg 1,4-DB eq	3.24	1,457.25	516.84
Marine Eutrophication Potential	MEP	kg N eq	0.03	12.75	4.52
Metal Depletion	MD	kg Fe eq	77.63	34,932.38	12,389.35
Natural Land Transformation	NLT	m2 x year	0.02	10.88	3.86
Ozone-layer Depletion Potential	ODP	kg CFC-11 eq	0.00	-	-

Particulate Matter Formation Potential	PMFP	kg PM10 eq	0.36	162.75	57.72
Photochemical Oxidant Formation Potential	POFP	kg NMVOC	0.61	272.63	96.69
Terrestrial Acidification Potential	TAP	kg SO2 eq	0.53	236.25	83.79
Terrestrial Ecotoxicity Potential	TETP	kg 1,4-DB eq	0.04	17.63	6.25
Urban Land Occupation	ULO	m2 × year	2.23	1,004.63	356.31
Water Depletion	WD	m3	752.22	338,500.88	120,054.98

Using a single LCA study to estimate the potential environmental impacts of the two case study bridges are a major limitation of this method. The environmental impacts of the two case study bridges will vary depending on the method of construction, type and quantity of materials used and the environmental impact factors used for the calculation of the LCA. The study used as a surrogate was for a construction of a bridge in Spain, as there was a lack of LCA studies on bridges constructed in Australia. The reliability of the results could be improved by using LCA results from similar bridges in Australia as surrogate data.

The main types of material used for construction (concrete, steel, asphalt and reinforcement) have been found to account for the major portion of the environmental profile of bridges (Hammervold et al. 2011, Du and Karoumi 2014, Du et al. 2014). The reliability of a streamlined LCA could be improved by focussing on the environmental impacts of the major material types used and the technology used for their manufacture and supply chains. The quantities of the materials used could be obtained through a detailed Bill of Quantities (BOQ) prior to the construction process and this information could be used for a streamlined LCA. Efforts to obtain data relating to the quantity of materials used from the relevant construction companies were unfruitful.

Monetary valuation of LCA results

Since the environmental impacts in LCA are presented in physical units, which have different units of measurement and varied seriousness on human and environmental health, they cannot be compared directly with each other or aggregated together. The monetary quantification of these environmental impacts makes it easier for comparison between environmental impact categories and also for aggregation purposes that would be helpful in CBA of public projects with social, environmental and economic impacts (Pizzol et al. 2015).

The benefit transfer method was used to value the environmental impact categories as specific monetary values for the environmental impacts in the study area were not available. Preference was given to valuation studies conducted in Australia, and in instances where Australian studies were not available, original studies conducted in other industrialised nations were chosen in order to increase the relevance of the monetary values used. In instances where multiple sources were available studies which were conducted closer to the year of reference for this research project (2012) was given priority. Although the use of different valuation studies aims at increasing the relevance of the values it has its shortcomings as well.

One shortcoming of this approach, of using different valuation studies, is the possible inconsistencies of methodologies across these studies. Such inconsistencies can pose a challenge when comparing the different impact categories with one another. For example, impact categories such as global warming potential and fossil fuel depletion are valued using market prices, while other impacts like toxicity are valued using abatement costs.

The values presented in the source documents were converted to represent the same reference unit as the reference units for the impact categories identified previously in this research. The monetary values obtained from literature was converted to 2012 dollars to account for inflation using the (Reserve Bank of Australia 2019) inflation calculator and values presented in foreign currency were converted to AUD using historical rates of the Reserve Bank of Australia. The monetary values for metal depletion and water depletion were not considered as there was no consistent method that could have been used to value these two impacts.

Using the shadow (Table 7-16) prices for the different impact categories, the potential environmental impact estimated through the LCA was monetarily valued. Table 7-17 shows the monetary value of the different environmental impacts for the two case study bridges.

Table 7-16 Sources for the monetary values for the different environmental impacts

Impact	Value	Currency	Unit	Year	Reference
ALO	78	AUD	ha year	2006	(Mallawaarachchi, Morrison and Blamey 2006)
GWP	23	AUD	Ton of CO2e	2012	(Clean Energy Regulator 2015)
FD	111.67	USD	Barrel of crude oil	2012	(US Energy Information Administration 2013)
FEPT	0.04	EUR	kg 1,4-DB eq	2000	(van Harmelen et al. 2007)
FEP	1.78	EUR	Kg P eq	2008	(De Bruyn et al. 2010)
HTP	0.0386	EUR	kg 1,4-DB eq	2008	(De Bruyn et al. 2010)
IRP	0.000902	EUR	kg U235 eq	2008	(De Bruyn et al. 2010)
MEPT	0.0001	EUR	kg 1,4-DB eq	2000	(van Harmelen et al. 2007)
MEP	12.5	EUR	kg N eq	2008	(De Bruyn et al. 2010)
MD					
NLT	1980	AUD	ha year	2006	(Mallawaarachchi et al. 2006)
ODP	96.8	EUR	kg CFC-11 eq	2008	(De Bruyn et al. 2010)
PMFP	14.3	EUR	kg PM10 eq	2008	(De Bruyn et al. 2010)
POFP	0.00215	EUR	kg NMVOC	2008	(De Bruyn et al. 2010)
TAP	0.233	EUR	kg SO2 eq	2008	(De Bruyn et al. 2010)
TETP	1.3	EUR	kg 1,4-DB eq	2000	(van Harmelen et al. 2007)
ULO	1102	AUD	ha year	2006	(Mallawaarachchi et al. 2006)
WD					

Table 7-17 Environmental impacts of reconstruction in monetary values

Impact	Thistlethwaite $	Clarke $
Agricultural Land Occupation	28.32	10.04
Global Warming Potential	1,816.77	644.35
Fossil Fuel Depletion	10,889.38	3,862.10
Freshwater Ecotoxicity	138.95	49.28
Freshwater Eutrophication Potential	124.02	43.98
Human Toxicity Potential	4,839.20	1,716.30
Ionizing Radiation Potential	19.96	7.08
Marine Ecotoxicity	0.35	0.12
Marine Eutrophication Potential	356.76	126.53
Metal Depletion	-	-
Natural Land Transformation	2.53	0.90
Ozone-layer Depletion Potential	-	-
Particulate Matter Formation Potential	5,209.63	1,847.68
Photochemical Oxidant Formation Potential	1.31	0.47
Terrestrial Acidification Potential	123.22	43.70
Terrestrial Ecotoxicity Potential	54.31	19.26
Urban Land Occupation	130.16	46.16
Water Depletion	-	-
Total	23,734.86	8,407.92

Disposal of old bridge

The demolition and disposal of the damaged bridge will also cause environmental impacts. The demolition and disposal will occur prior to the reconstruction phase, and the environmental impacts arising from it could be measured similarly to the reconstruction phase through an LCA. The types and quantities of the waste and the methods of disposal could be modelled in order to estimate the potential environmental impacts.

Such information relating to the damaged bridge that was demolished was not available from LVRC as the work had been carried out by a contractor and no information related to quantities of waste was retained. The amount of demolition waste was estimated by the Council to be between 250 and 450 tonnes per bridge. The total cost of waste disposal will include the private costs borne by the contractor and other external costs. The private costs are typically included in the reconstruction cost estimates. Therefore, only the external costs of the demolition and dumping needs to be accounted for at this stage to avoid double counting of costs.

The external environmental cost of landfilling construction and demolition waste was estimated to be $2.27 per tonne. This cost was estimated based on calculations by (Wang et al. 2018a) and converting to Australian Dollars using the benefit transfer method. The quantity of demolition waste generated from the two case sites was estimated to be 450 tonnes for the Thistlethwaite Bridge and 250 tonnes for the Clarke Bridge. The total environmental cost of demolition was thus estimated to be $1,021.50 and $567.50, respectively, for the two bridges.

7.3.6 Aggregation of impacts

One of the objectives of this research project was to propose a method that can be used to integrate the different social, environmental and economic impacts, allowing for a comprehensive assessment. The integration was carried out by assigning monetary weights to social and environmental impacts. This allowed for the varied impact categories to be aggregated together. Such an aggregation helped in visualising how the different types of impacts contributed to the wider impacts to the community and the environment.

The following table provides the types and sources of data used to convert the non-financial impacts to monetary values for aggregation purposes. Effort was taken to select monetary values that were most relevant to the case study area. Where monetary values for the locality or region were not available, values from regions with similar characteristics to the case study area were chosen. This method increased the relevance of the data points chosen and the reliability of the output.

The monetary values selected can either increase the generalizability of the findings or help in presenting more locally relevant values. If values common to an entire country or state are used, the output would be more generalizable to that country, while if local data are used the output will be more relevant to the locality under study. The use of monetary values to weight the different types of impacts thus helped in making the output derived from this framework more scalable.

Table 7-18 Sources of valuation studies used

Data point	Valuation method	Reference
Travel time values	Transport economics principles	(Transport and Infrastructure Council 2016)
Freight travel time values	Transport economics principles	(Transport and Infrastructure Council 2016)
Crash cost	Transport economics principles	(Austroads 2010)
External cost of transport	Benefit transfer	(Austroads 2014)
Agricultural Land Occupation	Choice modelling	(Mallawaarachchi et al. 2006)
Global Warming Potential	Market price	Clean energy regulator
Freshwater Ecotoxicity Potential	Shadow price	(van Harmelen et al. 2007)
Freshwater Eutrophication Potential	Shadow price	(De Bruyn et al. 2010)
Human Toxicity Potential	Shadow price	(De Bruyn et al. 2010)
Ionizing Radiation Potential	Shadow price	(De Bruyn et al. 2010)
Marine Ecotoxicity Potential	Shadow price	(van Harmelen et al. 2007)
Marine Eutrophication Potential	Shadow price	(De Bruyn et al. 2010)
Natural Land Transformation Potential	Choice modelling	(Mallawaarachchi et al. 2006)
Ozone-layer Depletion Potential	Shadow price	(De Bruyn et al. 2010)

Particulate Matter Formation Potential	Shadow price	(De Bruyn et al. 2010)
Photochemical Oxidant Formation Potential	Shadow price	(De Bruyn et al. 2010)
Terrestrial Acidification Potential	Shadow price	(De Bruyn et al. 2010)
Terrestrial Ecotoxicity Potential	Shadow price	(van Harmelen et al. 2007)
Urban Land Occupation	Choice modelling	(Mallawaarachchi et al. 2006)
Construction waste to landfill	Life Cycle Analysis	(Wang et al. 2018a)

The values presented in the source documents were converted to represent the same reference unit as the reference units for the impact categories identified previously in this research. The monetary values obtained from literature was converted to 2012 dollars to account for inflation using the (Reserve Bank of Australia 2019) inflation calculator and values presented in foreign currency were converted to AUD using historical rates of the Reserve Bank of Australia.

The contributions of the different types of impacts were compared against the financial cost of reconstruction of the two bridges. The financial impacts refer to the direct costs of reconstructing the bridge, which are generally borne by the local council, while economic impacts refer to wider impacts to the community and economy. Such a comparison was carried out as the financial cost estimates were the only systematic assessment process followed in PDR in Australia. This allowed in analysing how the other sustainability impacts measured against the financial impacts.

The actual cost of reconstruction was used as the financial cost to compare the social, environmental and economic impacts. The actual cost of reconstruction was $2,438,427.57 and $1,101,643.58 for the Thistlethwaite and Clarke Bridges, respectively. The duration of bridge closure was obtained from the Lockyer Valley Regional Council and the actual duration was used to estimate the socio-economic impacts. The Thistlethwaite Bridge was completely closed for five months during the reconstruction, while heavy vehicles could not access the bridge for 21 months as the damaged bridge was not suitable for heavy vehicle use. The Clarke Bridge was not serviceable for nearly two years even for pedestrian access. The total impacts of the two bridges are provided in Table 7-19.

Table 7-19 Total impact of the two case study bridges

Impact type	Cause	Thistlethwaite bridge ($)		Clarke Bridge ($)	
Financial cost	Reconstruction		2,438,427.57		1,101,643.58
Transport impacts	Vehicle Operating Costs	203,758.78		58,775.28	
	Freight delay	141,190.26		66,181.58	
	Passenger delay	177,096.01		181,006.92	
	Crash cost	30,886.80	552,931.85	21,326.76	327,290.54

Business impacts	Revenue loss		21,041.10		0
Environmental impacts	Demolition	1,021.50		567.50	
	Detour	13,031.12		4,246.92	
	Reconstruction	23,734.86	37,787.49	8,439.06	13,253.49
Total			3,050,188.00		1,442,187.61

The non-financial costs were categorised according to the three pillars of sustainability for easier representation and comparison with the financial costs.

Figure 7-7 Breakdown of total impacts of the Thistlethwaite Bridge

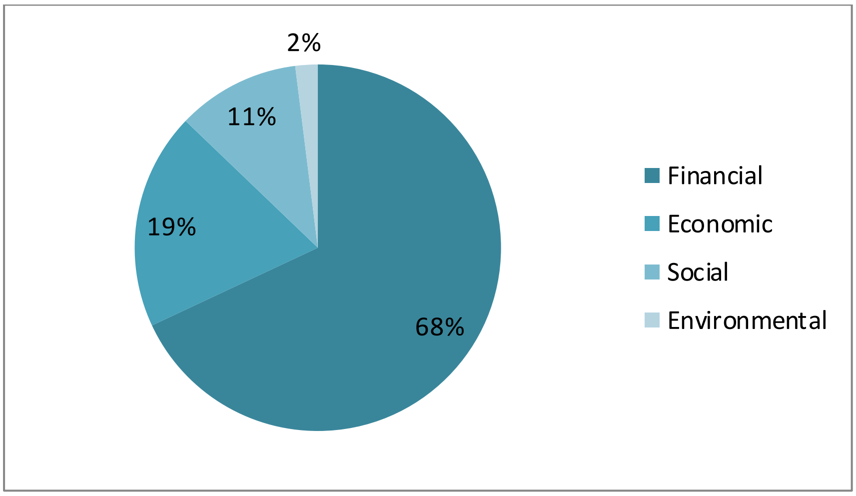
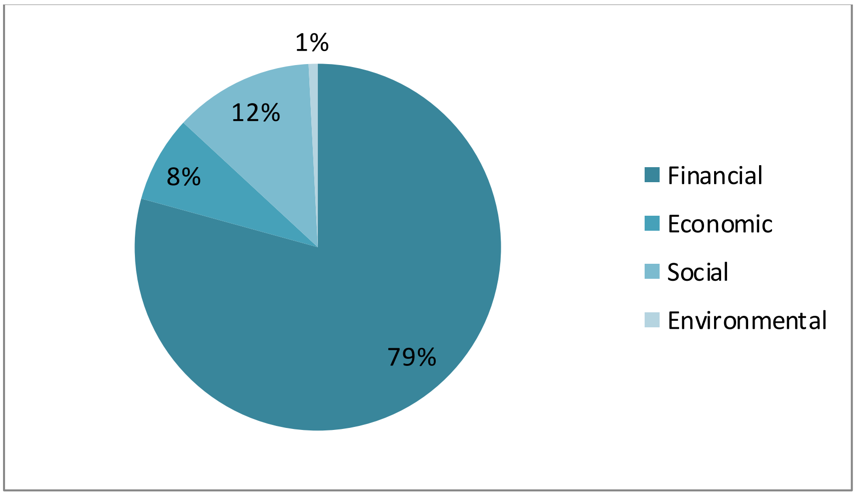


Figure 7-8 Breakdown of the total impacts of the Clarke Bridge



The analysis showed that the total non-financial impacts from bridge damage were 25.09% of the financial cost of reconstruction for the Thistlethwaite Bridge, while for the Clarke Bridge it was 30.91%. The highest contributing impact varied for the two bridges, with economic impacts being 15.01% of the financial cost for Thistlethwaite Bridge, while for the Clarke Bridge, social impacts were 18.37% of the financial impacts. Such a variation could be attributed to the fact that the Thistlethwaite Bridge is located in a more economically important area, while the Clarke Bridge was located in a more remote area of the council.

Table 7-20 Non-financial impacts as a percentage of financial impacts

	Thistlethwaite Bridge		Clarke Bridge	
Impact	Cost ($)	% of Financial cost	Cost ($)	% of Financial cost
Economic	365,990.14	15.01%	124,956.86	11.34%
Social	207,982.81	8.53%	202,333.68	18.37%
Environmental	37,787.49	1.55%	13,253.49	1.20%
Total	611,760.43	25.09%	340,544.03	30.91%

7.4 Summary

This chapter explains how the developed toolkit was used to measure a comprehensive set of social, economic and environmental impacts stemming from disaster induced bridge failure. The data requirements for such a purpose and the data collection process followed for this research were explained in the first section of this chapter. The next section explained how each of the different types of impacts was measured and included detailed equations that were developed to aid in this assessment. The results showed that the non-financial impacts could range between 25-30% of the financial impacts. A quick analysis of the final impacts exemplified that the socio-economic impacts accounted the most towards the non-financial impacts. Further analysis of these results and validation of the process and the toolkit is explained in the following chapter.

8. VALIDATION AND ANALYSIS

8.1 Introduction

The framework and the toolkit developed through the research were tested for its relevance and rigorousness for its ability to explain the actual impacts in a post-disaster context. This validation process included the use of multiple quantitative and qualitative methods in order to achieve a comprehensive outcome. Two sets of interviews were conducted to validate the framework through an independent validation process and evaluate the conceptual and theoretical underpinnings of the framework. These interviews included potential end-users of the framework and academics, whose feedback was used to modify and improve the final proposed framework. The results obtained through the application of the framework in a real life disaster scenario were validated in order to understand if the framework explained the actual behaviour reliably. This was done through a series of interviews, a questionnaire survey and the analysis of secondary data. Internal validity of the tool was tested through sensitivity analysis. This helped the researcher to identify the most significant factors influencing the socio-economic impacts and to refine future research direction. A qualitative what-if scenario analysis was also conducted in order to understand how external factors may influence the results of the model and in turn affect the decision making processes during post-disaster reconstruction.

8.2 Validation of framework and toolkit

The framework and the toolkit that was developed as a part of this research were validated through a series of independent interviews. The objective of these interviews was to validate the framework that was developed and to obtain feedback from experts working in both the practice and academic areas of disaster management and infrastructure reconstruction on the relevance and applicability of the framework. Two groups of interviewees were identified for this purpose: potential end-users who would be using the developed toolkit in practical post-disaster decision making, and academics working in the area of disaster resilience and infrastructure related decision making. The feedback received through these validation interviews were used to calibrate and improve the toolkit further.

8.2.1 Interviews with potential end-users

In-depth interviews with a group of potential end-users were conducted in order to obtain their feedback on the toolkit that was developed. As the toolkit was developed with assumptions and data relevant to case studies in the Lockyer Valley region, the end-user interviewees were selected from organisations within this area. Such a selection of participants also helped in validating the results that were generated through the toolkit and to understand if the output reliably represented the real life impacts on the ground. The interviews were conducted with representatives from three relevant government organisations, two of which (Lockyer Valley Regional Council and Queensland Reconstruction Authority) are end-user collaborative partners in the Bushfire and Natural Hazards CRC. The interviews were conducted during July and September 2019 and included face-to-face where the framework was presented to the participants through the use of a laptop. The participants were chosen from a number of different divisions within these organisations, which allowed for a diverse set of ideas to be obtained (Table 8-1).

Table 8-1 List of interviewees from potential end-users

Participant Code	Designation	Organisation
P20	Executive Manager - Infrastructure Works & Services	Lockyer Valley Regional Council
P4	Coordinator - Environment and Pest	Lockyer Valley Regional Council
P2	Manager - Disaster Coordination	Lockyer Valley Regional Council
P6	Community Development & Engagement Officer	Lockyer Valley Regional Council
P9	District Director – Program Delivery and Operations	Department of Transport and Main Roads
P19	Manager Technical Services	Department of Transport and Main Roads
P8	Director - Engagement and Technical Services, Operations	Queensland Reconstruction Authority
P21	Director – Resilience Policy	Queensland Reconstruction Authority

The developed framework and toolkit was presented to the interviewees with the objective of gaining their expert opinions on the conceptual underpinning of the framework and the relevance of the toolkit in post-disaster reconstruction efforts. As the participants were practitioners in the disaster reconstruction stages, their feedback on whether the toolkit captured all the critical impacts and areas of improvement was also obtained. The results of the interviews are presented below with specific reference to the three focus areas as highlighted.

Conceptual underpinning of the framework

All interviewees were happy with the methodology adopted in the framework, and agreed that it was a conceptually acceptable framework. Most participants agreed that monetising the impacts was beneficial as it resulted in less subjectivity in the process. The monetary valuation of social impacts was seen as a first step towards incorporating social impacts in the regular decision making processes. The interviewees agreed that the framework would aid in the post-disaster reconstruction phase in justifying and validating decisions and for prioritisation of reconstruction. Those interviewed from the Council mentioned that if this framework was adopted, it would increase the transparency in decisions made, especially in cases where there could be community backlash. Further, some participants were of the opinion that this framework will be critical for use by smaller-scale local government authorities who have less resources to fall back on in a time of a disaster.

Relevance in post-disaster decision making

The majority of the potential end-users interviewed suggested that the toolkit was relevant in post-disaster decision making and could be very useful in future events. The toolkit was identified to be relevant to the measurement of impacts due to bridge failure. Some of those interviewed saw that a similar framework could be followed and modifications made to the toolkit in order to assess impacts of other transport related infrastructure.

The scalability of tool was identified to be a vital benefit in its use in disaster recovery, as the availability of data and the level detail required would vary in different locations and for different organisations. Given the data constraints soon after a disaster, the toolkit was identified as portraying an accurate representation of the real life impacts. The database that was developed for the toolkit was considered an important outcome as it had a compilation of relevant data points from varied sources and data sets. End-users mentioned that given the lack of primary data and the challenge in obtaining reliable data in a time constrained post-disaster environment, the data base was seen to be of immense benefit for decision makers. One weakness that was identified by some participants was that the impacts to residents and businesses located in very close proximity to the bridge were not particularly well represented in the model.

Suggestions for improvements

The interviewees mentioned that the validity of the standard values used within the toolkit were critical in the acceptance of it among different organisations. While the option available to select the most appropriate values was seen as a positive outcome, the timely updating of such values and their reliability was a critical area of concern. In this context, the interviewees proposed that an online platform could help reduce such reliability issues among users.

Another aspect that was mentioned was to include impacts to the tool, although no specific data to measure those specific impacts were available. This was related to ecological impacts such as soil erosion during reconstruction, psycho-social impacts due to isolation and holding costs of keeping a damaged bridge partly serviceable until reconstruction begins. Although such impacts were identified during the research, they were not included in the tool as no reliable data was available for quantification. However, since such impacts cannot be completely overlooked, they were included in the final version of the toolkit.

Another vital aspect that was mentioned by the interviewees was the impact on the safety of the community and the risk of accidents during the reconstruction process. As this was one aspect that was not considered in the first version of the toolkit, this was included after the interviews. The safety related impacts was a social impact and was identified to have an influence in post-disaster contexts, with increased traffic on detour routes which does not have high capacity.

It was suggested that the tool should be flexible enough to incorporate partial closure of roads during certain times in the reconstruction phase. Interviewees from the Council mentioned that the Thistlethwaite Bridge was closed fully for all traffic only after the reconstruction of the new bridge commenced. From the time of the disaster to the commencement of the reconstruction, the bridge was load limited and open to light vehicles with speed restrictions. This aspect had not been considered within the initial version of the tool. With these recommendations, the tool was modified to allow calculating such partial closure of roads and limits to speed and heavy vehicle use leading up to the full closure of the bridge.

Recommendations were received on how the utilisation of the tool could be carried out. It was suggested that involving the State and Federal level authorities will increase the acceptance and adoption of the tool across all agencies. The interviewees opined that since the tool would be beneficial at all levels of government, the buy-in of higher level authorities will be critical. Most interviewees agreed that the front-end of the tool needs to be improved, which will make it more user-friendly. As the validity of the standard data used in the model was a significant factor for most end-users, it was suggested that such values could be linked directly to the data source, which will reduce any ambiguities of the outputs. Interviewees from an engineering background mentioned that the tool need not include methods to estimate the cost of reconstruction as there are widely accepted methods for such estimation purposes. The option of including the cost of reconstruction as a single input value would be beneficial more for comparison with the sustainability impacts rather than for estimation of costs.

8.2.2 Interviews with academics and researchers

A group of academic researchers working in multiple areas related to the scope of this research were interviewed in order to obtain their views on the theoretical foundation of the framework and the tool. These interviews were carried out in addition to the annual PhD milestone presentations where the framework was presented and feedback from faculty members was received. The interviews focussed purely on the validation of the framework, while their opinions on the rigorousness of the framework and the validity of the techniques used within the toolkit were obtained. The following academics were interviewed as part of this validation step.

Table 8-2 List of academic researchers interviewed

Participant Code	Area of expertise	Affiliation
P22	Infrastructure resilience and Sustainable Engineering	School of Engineering, RMIT University
P23	Earthquake Engineering and Natural Hazard resilience	School of Engineering, RMIT University
P24	Traffic engineering and Transport modelling	School of Engineering, RMIT University
P27	Life Cycle Assessment and Waste & resource efficiency	School of Industrial Design, RMIT University
P26	Infrastructure interdependency and resilience	School of Property, Construction and Project Management, RMIT University
P25	Environmental Engineering and Infrastructure asset management	Cities Research Institute, School of Engineering and Built Environment, Griffith University

The participants for these interviews were chosen from across different disciplines and specialisations to obtain feedback from diverse points of view. The participants were first asked to focus more on the specific section of the tool, which was within their area of expertise to ascertain the theoretical rigour of the specific techniques. This resulted in some of the equations and assumptions that were used in the preliminary version of the tool being modified. The interviews also asked the participants to comment on the framework from a conceptual and holistic viewpoint in order to understand the applicability of the integration and results of the model. The feedback received helped to improve the final version of the toolkit and is explained in detail below.

Applicability of techniques

The different techniques and the assumptions used within the model were considered to be applicable to the scope of the research. As with most of the end-users who were interviewed, the academics agreed that the tool should focus more on the wider impacts and less on estimating the cost of reconstruction. Most interviewees mentioned that the tool presented the impacts in a rural area and was a good representation given the resource and data constraints that would be experienced in a post-disaster time. Though the lack of data for environmental impacts was seen as a constraining factor in the case study, it was suggested that the final tool should capture these impacts in a more holistic manner. Suggestions for improvement were provided if the tool was to be used in a more urban area, especially on the transport impact category, which would improve the accuracy of results. The inclusion of costs due to increased congestion was considered an important element in more rural areas.

Integration and data gathering

Feedback on the integration techniques used within the framework and the relevant monetary values used to monetise the impacts were also obtained. The monetary valuation of the different impacts was seen to be beneficial and helped in a useful comparison of the different impact categories. It was suggested that providing detailed explanations in instances where there could be inconsistencies across methods would increase the transparency and validity of the tool. The database that was compiled for the use of the toolkit was identified as a good outcome, as there was no similar database available in an Australian context. Participants mentioned that the database could be upgraded as an online real time tool, which then can be used in other transport infrastructure related projects.

Results and analysis

The output of the first version of the tool was seen as a basic representation of an aggregation of the results. Feedback received from the academics showed that a more dynamic set of results, which showed comparisons between different options, interdependence of outputs and interactions of input factors would be beneficial. A more analytical set of results was identified as adding value to the toolkit. Most participants mentioned that the time taken for reconstruction was a significant aspect that needed to be analysed during post-disaster reconstruction. As such understanding how impacts varied with the time taken for reconstruction and the baseline time required for funding approvals were seen to add value to the final analysis and results.

8.2.3 Improvements made to the final version of the toolkit

Based on the feedback received from the end-users and academics interviewed the toolkit was improved and modified. The final version of the toolkit with these improvements and modifications was presented in Chapters 6 and 7. The changes made to the first version of the framework and toolkit based on the interview results are presented below. This provides the reader the opportunity to recognise what specific modifications were made during this stage of the research, as the development of the toolkit was an iterative process. Feedback received through the interviews was also used for further sensitivity analysis, as explained in section 8.4.

Estimation of cost of reconstruction

The majority interviewed mentioned that the tool should focus on measuring the socio-economic and environmental impacts, rather than on estimating the financial cost of reconstruction. Based on this feedback, the section of the tool to estimate the cost of reconstruction was simplified to include one final value, without any calculations or estimations to be done within the tool. This allows the users to include the financial cost of reconstruction into the tool so that the wider sustainability impacts could be compared with the financial impacts. However, the different methods that can be used for initial cost estimation are presented in this thesis for comprehensiveness of the research.

Refinement of transport impacts

Based on comments received, the transport impacts were refined to include more relevant and representative results. It was identified that there were instances where damage to bridges results in only a partial closure after a disaster. The Thistlethwaite Bridge was one such example where the bridge was assessed for its safety after the flood and a load limit for the vehicles using the bridge was mandated. In this case light vehicles were allowed to use the bridge until reconstruction began, while all heavy vehicles needed to use an alternative route until the new bridge was reopened. This aspect of different types of vehicles having varied durations of detours due to load limits and partial closures of routes was included in the toolkit. This modification allowed for a better assessment of how different types of interventions to rehabilitation and maintenance influence the socio-economic impacts.

The interviews also showed that there could be an increased risk of accidents during the time of reconstruction. Such an increase could be due to heightened road works around the structure, the lack of capacity of the detour routes to handle increased traffic volumes and drivers using unfamiliar routes during the reconstruction. This aspect of the probability of increased accidents was also included in the final version of the toolkit.

Capturing environmental impacts

The environmental impacts were not captured in a representative manner within the initial version of the tool and the case study, due to the lack of data needed to measure environmental impacts. However, as environmental factors were considered an important aspect in the reconstruction phase by end-users, it was decided to include the methods to capture a wider and more relevant set of environmental impacts within the tool. The relevant equations to capture these impacts were explained in Chapter 7. These methods were included in the utilisation phase of the tool so that users were given the opportunity to estimate a more relevant set of environmental factors.

Utilisation of the toolkit

The majority of end-users claimed that the utilisation of the toolkit within the relevant agencies would depend on the enhanced useability of the tool. Some specific factors that would enhance user-friendliness were also identified through the interviews. Some of these factors were transitioning from an Excel-based tool to a web-based application, real time linking of the database to original data sources and including the level of detail required by the different agencies that will use the product. An utilisation project through the BNHCRC's Utilisation and Agency Funding Support program has been planned for this purpose.

8.3 Validation of results

The sustainability impacts that were measured using the toolkit were analysed in order to validate the reliability and relevance of the results. The validation helped in understanding whether the results obtained from the toolkit represented the actual behaviour of the system comprehensively. This was an important aspect that needed to be considered as longer-term behavioural changes after a disaster can be different to those that are predicted soon after the event. The validation of the results was carried out by conducting a questionnaire survey among residents of the two areas affected by the damage to the bridges and by analysing secondary data obtained through a desktop search. The possible variations to the results identified through the validation process were then used as a basis for sensitivity analysis of the results.

8.3.1 Questionnaire survey

A questionnaire survey was conducted among the residents of the Lockyer Valley region who typically use the two case study bridges in order to understand how they were affected by the damage to the bridge and the resulting reconstruction process. The ethics approval obtained for the PhD project included the data collection carried out by this survey.

Design of the questionnaire

The questionnaire was designed to obtain information on how the damage to the two case study bridges affected the daily lives of people living and working in the area. The details include their travel patterns before and after the event, types of routes used, time spent traveling, effects on business activities and work lives and changes to general social mobility. The questions were designed to gather primary data for the use in the specific techniques that were part of the developed toolkit. Questionnaires that were used in previous literature were analysed as a first step to get a basic idea of what types of questions need to be asked. The final questions were selected by working backwards from the desired outcome of the toolkit and the different techniques within it. This ensured that the questionnaire included only the exact questions that were required for the analysis as the time taken to complete the questionnaire was designed to be no more than 20 minutes. Two separate questionnaires were designed for the two case study areas as the detour options differed for the two bridges.

The approximate time taken to fill out the questionnaire was tested by giving out the questionnaire to a group of volunteer students, who were asked to complete it by thinking of a hypothetical situation of a road closure. This exercise also helped the researcher to identify any ambiguities in language that were apparent and correct such flaws in the questionnaire. The questionnaire was shown to the Community Engagement Officer of the LVRC in order to check for its relevance in the given area. This was an important step as the socio-cultural background of the respondents needed to be considered, as the interpretation of some key words may have an effect on the responses. In addition, this allowed the researcher to confirm that the questions would not evoke any sensitive emotions of the residents given that the questionnaire dealt with a post-disaster time period. The use of technical jargon was avoided throughout the questionnaire, while the terms used were simple and comprehensible to lay people. A copy of the questionnaire is provided in Appendix X of this thesis.

Selection of participants

The participants for the survey were identified as the residents of the Lockyer Valley region who live within close proximity to the two case study areas. The specific postal codes and localities as per Australia Post categorisations were obtained and matched against the access roads of the two case study areas. Figures 1 and 2 below show the localities that were identified to have been directly affected by the damage to the bridges. The damaged bridges are marked in a white circle, while the boundary of each locality is highlighted in white. The number of postal addresses in each locality was obtained from Australia Post, which included both business addresses and private residences.

Figure 8-1 Map showing the area the questionnaire for the Thistlethwaite Bridge was distributed

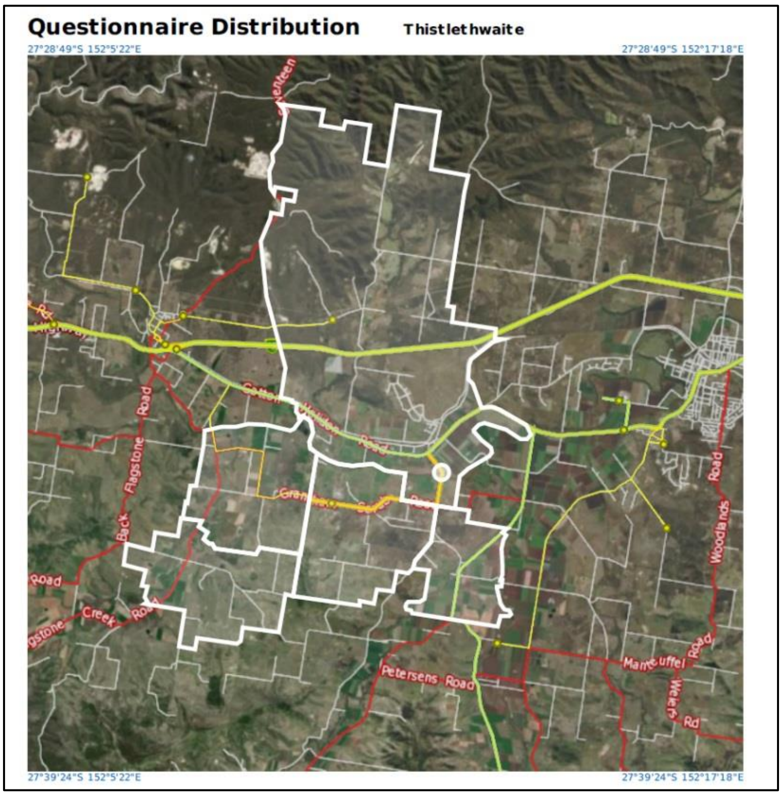
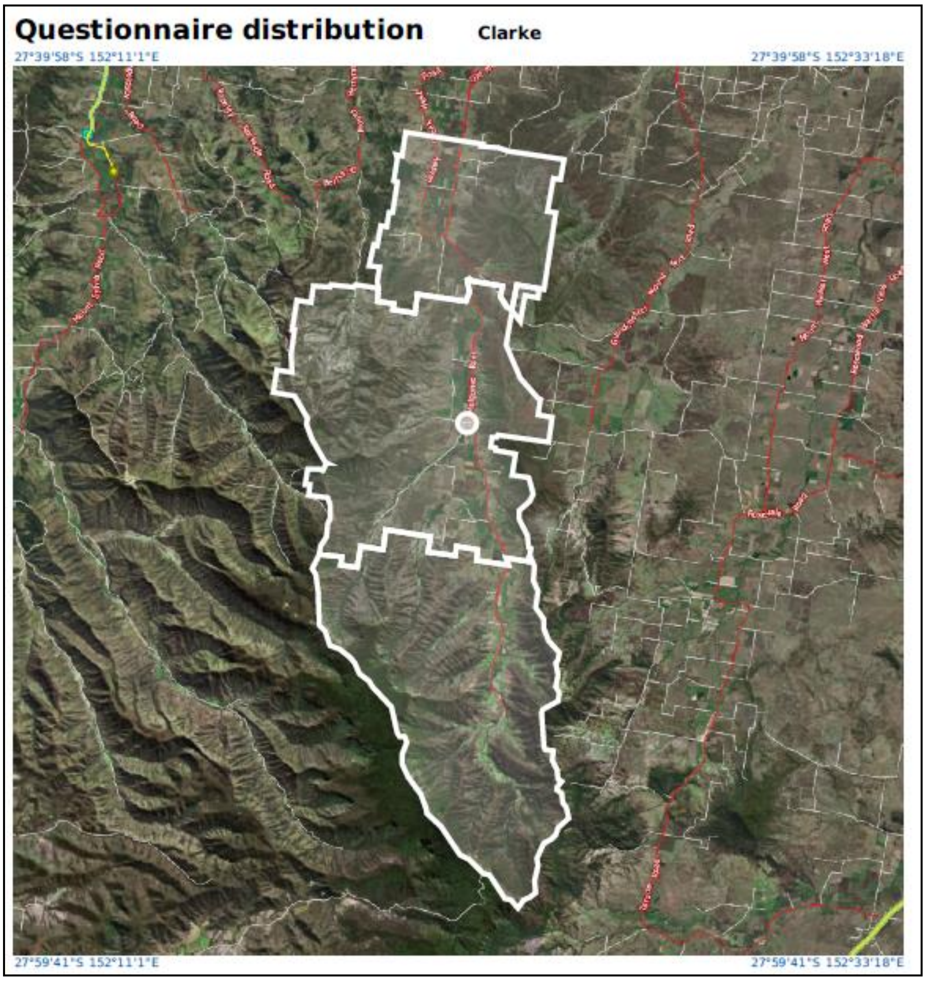


Figure 8-2 Map showing the area the questionnaire for the Clarke Bridge was distributed



A breakdown of the number of postal addresses within these two areas is provided in Table 1. Some of the localities within these areas were identified as less relevant to the study as the majority of the residents within such areas may not have used the bridge as frequently as others. The areas with less impact were Grantham and Mulgowie, which were both located north of the two structures. A total of 171 addresses for Thistlethwaite Bridge and 90 for the Clarke Bridge were identified as being extremely relevant for the survey.

Table 8-3 Number of sample residences

Bridge	Locality	Number of addresses	Relevance
Thistlethwaite	Winwill	61	High
	Veradilla	43	High
	Grantham	292	Low
	Carpendale	42	High
	Lilydale	25	High
Clarke	Thornton	69	High
	Townson	21	High
	Mulgowie	59	Low

Distribution of questionnaire

The Australia Post Unaddressed Mail service was utilised to deliver the questionnaires to the selected addresses in the two areas. A copy of the relevant questionnaire, the Participant Information Sheet and a reply paid envelope were delivered in a sealed envelope in this manner. Two separate batches of envelopes were dispatched to Auspost for delivery in the two areas as identified. However, Auspost made a blunder with the delivery of the questionnaires, where the batch designed for the Clarke Bridge was delivered to another area in Queensland and the batch for the Thsitlethwaite Bridge was delivered in the Thornton area, where the Clarke Bridge is located. As a result, a second batch of questionnaires had to be delivered to these two areas through a private letter box drop company.

A web-based version of the questionnaire was built and distributed using the Qualtrics online survey tool. The Questionnaire on Qualtrics was exactly the same as the hard copy questionnaires that were distributed among residents in order to maintain accuracy of the results. A link to the online questionnaire was provided in the paper-based questionnaires that were distributed. A number of online survey distribution tools were adopted to reach potential respondents.

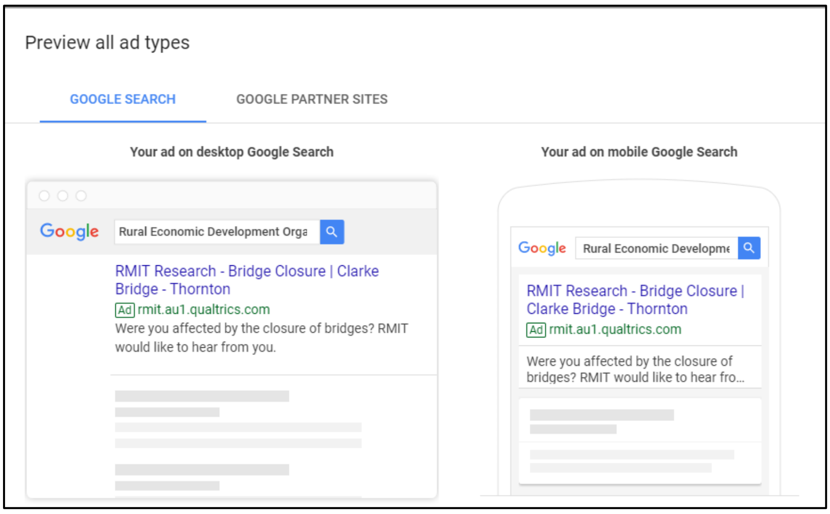
The most effective method to approach potential respondents was to directly email organisations that were located in the vicinity of the case study areas. A list of such organisations was compiled in consultation with the LVRC staff. This included schools, council offices, business enterprises and community organisations. In cases where organisations had Facebook pages, direct Facebook messages were sent, and follow-up telephone calls were made in instances where telephone numbers were available publicly.

Table 8-4 Organisations contacted for survey distribution

Name of organisation	Type of organisation
Thistlethwaite Bridge	
Permaculture Lockyer Valley Inc.	Community
Grantham Community Network	Community organisation
Grantham State School	School
Tent Hill Lower State School	School
Grantham Community Store	Business
Floating Café Grantham	Business
Whispers of the valley	Business
Stanbroke Meats	Business
The Organic farm Gate	Business
Woodlea Rural Fire Brigade	Fire service
Clarke Bridge	
Mulgowie Markets	Community
Mulgowie Hotel	Business
Thornton State School	School
Holmwood Produce Lavender farm	School
Edmond Park Adventure Education	School
Mulgowie Farming company	Business

A geographically targeted online advertisement campaign was also conducted in order to attract potential respondents to answer the questionnaire survey, which included Google advertisements as well as Facebook advertisements. The advertisements were targeted at people accessing the internet from the geographic vicinity of the two case study bridges and clicking the ad diverted the user to the Qualtrics survey link. The Google advertisement targeted at residents around the Thistlethwaite Bridge attracted 1,267 impressions and 7 clicks, while for the Clarke Bridge it was 547 impressions with 6 clicks. A similar target ad campaign on Facebook resulted in reaching 2,425 users and 66 link clicks over a period of 16 days.

Figure 8-3 Preview of Google advertisement



Survey results

A total of 32 responses were received for both the online as well as postal surveys. The response rate for the postal survey was very low. This could be mainly attributed to the fact that the first round of distribution was not carried out correctly, with the questionnaire for the Thistlethwaite Bridge being distributed among residents in the vicinity of the Clarke Bridge. The responses received from the online survey was more reliable as the option of choosing which bridge affected travel patterns was provided. However, due to the low number of responses for the survey, a statistical analysis of the results was not possible. Instead, a detailed analysis of each of the relevant responses was carried out in order to better understand if the assumptions and values used in the framework were a proper representation of actual travel patterns after the disaster. The responses received for the questionnaire were analysed against the relevant assumptions made during the measurement of impacts, and their implications for the analysis is described below.

Changes to travel patterns

All the respondents that had to change travel patterns due to the damage to the bridge mentioned that they used alternative routes to overcome this issue. Most of the users of the Thistlethwaite Bridge only had to rely on using alternative routes, although users of the Clarke Bridge mentioned that they took more varied approaches. This included cancelling of trips, combining trips, using different vehicles and changing the time of the trip. Respondents mentioned that travel patterns were severely affected due to the bad road conditions on the alternative routes and this may have led to them cancelling and using different travel modes.

Changes to travel times

The responses for the incremental time incurred using the alternative routes were different for the two case study bridges. Users of the Thistlethwaite Bridge indicated that using the alternative routes only added a couple of minutes of extra travel time. This was consistent with the 2-3 minutes of incremental time calculated. However, users of the Clarke Bridge noted that incremental time on the alternative routes were 8-10 minutes, which was nearly twice the amount of time calculated for the application of the model. This again could be due to the bad road conditions of the alternative route.

Vehicle operating costs

Some of the respondents mentioned that the poor road conditions on the alternative routes of the Clarke Bridge resulted in damage to the vehicle. Such damage would typically increase the vehicle operating costs that are estimated.

Business impacts

The most common factor affecting businesses was identified as shipping and transport delays, although the precise monetary impacts were not identified. Businesses located in close proximity to the case study bridges experienced reduced sales revenue due to lower customer access to the premises. The types of businesses that experienced a reduction in revenue were tourism related businesses that relied on customer traffic. Although no businesses close to the Clarke Bridge were identified that would be affected by reduced customer traffic during the case study, the questionnaire survey showed that a lavender farm partly relied on visitors to the farm for revenue generation. The decrease in customers for this specific business was estimated at 50% of normal rates. This was higher than the 30% reduction in turnover that was estimated for the most affected businesses. However, since the responses for questions regarding the revenue estimates and monetary value of business impacts were low, it was impractical to conduct any statistical analysis for comparisons.

Discussion of results

A major limitation of the questionnaire survey is the low number of responses received. The reasons for the low response rates could be mainly due to the initial error in distributing the wrong batch of questionnaires in the wrong areas, which was out of the researcher's control. This resulted in some residents calling up the researcher and asking for explanations, while one respondent returned the questionnaire with very harsh comments. However, as the mistake in distribution of the survey was not the researcher's fault, little could be done regarding this. The comments on the erroneously delivered questionnaires also exemplified that some of the residents had a deep mistrust of authorities. Another reason for the low response rate could be due to survey fatigue in the region as many research projects have been conducted in the Lockyer Valley region, although they were not specific to travel patterns due to bridge failure. The timing of the survey could also have had an impact on the response rate as South East Queensland was experiencing a severe drought at the time of distribution, and residents may have been more concerned about the lack of rain rather than a flooding event that occurred five years previously.

One of the major implications of the results of the questionnaire is that the road conditions of the alternative routes play a big influence on transport related impacts. Changes in road conditions may be of a higher significance in more rural areas, where less used alternative roads may not be of the same quality as the main roads where access is limited. Increased traffic on such roads could exacerbate this situation as they may not be suitable for use by all vehicle types and may cause higher deterioration of the already low quality roads. Such factors can add to the incremental travel times and vehicle operating costs, which need to be considered.

8.3.2 Analysis of secondary data

The results of the case study were also validated through the analysis of secondary data. The financial cost of reconstruction estimated through the toolkit was validated by comparing them against the actual cost spent by the council, while impacts on detour times and distances were analysed against publicly available data.

Validation of reconstruction costs

The three estimates explained above were validated by comparing the estimate values against the actual cost of construction – figures obtained from the Council. The actual costs of construction for the Thistlethwaite and Clarke bridges were $2,438,427.57 and $1,101,643.58, respectively.

Table 8-5 Variation of estimated reconstruction costs

	Estimates based on Rawlinson unit rates ($)	Variance from actual cost	Estimates based on TIC unit rates ($)	Variance from actual cost	Council estimates ($)	Variance from actual cost
Thistlethwaite Bridge	834,300.00	-65.79%	2,202,300.00	-9.68%	3,502,707.90	43.65%
Clarkes Bridge	299,186.16	-87.73%	721,848.00	-34.48%	1,265,829.00	14.90%

From the above analysis, it could be seen that the estimates based on the (Transport and Infrastructure Council 2015) unit rates are more reflective of the actual cost in contrast to the unit rates obtained from (Rawlinsons 2013). Comparing the estimation carried out by the author with those of the council, it could be seen that the council has overestimated the costs. A reason for this could be that the council uses a precautionary approach for estimation purposes; as such estimates are used to obtain funding from the State Government in disaster reconstruction efforts.

Further, the estimates based on the (Transport and Infrastructure Council 2015) unit rates and the council estimates based on historical costs show a great deal of variation from the actual costs of construction. In two instances the variations of the estimates have exceeded the error rate generally accepted for conceptual cost estimations of ±10=20% (Holm et al. 2005). The reasons for such discrepancies could not be analysed as the Council did not provide a detailed breakdown of the actual costs incurred.

A probable reason for the variation of the TIC estimate for the Clarke Bridge could be that the Clarke Bridge is more reflective of a typical bridge owned by a Regional Council. This bridge is a one-lane 4.2 metre wide bridge, situated on a local access road, while the square metre rates provided by TIC are for bridges on rural arterial roads. The historical costs used by the TIC for calculating the square metre costs of bridge construction include costs of bridge construction provided by state road authorities and do not include construction carried out by local councils. As such the TIC estimates would not reflect the costs of construction for more rural roads, which are generally constructed by councils. The lower variation of the council estimates also show that the council would have better knowledge and historical costs related to bridges similar to the Clarke Bridge.

Further to this point, the damaged Thistlethwaite Bridge was a single-lane timber-concrete bridge, which was replaced by a better designed concrete span bridge. It could be assumed that the construction costs of the newer bridge were more in line with the historical costs obtained to estimate the square metre rates in (Transport and Infrastructure Council 2015) report, rather than the typical bridge that the council would own. This could be another reason that the TIC unit rates were more accurate than council estimates for the Thistlethwaite Bridge.

Thus it could be concluded that it is vital to choose a representative square metre rate during estimation processes. In this case the TIC rates were deemed more accurate for the estimation of the costs of the Thistlethwaite Bridge, while the council rates were accurate for the Clarke Bridge as the Clarke Bridge is similar to most bridges constructed by the council.

Validation of transport related impacts

As the response rate of the questionnaire survey was very low a desktop search of secondary data relating to the case study regions was conducted. These results were used to complement the primary data obtained through the questionnaire survey. The major sources that were analysed were newspaper articles referring to the two case study bridges. The secondary sources confirmed that there were weight restrictions on the Thistlethwaite Bridge before the construction of the new bridge began (Lyne 2013). However, it was also revealed that the extra travel time during the construction period was 10 minutes (Lyne 2014), which was much higher than the 2-3 minutes delay that was calculated. A reason for this discrepancy was due to the alternative route specified for heavy vehicles being different to the alternative route which was assumed in the calculations. The alternative route proposed by the Council was a much longer route and would have been proposed due to the better quality of it and its capacity to carry heavy vehicles. The respondents to the questionnaire may have taken the lower capacity route for the personal travels. The follow-up interviews with Council staff corroborated this view and showed that residents and businesses located closer to the bridge may have had higher increased travel times as opposed to those travelling through the region.

Another factor that was identified during the analysis of secondary data was that the Clarke Bridge was located along the Bicentennial National Trail. The closure of the bridge would have added extra time and inconvenience to trekkers who were following this train on foot, mountain bike or on horse. As the Clarke Bridge provided access to the Centenary Park Camp grounds, the un-useability of the bridge would have added an extra one hour on foot for trekkers wishing to use the camp ground. However, as the benefit derived from trekking is intrinsically in the activity itself, measuring any inconvenience to trekkers can be problematic.

The results obtained through the toolkit could not be compared against previous literature in a meaningful manner as the results of each research project were very case specific. Not only was there very limited literature on impacts due to damage to bridges, but also such impacts varied according to the level of damage to the infrastructure, the duration of road closure, the level of traffic and socio-economic setting of the area (Winter et al. 2016b). As a result a meaningful comparison against previous literature could not be carried out.

8.4 Sensitivity analysis

Sensitivity analysis was carried out in order to study how the model output values are affected by changes in model input values (Loucks and Van Beek 2017). Sensitivity analysis, analyses the importance of imprecision or uncertainty of model inputs in a decision-making or modelling process and can be used to explain how uncertainty in the outputs can be apportioned to different sources of uncertainty in the model input. This is in contrast to uncertainty analysis, which tries to quantify the uncertainty of the entire model by analysing all possible outcomes and their possibility of occurrence (Saltelli et al. 2008). A two-step approach was adopted for the sensitivity analysis. The first step was to identify significant input variables that would need to be analysed while the second step was a one-at-a-time sensitivity analysis of the identified significant variables. A further what-if scenario analysis of changes to qualitative assumptions was also employed to validate the model.

8.4.1 Screening to identify significant input variables

As the framework and toolkit used to assess post-disaster impacts have multiple input parameters it was important to identify the most significant variables. Screening of the factors helped in focussing on the most influential factors for the sensitivity analysis, which reduced the time taken for the analysis. In most cases, only a handful of influential factors are found, even where there are multiple parameters, conducting sensitivity analysis for all factors will not provide any meaningful outcomes (Saltelli et al. 2008). A first-step sensitivity analysis was performed using a very limited number of runs and a sampling-based approach in order to identify the most influential factors (Becker, Tarantola and Deman 2018). The screening step did not focus on obtaining precise values of sensitivity measures, but laboured to identify the most influential factors. This was done by varying the input variables in order to see how they influence the final outputs.

As a first step, the input parameters relating to project specific data values were increased by 50% and compared against the baseline output values to assess how variations affected the final outputs. This method helped in identifying critical factors that interact and which can generate extreme values. Increasing the project specific parameter values one at a time showed that the duration of road closure and traffic counts were the most significant input variables. The standard input values used for calculating the different types of impacts were also analysed in the same manner. The table below shows the results of the screening process with the variables presented in the descending order of significance.

Table 8-6 List of factors according to order of influence

Input variable	Influence on output	
	Thistlethwaite Bridge	**Clarke Bridge**
Duration of road closure	48%	49%
Traffic counts	46%	49%
Time on alternative route	27%	39%
Travel time values	25%	38%
Vehicle occupancy rates	25%	38%
Percentage of heavy vehicles	20%	2%
Distance on alternative route	19%	10%
Vehicle Operating Costs	13%	9%
Number of businesses	4%	-
Crash costs	3%	3%
Freight travel time values	2%	1%
Average business revenue	2%	-
Life cycle environmental impacts	2%	1%
Environmental cost of transport	1%	1%
Environmental cost of demolition	0%	0%

The variables that exhibited the highest influence were transport related variables, as the vast majority of the non-financial impacts were due to transport related impacts. However, a simple one-factor-at-a-time analysis was not sufficient in some cases as some of the variables were correlated. For example, the distance and time on the alternative route were correlated, and it was not realistic to increase one of these variables while keeping the other constant. Increasing both the distance and time on the alternative route by 50% together, showed that this caused the output values to increase by 46-49%. Although the influence of the percentage of heavy vehicles was low for the Clarke Bridge, it had a high influence on the Thistlethwaite Bridge. This screening process resulted in identifying the significant factors that were considered for the more in-depth sensitivity analysis. These factors are:

1. Duration of road closure
2. Traffic counts
3. Distance and time on alternative routes
4. Travel time values
5. Vehicle occupancy rates
6. Percentage of heavy vehicles

8.4.2 One-at-a-time sensitivity analysis

The six most significant factors identified in the preceding section were then used to conduct a more detailed sensitivity analysis. The sensitivity analysis helped to assess the robustness and the precision of the model, as well as provide insight into possible errors in various parameters.

Sensitivity analysis can help in corroborating the model and to understand if it is overly dependent on specific parameters and any fragile assumptions (Loucks and Van Beek 2017). Such an analysis can also be a stepping stone for the simplification of a model where some factors can be combined to ease the data collection and assessment stages.

Duration of road closure

The initial screening step explained in the preceding section showed that the duration of road closure was the most significant influential factor on the SEE impacts. The academics who were interviewed also mentioned that the effect of time on the wider impacts needed to be analysed in more detail. This section explains the further analysis that was carried out in order to identify how time affects the total SEE impacts. The analyses of the two bridges were conducted separately as there were differences in the time taken for reconstruction of the two bridges.

The first step was to identify the type of impacts that were expected to vary with time and those that were fixed over the period of analysis. The impacts that were considered to vary with time were: vehicle operating costs, freight delay costs, passenger delay costs, crash costs, loss of business revenue and environmental cost of detour. The costs that were expected not to vary with time were: the environmental cost of demolition and reconstruction of the bridge. The daily costs for each of these impacts are given in the table below.

Table 8-7 Cost of impacts per day

Impact type	Thistlethwaite ($)	Clarke ($)
Vehicle operating costs	553.91	83.96
Freight delay	502.56	94.55
Passenger delay	1,180.64	258.58
Crash costs	161.07	30.47
Loss of business revenue	140.27	-
Environmental cost of detour	38.45	6.07
Total daily costs	2,576.90	473.62

The total daily costs calculated above represent the social, environmental and economic cost of full closure of the bridge for a day. By comparing these costs with the financial and environmental costs of reconstruction it was estimated that having the Thistlethwaite Bridge fully unserviceable for 474 days would result in a socio-economic cost to the community adding up to 50% of the financial cost of reconstruction. In contrast the Clarke Bridge would need to be closed for more than double that time (1,163 days) for the community impacts to reach 50% of the cost of reconstruction.

The case study of the Thistlethwaite Bridge provided the opportunity to calculate the costs of partial and full closure of bridges. While the full closure of the Thistlethwaite Bridge was estimated to cost $2,576.90 per day, the partial closure of the bridge with access only to light vehicles resulted in a cost of $417.64 per day. Due to the higher traffic volumes on the

Thistlethwaite Bridge, the daily cost of partial closure is almost the same as the daily cost of full closure of the Clarke Bridge.

Analysing the effect of the duration of road closure on wider socio-economic impacts provides asset owners the opportunity to assess whether temporary repair of the bridge allowing partial usage could be socially beneficial. Interviewees from the local councils mentioned that there is a holding cost incurred to keep a damaged bridge open for traffic. Such costs include continuous inspection of the structures, traffic control procedures and maintenance and repairs to keep the structure safe for use. Analysis of the Thistlethwaite Bridge found that, the full closure of the bridge for the entire duration until the reopening of the new bridge would have increased the SEE impacts by more than $1 million.

The social, environmental and economic benefit of allowing light vehicles to use the bridge was estimated to be $2,159.26 per day for the Thistlethwaite Bridge. Similarly if some manner of repair allowed for light vehicles to use the Clarke Bridge until reconstruction began the benefit to the community would have been $432.28 per day. Thus it can be concluded that if holding costs per day were below these values it would have been beneficial for the asset owners to partially open these bridges for limited loads of vehicular traffic.

Traffic counts

Traffic counts were identified to be the second most significant input factor influencing the socio-economic impacts due to bridge closure. The screening step showed that the traffic counts were very closely related to changes in impacts, with a 50% increase in traffic counts leading to a 48-49% increase in impacts. As such a more in-depth analysis of how changes to traffic impacted the results was required. Two factors that were linked to traffic counts were a breakdown of the different types of vehicles, and the assumptions of the use of private passenger vehicles. The daily estimated traffic counts were divided according to different types of vehicles using registered vehicle numbers in the Lockyer Valley region, and the use of passenger vehicles was based on usage patterns in Queensland (Australian Bureau of Statistics 2012).

The number of light vehicles was categorised as passenger vehicles (72%) and commercial vehicles (28%), while the use of passenger vehicles was categorised into personal use (53%) and business related use (47%). As part of the sensitivity analysis of traffic counts, these percentages for categorisation were also changed to understand how they would influence the final values.

Table 8-8 Sensitivity of impacts to changes in traffic volumes and percentage breakdown of light vehicles – Thistlethwaite Bridge

	Changes to traffic volume				
Passenger vehicle to Commercial vehicle ratio	**20% decrease in traffic**	**10% decrease in traffic**	**Baseline traffic volume**	**10% increase in traffic**	**20% increase in traffic**
82/18	-17.7%	-8.4%	0.9%	10.3%	19.6%
77/23	-18.1%	-8.8%	0.5%	9.8%	19.1%
Baseline (72/28)	-18.5%	- 9.3%	0%	9.3%	18.5%
67/33	-18.8%	-9.6%	-0.4%	8.8%	18%
62/38	-19.2%	-10.1%	-0.9%	8.3%	17.4%

Table 8-9 Sensitivity of impacts to changes in traffic volumes and passenger vehicle use – Thistlethwaite Bridge

	Changes to traffic volume				
Ratio of personal/ business use	**20% decrease in traffic**	**10% decrease in traffic**	**Baseline traffic volume**	**10% increase in traffic**	**20% increase in traffic**
63/37	-20.5%	-11.5%	-2.5%	6.5%	15.5%
58/42	-19.5%	-10.3%	-1.2%	7.9%	17.1%
Baseline (53/47)	-18.5%	- 9.3%	0%	9.3%	18.5%
48/52	-17.4%	-8.0%	1.3%	10.7%	20.1%
43/57	-16.4%	-6.9%	2.6%	12.1%	21.6%

It can be concluded from this analysis that the results have a higher sensitivity to changes in traffic volume rather than changes to vehicle types and usage assumed in the model. As such estimating accurate traffic volumes can lead to higher accuracy of the results of the model. Accuracy of results could be increased by using more recent traffic counts and relying on annual average traffic counts rather than daily traffic counts.

The analysis also shows that increases in the percentage of passenger vehicles and increase in the ratio of passenger vehicles used for business purposes have a positive effect on socio-economic impacts. An underlying factor for this is the travel time value for business related car travel, which is $48.63 per person hour. This value is derived from average weekly earnings in Australia and is higher than the other travel time values for other values such as personal travel time and freight personnel travel time values. The effect of travel time values on the results are analysed in the proceeding section.

Distance and time on alternative routes

The alternative routes available during the time a bridge is closed for reconstruction were identified as a significant factor. As such sensitivity analysis was carried out to evaluate how an increase in the distance of an alternative route could affect wider impacts to the community and environment. An increase in the distance of an alternative route also means that the time taken would increase in tandem. The average speeds for the two bridges were calculated as 47.77 km/h for the Thistlethwaite Bridge and 43.2 km/h for the Clarke Bridge. For the purpose of analysis, it was assumed that an increase in the alternative distance by 1 km would increase the time taken to travel in line with the average speed calculated for each bridge.

The survey results showed that there were instances where the time taken to travel is longer than the average time calculated based on the Google Maps routing function. This was due to the alternative routes also being damaged due to flooding. A further sensitivity to an increase in travel times without an increase in travel distances was also analysed to understand how impacts would vary due to changes in travel speeds on alternative routes.

Table 8-10 Sensitivity to change in distance and speed of alternative routes

	% change of impact due to increase in distance by 1km		% change of impact due to decrease in speed by 10km/h	
	Thistlethwaite	**Clarke**	**Thistlethwaite**	**Clarke**
Economic	45.2%	27.8%	10.2%	16.0%
Social	48.1%	27.8%	22.5%	26.9%
Environmental	16.5%	8.9%	0.0%	0.0%
Total SEE	44.4%	27.1%	13.8%	21.9%

The analysis shows that the distance on the alternative route and the corresponding increase in travel time have a higher influence than reduction in speed. The difference of the influence of distance on the two bridges is attributable to the difference in the number of heavy vehicles on each route. The higher number of heavy vehicles on the Thistlethwaite Bridge contributes to a high economic and environmental impact. The effect of a decrease in speed is seen to have a higher influence on the Clarke Bridge. This analysis shows that the sensitivity to different variables will vary from structure to structure based on the characteristics of each of them. The advantage of such an analysis is that road authorities can estimate how wider SEE impacts will vary with changes to alternative detour routes and prescribed speed limits during the reconstruction period.

However, it should be noted that changes to incremental distance will most often be more than just a couple of kilometres, especially in regional areas, where road density is much lower. This has been analysed in section 8.4.3, and shows that the changes to alternative routes in regional areas can have drastic consequences on the communities and economies in the area.

Travel time values

The sensitivity of the socio-economic impacts to changes in travel time values was analysed. The travel time values used for this research were calculated based on Average Weekly

Earnings in Australia (Transport and Infrastructure Council 2016). More accurate travel times relevant to the case study region could be calculated by using the average weekly earnings of the Lockyer Valley region. The median weekly income for the Lockyer Valley region was 19% lower than the Australian median income (Australian Bureau of Statistics 2016). With such a difference observed, the possible changes to travel time values were calculated based on five different scenarios, where possible reductions of 10%, 20% and 25% and increases of 10% and 20% of travel time values were assumed.

Table 8-11 Sensitivity to change in travel time values – Thistlethwaite Bridge

Type of impact	% change due to reduction in travel time by			Baseline ($)	% change in impacts due increase in travel time by	
	25%	**20%**	**10%**		**10%**	**20%**
Economic	-7.8%	-6.2%	-3.1%	365,990.14	3.1%	6.2%
Social	-21.3%	-17.0%	-8.5%	207,982.81	8.5%	17.0%
Environmental	0.0%	0.0%	0.0%	37,787.49	0.0%	0.0%
Total SEE	-11.9%	-9.5%	-4.8%	611,760.43	4.8%	9.5%

Table 8-12 Sensitivity to change in travel time values – Clark Bridge

Type of impact	% change due to reduction in travel time by			Baseline ($)	% change in impacts due increase in travel time by	
	25%	**20%**	**10%**		**10%**	**20%**
Economic	-12.4%	-9.9%	-4.9%	124,956.86	4.9%	9.9%
Social	-22.4%	-17.9%	-8.9%	202,333.68	8.9%	17.9%
Environmental	0.0%	0.0%	0.0%	13,253.49	0.0%	0.0%
Total SEE	-17.8%	-14.3%	-7.1%	340,544.03	7.1%	14.3%

The sensitivity analysis shows that the travel time values have a very strong relationship with social impacts. The reason for this is that the monetary values for the social impacts were mainly derived from the travel time values. It could be seen that in the case of the Clarke Bridge, the total SEE impacts have a higher sensitivity to travel time values in contrast to the Thistlethwaite Bridge as the social impacts account for more than 50% of the total SEE impacts.

Vehicle occupancy rates

Two extreme values for vehicle occupancy rates for all types of vehicles were assumed. The lower bound was estimated at one person per vehicle, which is the absolute lowest possible value, while the upper bound was assumed at two persons per vehicle. These upper and lower bounds were assumed for all types of vehicles. The highest vehicle occupancy rate calculated by (Transport and Infrastructure Council 2016), was 1.7 persons per vehicle relating to occupancy of passenger vehicles for private travel in non-urban areas. Hence an upper bound of two persons per vehicle was assumed to be relevant for the purpose of this sensitivity analysis. The sensitivity to changes in the vehicle occupancy rates are provided in the table below.

Table 8-13 Sensitivity to changes in vehicle occupancy – Thistlethwaite Bridge

Type of impact	Minimum occupancy		Baseline	Maximum occupancy	
	$	%Change		$	%Change
Economic	353,631.43	-3.4%	365,990.14	455,335.58	24.4%
Social	157,019.69	-24.5%	207,982.81	283,152.59	36.1%
Environmental	37,787.49	0.0%	37,787.49	37,787.49	0.0%
Total	548,438.61	-10.4%	611,760.43	776,275.66	26.9%

Table 8-14 Sensitivity to changes in vehicle occupancy – Clarke Bridge

Type of impact	Minimum occupancy		Baseline	Maximum occupancy	
	$	%Change		$	%Change
Economic	112,325.23	-10.1%	124,956.86	161,542.79	29.3%
Social	150,245.12	-25.7%	202,333.68	279,163.48	38.0%
Environmental	13,253.49	0.0%	13,253.49	13,253.49	0.0%
Total	275,823.84	-19.0%	340,544.03	453,959.76	33.3%

This analysis showed that the possible variations to the socio-economic impacts with two extreme values of vehicle occupancy were a maximum of a 33% increase in total SEE impacts. It could be noted that the sensitivity to vehicle occupancy is comparatively low. However, it should be noted that the maximum value used for passenger vehicle occupancy was 2 persons per vehicle, which was close to the value of 1.7 persons per vehicle that was used in the model. This value of 1.7 persons was the Australian average for non-urban private travel. Hence further analysis could be carried out to ascertain if average vehicle occupancy within the Lockyer Valley regions exceeds the figure of two persons per vehicle.

Percentage of heavy vehicles

The sensitivity of the results to changes in the heavy vehicles percentages was calculated. The possible changes to the percentage of heavy vehicles travelling on the two routes were calculated by assessing the number of heavy vehicles on routes adjacent to the case study bridges and variations in heavy vehicles on the route over the years. The sensitivity of the results to three different probable scenarios was calculated.

The lower value of heavy vehicles for the purpose of the analysis was taken as 50% of the baseline figure, which was 4.35% for the Thistlethwaite Bridge and 2.2% for the Clarke Bridge. Two possible scenarios for the increase in the percentage of heavy vehicles for the Thistlethwaite Bridge were looked at. One was 13.5%, which was obtained from a traffic count on the same road in 2015, and the other was 28%, which was from a traffic count on the Grantham-Scrub Road, which is an adjacent road. Similarly, the upper values for the Clarke

Bridge were estimated at 11.1%, which was the average of heavy vehicles in the Lockyer Valley region, and 13.5%, which was the count on Peters Road adjacent to the Thornton State School Road. The following tables show the sensitivity of the final results to changes in the heavy vehicle percentages.

Table 8-15 Effect of Heavy vehicles on SEE impacts of Thistlethwaite Bridge

	Decrease to 4.35%		Baseline (8.7%)	Increase to 13.5%		Increase to 28%	
	$	Change		$	Change	$	Change
Economic impact	248,386.90	-32.13%	365,990.14	495,759.22	35.46%	887,770.00	142.57 %
Social impact	213,057.42	2.44%	207,982.81	202,383.23	-2.69%	185,467.83	-10.83%
Environmental impact	33,187.91	-12.17%	37,787.49	42,862.88	13.43%	58,194.81	54.01%
Total SEE	494,632.23	-19.15%	611,760.43	741,005.33	21.13%	1,131,432.64	84.95%

Table 8-16 Effect of Heavy vehicles on SEE impacts of Clarke Bridge

	Decrease to 2.2%		Baseline (4.4%)	Increase to 11.1%		Increase to 13.5%	
	$	Change		$	Change	$	Change
Economic impact	13,717.93	-9.0%	365,990.14	159,184.52	27.4%	171,445.17	37.2%
Social impact	206,499.11	2.1%	207,982.81	89,648.05	-6.3%	185,103.94	-8.5%
Environmental impact	12,821.28	-3.3%	37,787.49	14,569.74	9.9%	15,041.24	13.5%
Total SEE	33,038.32	-2.2%	611,760.43	363,402.31	6.7%	371,590.35	9.1%

The above analysis shows that changes to the proportion of heavy vehicles using the bridges can have a major influence on economic impacts. The increase in economic impacts was due to the increase in vehicle operating costs and the increase in freight delay costs. The increase in heavy vehicle operating costs accounted for a major portion of the increase in economic impacts.

Another aspect that can be seen in the analysis is that social impacts decrease as the percentage of heavy vehicles increases. This is due to the fact that the as the proportion of heavy vehicles increases, the amount of light vehicles, which account for the majority of the social costs, would decrease. However, in reality an increase in the number of heavy vehicles will not necessarily decrease the amount of light vehicles. Therefore it could be observed that an absolute increase in the number of heavy vehicles can have a larger impact on the economy than is shown in the analysis above.

There can also be instances where an increase in heavy vehicles could increase the social impacts. This would depend on the type of heavy vehicles plying the given road section. For example, heavy vehicles such as buses, fire trucks, garbage trucks and military trucks would affect the social impacts more than the economic impacts. Therefore, a more detailed assessment of the type of facilities surrounding the structure and the type of heavy vehicles in the area can give a better indication to whether more social or economic impacts would occur.

8.4.3 What-if scenario analysis

A qualitative, what-if scenario analysis was carried out in order to assess the external validity of the framework in disaster recovery. The objective of such an analysis was to identify how different factors external to the assumptions within the model could impact the outcomes generated. As these factors were not included within the developed framework and toolkit, a more qualitative analysis of such scenarios was carried out. These factors were chosen based on the expert opinions obtained through the interviews with practitioners and academics.

Type of bridge

The reconstruction of bridges that are damaged by disasters can be conducted in various ways, with a special emphasis on the type of the new structure being a critical decision to be made. Often, relevant authorities take steps to replace damaged bridges with more robust and strengthened structures with the expectation that damage in future disaster events will be minimised. The type of bridge selected to replace a damaged bridge can thus influence the impacts on the community and economy.

Both the damaged bridges that were used as case studies during this PhD were timber bridges that were replaced by concrete bridges. This decision to replace timber bridges with a more robust concrete structure had been made based on a number of factors as identified through the interviews. A concrete bridge was selected as it would comply with newer regulatory standards, and was also expected to withstand similar flood events in the future. However, the construction of a concrete bridge would take longer and cost more than a similar timber structure. The construction of timber bridges cost up to 30% less than comparative concrete bridges (Tazarv et al. 2019) and is one major reason for the widespread use of timber bridges in Australia (Balendra, Wilson and Gad 2010).

A 30% reduction in the cost of reconstruction would in effect increase socio-economic and environmental costs as a percentage of the reconstruction costs. However, as a timber bridge can be expected to take a shorter time to construct, the socio-economic impacts could be expected to decrease. If specific time frames of construction of different types of bridges and their costs were available, the impacts on wider socio-economic impacts due to the selection of specific bridge types could be analysed further.

Another aspect that needs to be considered is that a more robust concrete structure may have higher ecological impacts during the construction process. The use of heavy vehicles and equipment during construction can cause the erosion of streambed or bank materials and thus cause changes to the geomorphology of the stream (Biswas and Banerjee 2018). Such changes to the stream channel may cause bigger damage to both the structure as well the surrounding environment in the rainy season thus increasing the risk of flooding. It is therefore vital to assess how the construction of more robust structures can in turn have higher impacts to the environment.

Isolation of communities

In instances where a particular bridge is the only way out for a remote community, the unserviceability of such a bridge could result in communities being isolated. Such isolation could impact evacuation and rescue operations soon after a disaster and thus cause severe human health impacts to those communities. Isolation will have more pronounced effects in the longer term recovery and reconstruction phases where communities will have reduced access to food and medical supplies. Isolation could also affect economic wellbeing as residents may not be able to travel to work, not be able to ship goods to market and have reduced access to their business premises.

Although such isolation would be more prominent in regional areas, the two case study regions were not characterised by this factor. However, incorporating the cost of isolation into the developed tool was not carried out, as monetising the effects of isolation was challenging. The number of people isolated due to the damage to the bridge could be an indication of the level of isolation within the community. It was mentioned by council staff that such a number may not be completely representative of the impact on society, as some individuals like children, older people and the sick will be impacted more due to isolation even for a very short time. The interviews showed that in cases where damage to bridges caused isolation in areas, the reconstruction of those bridges needs to be prioritised.

Another aspect related to isolation is that very long detours in regional areas, sometimes in excess of 30 minutes, could result in essential services being disrupted. Interviews showed that cases like this were reported in some remote areas, where postal services were disrupted owing to very long detours. This had resulted in residents not receiving mail and not being able to pay bills, resulting in essential services being cut off. Therefore, the possibility of isolation is a factor that needs to be considered during the decision making although this tool does not account for it.

Damage to alternative routes

Another factor that can have a major impact on communities is the possible damage to alternative routes. Widespread flood damage to large areas within a region can leave a number of roads and transport infrastructure unusable. In such instances, selecting alternative routes may not be a straightforward exercise as some structures, even though standing, may pose a health and safety risk to users. Road authorities will have to inspect and assess all structures before allowing vehicles to use the sections of roads, which will cause additional delays. If the easiest or closest route is inaccessible due to structural damage, this will lead to longer detour distances and hence higher SEE impacts. In regional areas where the number of alternative routes is limited, this may result in major impacts to transport times.

A what-if scenario, where damage was caused to a bridge along the alternative route for the Thistlethwaite Bridge, was analysed to understand how it will affect the community. The unserviceability of one such bridge added an extra 10 km to alternate route distance and eight minutes to travel time. Analysing this increase in alternative time and distance due to a normal route being damaged caused the total SEE impacts to increase by 134%. As such, it could be concluded that the effect to the community would drastically increase if multiple structures are damaged during the flooding events.

Funding mechanisms

The funding mechanism of post-disaster reconstruction activities has an influence on the prioritisation decisions made. Typically, local government authorities and state road authorities will have access to state or federal disaster relief funds that can be utilised for reconstruction activities. Road asset owners will use such disaster relief payments to fund reconstruction of bridges, which would typically cost more, while council funds will be used for the reconstruction of less expensive projects. However, receiving state or federal funding can be a timely process, sometimes taking in excess of over a year and half from calling for tenders to the completion of the reconstruction.

The specific funding mechanisms also regulate the type of reconstruction that can be carried out for the damaged asset. While some funding allows for more robust structures, which may reduce the vulnerability of the structure to future flooding events, others allow only a like-for-like rebuilding. Such variations in funding regulations will need to be considered during the decision making and prioritisation stages. As such relying solely on the proposed framework for prioritisation may not be appropriate. Importantly however, the tool could be used to assess how the time taken during the funding stages would impact the communities and be complementary tool to the funding proposals.

The availability of funding for post-disaster reconstruction efforts can also be considered a positive impact to the region. The damage to the bridges resulted in the old bridges being replaced by newer structures with up-to date designs and specifications, which the local council may not have been able to carry out without state-level funding. The analysis of the reconstruction costs showed that 79% of the costs for the Thistlethwaite Bridge and more than 90% of the cost of the Clarke Bridge was obtained through state-level funding mechanisms. If the funding received by the local council was considered a benefit towards the region, the analysis shows that the damage to the bridge would result in a net benefit to the region. This net benefit relies only on the assumption that the cost benefit analysis is conducted for the geographical and administrative boundary of the local government authority. However, an important point to note is the distribution of cost and benefit across the society where the group that bears the benefit is not the same as the group that bears the cost (Allenby and Rajan 2012).

Effect of congestion

The effect of congestion during reconstruction work is another factor that will increase the social and economic impacts. Increased congestion could occur due to higher traffic volumes on alternative routes and it could be exacerbated if the alternative routes have less capacity than the original routes. Congestion was seen to be a significant factor in more urban areas, while it was less important in rural areas where traffic volumes were very low. As this research focused purely on community impacts in rural areas, the effect of increased congestion on communities was not considered within the model. However, if this framework is to be used in more urban areas, the effects of congestion on communities may need to be included.

Reconstruction work and partial road closures generally result in changes to speed limits on roads. Such changes may increase congestion as well as increase fuel consumption due to stop-go results of the vehicles. For example, 1000 speed changes from 80 km/h to 24 km/h and back to 80 km/h cause an additional fuel consumption of 55 l for light vehicles (Matthews et al. 2015), thus increasing vehicle operating costs during the reconstruction period.

8.5 Implications and recommendations

The preceding section analysed the SEE impacts occurring during the reconstruction process of two case study bridges. This analysis provides the opportunity to understand the implications to the post-disaster reconstruction process and provide practical recommendations that can minimise socio-economic impacts to the community.

A major implication of this thesis is that the significance of a bridge to society cannot be valued through the cost of replacement or reconstruction. As road infrastructure is not traded in a market, there is no attached market price and the value of such assets should be assessed based on the value they create for the wider society. As such making reconstruction decisions based on purely financial aspects may lead to less than optimum social outcomes. Estimating and including a wider array of SEE impacts in the decision making phase can thus lead to more socially optimal decisions being made. It is recommended that road asset users should prioritise reconstruction of damaged infrastructure based on SEE benefits the investment will generate.

The analysis showed that the duration of road closure was the most significant parameter influencing the wider impacts. Although the duration of road closure depends on the reconstruction timelines of contractors and funding authorities, road asset owners could take several steps to reduce the resulting impacts to the community. Assessing alternative types and methods of reconstruction of bridges against the estimated times for construction of these different options can be taken at a very early stage in the decision making process. As it was identified that building more robust structures can take a longer time, the socio-economic impacts during their reconstruction can be much higher. Road agencies could take steps to identify the most suitable methods, especially in regions with a high recurrence of disasters.

Another recommendation resulting from this analysis is that a cost-benefit analysis of partial closure as opposed to full closure of routes can be looked into. Socio-economic benefits of a partial closure could be compared to the holding costs of keeping the bridge partially open, as proposed in the previous section. Assessing the total benefits flowing to the community due to such decisions needs to be done through a SEE impact analysis, which will provide a more holistic outcome to the decisions. The framework proposed in this thesis can be used for such an analysis.

This research revealed that the lack of many alternative routes in rural areas can have drastic impacts on communities after a disaster. Furthermore, high-intensity disaster events can cause damage to multiple structures and routes and thus exacerbate these impacts further. As such road authorities should pay close attention to regions where road density is lower, as the impacts on the community can be very high. This could be more significant if alternative routes have less capacity and tonnage than the damaged routes. Authorities should conduct CBA to identify whether temporary strengthening to alternative routes which have lower capacity and tonnage can reduce the wider impacts during the period of road closure. It is vital for decision makers to identify infrastructure that has high social value (e.g. a route that will reduce alternative time and distance significantly), even though it may vary drastically from the replacement cost.

The analysis of the interrelationships between factors showed that the reconstruction process may affect the surrounding environment in a negative manner, which may cause greater socio-economic damage in future disaster events. It has been found that new road infrastructure can worsen the impacts of floods as the location of the infrastructure in relation to the water body changes the balance between the intensity of the flood and the resistance to the water flow (Jones et al. 2000). As such decision makers need to consider how alternative methods of reconstruction affect the natural environment surrounding the structures and how that in turn can exacerbate or mitigate the occurrence of disasters in the future. Such factors are vital especially during the reconstruction of bridges, as the damage to the stream bed and surrounding flora can be higher when more robust structures are built. Minimising earthwork in saturated soils, scheduling heavy equipment work during drier periods and limiting the number of times construction vehicles cross the stream bed could be a few options that could reduce impacts.

8.6 Summary

This chapter explains the process followed to validate the framework and toolkit that was developed through the PhD research. The validation process showed that the framework was relevant to capture the SEE impacts of bridge failure in regional areas. This tool was seen to be useful by potential end-users to aid them in their decision making and prioritisation of reconstruction in a post-disaster context. It was identified that modifications were needed for the tool if it was to be used in a more urban setting. The end-user feedback on improving the useability of the tool and how it could be developed further to be used across agencies were received and this information will be used for a CRC utilisation project.

The sensitivity analysis of the results showed that traffic volumes, detour times and distances on alternative routes were the most significant input variables. As such steps should be taken to increase the accuracy of these variables, which will provide more accurate results for decision making purposes. Implications of the results and recommendations on how community impacts could be reduced during the reconstruction process were also presented as part of this chapter.

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

The research presented in this thesis has aimed at addressing a gap in knowledge in the area of sustainability impact assessment of post-disaster bridge failure.

An initial literature review identified a lack of research and necessary tools to assess social, environmental and economic impacts resulting from bridge failure. The research process involved a thorough review of literature in the areas of disaster impact assessment, road infrastructure analysis and sustainability assessment techniques, in order to identify suitable techniques that could be used for the purpose of this research. In-depth end-user interviews were carried out in order to understand how post-disaster reconstruction is carried out in disaster prone areas in Australia. These interviews helped in developing a framework to be used to assess the wider socio-economic and environmental impacts of bridge failure. The framework was developed with suitable level detail and flexibility needed to capture the critical impacts. The theoretical and conceptual aspects of the framework were utilised to develop a toolkit that was aimed at being used in real life disaster impact assessment. The application of the toolkit in a real life disaster scenario was assessed through a case study in regional Queensland.

This research is the first of its kind to capture a comprehensive set of social, environmental and economic impacts of road infrastructure failure in regional settings. A second round of interviews was conducted with academics and practitioners to validate the framework and toolkit. This validation process helped refine the toolkit by improving its relevance and rigor in capturing a broad set of impacts. The framework research presented in this thesis can be used by academics in assessing wider impacts to the community and environment due to road infrastructure failure. It can also be used by practitioners in the post-disaster reconstruction of road assets in order to make more socially optimal decisions. It should be noted that although this research was conducted with a focus on road bridges, the methodology adopted can be expanded to other transport infrastructure assets.

The remainder of this final chapter revisits the objectives of the research and presents the major findings and contributions of this research, limitations of the research and recommendations for future research.

9.2 Conclusions based on research objectives

Six research objectives were pursued throughout this research project, and the conclusions in reference to these are presented below. The research objectives pursued were:

1. To understand the current methods and techniques used in consequential impact assessment of post-disaster road failure.
2. To modify and improve suitable methods in order to measure SEE impacts of disaster related bridge structure failure.

3. To develop a conceptual framework that can measure and integrate the socio-economic and environmental impacts of bridge failure.

4. To develop a toolkit based on the framework that can aid in effective decision making.

5. To validate the framework and toolkit by using case studies from regional Queensland.

6. To propose recommendations that can be used by practitioners to reduce overall negative impacts during post-disaster reconstruction.

9.2.1 Understand the current methods used in consequential impact assessment of post-disaster road failure

The first objective of this research was to understand the state-of-the-art in post-disaster impact assessment of road infrastructure failure. This was conducted through a comprehensive literature review, which was presented in Chapters 2 and 4 of this thesis. The literature review showed that much of the impact assessment focused on economic impacts due to infrastructure failure with a lack of studies focussing on the environmental impacts.

The literature review also provided the opportunity to analyse the different methods and techniques that have been used by academics to measure a diverse set of sustainability related impacts of road structure failure. A major outcome at this stage of the research was the publication of a state-of-the-art review in a peer reviewed journal.

In addition to the literature review, interviews were conducted with practitioners working in the disaster management and road infrastructure fields to understand how impact assessment is carried out in practice. This proved helpful in understanding how this research could contribute to the practical aspects of the disaster management field. To the best of the researcher’s knowledge this was the first time that disaster management practitioners were interviewed to understand how post-disaster reconstruction of road infrastructure is approached in disaster prone areas in Australia. The results of these interviews have led to the development of a journal article, which has been revised and resubmitted to a double-blind peer reviewed journal.

The major finding related to this stage of the research was that the assessment of post-disaster impacts is carried out in a siloed manner, with the lack of a holistic approach being evident. This was found to be the case in both academic literature that focussed on post-disaster impact assessment and also within the disaster management practitioners. It was found that cross functional teams from across divisions and academic disciplines will facilitate holistic system level thinking in disaster management. Such practices could lead to more resilient and sustainable outcomes within the infrastructure management field, especially in disaster prone regions.

9.2.2 Modify and improve suitable methods in order to measure SEE impacts of disaster related bridge failure

The different methods used in previous literature to measure impacts were analysed to select the most suitable methods to assess the social, environmental and economic impacts of bridge failure. The analysis of the different methods showed the advantages and disadvantages of each method, and was then used to select the most appropriate method to measure different impact categories. The assessment of the different methods and the selection process adopted were explained in Chapter 4. Some of these methods needed to be adapted to suit the level of detail and complexity needed to assess impacts with regard to bridge failure. These modifications and improvements to the methods were explained in chapters 6 and 7 where relevant.

The key outcomes were the adaptation of socio-ecological assessment methods to cater to the specific objective of assessing sustainability impacts of bridge failure. Methods and techniques that were used by scholars to assess impacts in varied settings were modified so that they could be used within a rapid impact assessment soon after a disaster. Such methods focussed on assessing the environmental impacts of reconstruction and economic impacts to businesses.

9.2.3 Develop a conceptual framework that can measure and integrate the socio-economic and environmental impacts of bridge failure

A framework designed to measure a comprehensive set of social, environmental and economic impacts due to post-disaster bridge failure was developed as the next step of the research, and was presented in Chapter 6. This framework integrated the methods that were selected to best capture the different impact categories, so that the wider SEE impacts could be measured on a common platform. The framework aimed at incorporating a comprehensive set of impacts, with a focus on socio-ecological impacts that were not prioritised in previous literature. The framework also involved an integration mechanism so that different types of impacts could be compared against each other and for the outputs to be presented using a common indicator.

A significant outcome through the development of the framework was the proposed techniques to estimate the environmental impacts during reconstruction. A streamlined LCA was proposed as the most suitable method to assess the environmental impacts of resource use during reconstruction. Section 6.4.4 of the thesis explains the method that such a streamlined LCA could be carried out.

9.2.4 Develop a toolkit based on the framework that can aid in effective decision making

The fourth objective of this thesis was to develop a toolkit that can be used by practitioners in post-disaster reconstruction of bridges. The toolkit was developed after interviews with practitioners so that the level of detail and flexibility needed could be incorporated without compromising on the academic rigor of the framework. The toolkit was developed as an Excel spread-sheet so that changes and improvements could be made easily. Follow-up interviews with academics and practitioners helped in improving the toolkit in an iterative process. The basic layout of the tool was presented in Chapter 6, while more detailed equations and calculations used within the tool were explained in Chapter 7.

The toolkit is an interactive model that allows users to enter data that will be typically available soon after a disaster to estimate the SEE impacts of bridge closure. It has been designed for application in a post-disaster setting, which is typically characterised by data and time constraints. The spread-sheet based version allows for flexibility and customisation that is required at the initial stage of development of such a tool. The significance of this tool is that it allows users to estimate a broad range of social, environmental and economic impacts, even with a limited dataset.

The toolkit is designed for use in assessing the impacts of different reconstruction options available and also for prioritising infrastructure reconstruction projects. The different options available to asset owners could be fed into the model to understand how the socio-economic impacts of each option vary. Such a dynamic process was seen to add value to decision makers in disaster prone regions.

The toolkit will be developed into a more user-friendly application that will increase its use within the disaster management and road authorities across Australia. A BNHCRC Utilisation Project will be used for this purpose as the utilisation phase was not an objective of this particular research. However, it should be noted that the toolkit was developed with end-user utilisation in mind.

9.2.5 Validate the framework and toolkit by using case studies from regional Queensland

The application of the toolkit was tested through a case study in regional Queensland. This process helped in understanding explanatory power of the tool in a real life setting, which was then used to improve the final version of the tool. A regional area was chosen for the case study as there was a lack of research of road infrastructure impacts in regional areas. Two case study bridges were chosen for this analysis, which helped in understanding how varied settings influence the wider impacts. The results of these two case studies were presented in Chapter 7. Further validation of the tool was conducted by interviewing academics from a broad range of disciplines, whose areas of expertise overlapped different areas of the toolkit. These interviews resulted in validating the theoretical and conceptual underpinnings of the tool and validating the academic rigor of the methodology incorporated within the model.

9.2.6 Propose recommendations that can be used by practitioners to reduce overall negative impacts during post-disaster reconstruction

The final objective of this research was to propose recommendations that can be used to minimise the overall negative impacts to the community and the environment during the reconstruction process. A sensitivity analysis was carried out to understand which impact categories were the most significant in contributing to the overall impacts. The different inputs used within the framework were analysed in order to understand how changes to the different variables influenced the final impacts. This sensitivity analysis was then used to propose intervention methods that could minimise impacts.

The following major recommendations were made based on the findings of the thesis:

- Decision makers should prioritise reconstruction based on a comprehensive SEE impact assessment as making decisions based purely on financial and technical aspects may lead to less than optimal decisions being made.

- Assessing alternative methods of reconstruction of bridges against the estimated times for construction can lead to methods that lead to less social impacts to communities without simply relying on strengthening of structures.
- Keeping road networks open, even partially, during reconstruction will reduce the socio-economic impacts to communities drastically.
- Decision makers need to consider how alternative methods of reconstruction affect the natural environment surrounding the structures and how that in turn can exacerbate or mitigate the occurrence of disasters in the future.
- Cross functional teams in the initial decision making process can lead to more holistic view being taken and can lead to diverse options that will have less SEE impacts

9.3 Research contributions

The contributions of this research can be categorised into two areas: contributions to the academic body of knowledge and to industry practice. Contributions to the body of knowledge include theoretical and methodological contributions in the areas of sustainable engineering, infrastructure management and disaster management, while the outcomes of this research have contributed to the industry practice in the road infrastructure management and disaster recovery fields, both at local government and state level.

9.3.1 Contributions to the body of knowledge

The extensive literature review conducted for this research systematically analysed various methods and techniques used by the researchers to measure a wide range of SEE impacts related to road infrastructure failure. This review was an in-depth methodological analysis of the different methods that have been used to measure SEE impacts in previous literature, and provides academics a base on which future research can be founded. This work resulted in the publishing of a state-of-the-art review paper.

Although many different models have been used in previous literature, there was a lack of scholarly work on how the most appropriate method for a given context should be selected. This thesis also presented the advantages and disadvantages of different measurement techniques and provided a process that could be followed in selecting the most suitable methods to measure different impacts. A number of criteria that need to be considered and how they can be used in selecting an appropriate method were explained.

One of the major methodological contributions of this research was the development of a framework that measures a comprehensive list of SEE impacts due to disaster induced bridge failure. To the best of the author’s knowledge, this is the first framework of its kind catered to the post-disaster impact assessment of road infrastructure. Although the framework focussed on measuring impacts due to road bridge failure, this framework could be extended to measure impacts of other road related assets and even other infrastructure assets. The research also exemplified how different types of impacts could be integrated to ease assessment and comparisons across impact categories.

The novelty of this research is that, to the best of the author’s knowledge, this was the first instance where a research project targeted the measuring of a comprehensive set of SEE impacts due to road failure. This project focussed on a number of different aspects where there is a lack of academic research in the disciplines of disaster and infrastructure management. This research contributed to academic knowledge in understanding how road failure impacts regional communities in Australia, and looked at measuring impacts from an ex-post perspective where there was a lack of research.

Another area of contribution was that this research provided the opportunity to understand how post-disaster reconstruction of road infrastructure takes place in selected disaster prone regions across Australia. Assessing the literature in the discipline and through the results of a series of interviews with practitioners, the gaps between academic knowledge and practice were revealed. Through practitioner interviews and the assessment of impacts through the tool developed for this research, interrelationships between different factors and their influence on the reconstruction process and wider socio-ecological impacts were identified.

9.3.2 Contributions to practice

This research also contributed to industry practice in a number of ways. The framework that was developed through this research is designed to help practitioners in the areas of infrastructure and disaster management to measure a broad array of SEE impacts. The methods of selecting the most appropriate technique, data requirements for each method and the level of detail and sophistication of the available methods have been explained. This framework can be used by practitioners to measure impacts due to road infrastructure failure and could be modified to measure the impacts of other infrastructure assets. The framework can also be used to assess the SEE impacts due to different reconstruction options to choose the best option that has the lowest negative impacts on the region.

A major contribution towards the disaster management practice is the development of a toolkit to measure a wide range of SEE impacts due to road bridge failure. The toolkit was developed with practical use in mind, and has been reviewed by practitioners through a series of interviews. The feedback received was used to improve the toolkit in an iterative process. The toolkit can be used by practitioners during post-disaster reconstruction decision making to estimate how damage to assets impacts the community and help them make more optimal decisions in a short time frame. A BNHCRC Utilisation Project is planned to upgrade the toolkit to a more user-friendly web-based version, which will then be used across a number of road authorities and local government authorities across Australia.

Another practical contribution of this research was the compilation of a comprehensive database that can be used by practitioners and researchers. The database has over 200 data points gathered from a number of government agencies and reports covering a broad array of factors required to assess the sustainability impacts of road infrastructure. Although the database was compiled focusing on factors related to the specific scope of the research, it was extended to include a wider set of data points, which will aid decision makers working in a data and resource constrained post-disaster context. This is the only collection of such an extensive group of data points related to SEE impacts of road infrastructure projects in Australia.

9.4 Research limitations

An inherent limitation of a case study based research design is the lack of generalizability of the findings. This limitation was identified during the research design stage. Steps were taken to generalise the findings of the research by obtaining feedback from a geographically and technically diverse group of individuals. However, it should be noted that the use of case studies helped the research to explore the issue in more depth and to provide more relevant recommendations to the given case.

One of the major limitations of this research was the lack of responses to the questionnaire survey. The aim of the questionnaire survey was to identify how users of the two case study bridges were affected by the closure of the structure and how they changed their travel patterns. Due to the lack of substantial responses for the survey, such an analysis could not be conducted. As a result the behavioural changes predicted in the model could not be validated in detail. Although steps were taken by the researcher to increase the number of responses and the use of other methods for validation, this was not considered as rigorous as a questionnaire survey.

Another limitation was the lack of data available for a detailed analysis of the environmental impacts of reconstruction. As the construction was outsourced by the council to a private contractor, the council did not have the relevant information and Bills of Quantities required for a streamlined LCA. Attempts to obtain the relevant data from the contractors were not successful as they did not wish to share information due to privacy reasons. As a result, the research had to rely on a novel method to estimate the environmental impacts during the reconstruction phase.

9.5 Directions for future research

The next immediate direction for future research is to improve the toolkit for it to be utilised across road asset owners and disaster recovery agencies in Australia. The toolkit could be further developed by taking into consideration the specific requirements of the agencies. This will involve more industry partnerships and research from a practical perspective to understand the typical data availability of the relevant agencies. The database used within the toolkit can also be refined to cater to industry specific outcomes.

One of the major objectives of this research was to integrate a comprehensive set of social, environmental and economic impacts of bridge failure. However, one significant limitation with adopting a simple integration technique was that interdependencies across the various impact categories were overlooked. During this research it was learnt that interdependencies across impact categories could have a significant influence on the sustainability and resilience of disaster-prone regions. Future research could focus on how such interdependencies could be assessed and incorporated into decision making frameworks.

The scope of this project was limited to measuring SEE impacts in a regional context in Australia. Therefore, future researchers could extend this research to assess impacts in more urban settings, which will provide an opportunity for further comparisons and modifications of the tools if necessary.

Although psychological impacts due to road closures were highlighted through the interviews conducted as part of this research, psychological impacts were not considered as this was outside the researcher's scope of expertise. As such, future work could aim at understanding the psychological impacts and incorporating it with the SEE impacts measured by this research.

Another area of research could look into amalgamating the wider SEE impacts together with the structural engineering processes. Such research can help practitioners to foresee how different technical solutions will impact socio-ecological aspects of the region. Future work can also aim at researching on the correlation between the robustness of structures and their resilience to natural hazards.

With increased interest in prefabrication technology within the construction industry, future research in understanding how prefabrication can be used to reduce transportation related impacts and ecological impacts during the reconstruction period will be useful. Assessing the wider SEE impacts of prefabricated bridges and on-site reconstruction can help reduce longer-term impacts on disaster affected communities.

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Appendix A – Ethics Approval

RMIT UNIVERSITY

College Human Ethics Advisory Network (CHEAN)
College of Science, Engineering and Health

Email: seh-human-ethics@rmit.edu.au
Phone: [61 3] 9925 4620
Building 91, Level 2, City Campus/Building 215, Level 2, Bundoora West Campus

2 October 2017

Associate Professor Kevin Zhang
School of Engineering
RMIT University

Dear A/Prof Zhang

SEHAPP 75-17 Measuring social, environmental and economic impacts of road structure failure due to natural disasters

Thank you for submitting your amended application for review.

I am pleased to inform you that the CHEAN has approved your application for a period of **14 Months** from the date of this letter to **31 December 2018** and your research may now proceed.

The CHEAN would like to remind you that:

All data should be stored on University Network systems. These systems provide high levels of manageable security and data integrity, can provide secure remote access, are backed up on a regular basis and can provide Disaster Recover processes should a large scale incident occur. The use of portable devices such as CDs and memory sticks is valid for archiving; data transport where necessary and for some works in progress.
The authoritative copy of all current data should reside on appropriate network systems; and the Principal Investigator is responsible for the retention and storage of the original data pertaining to the project for a minimum period of five years.

Please Note: Annual reports are due on the anniversary of the commencement date for all research projects that have been approved by the CHEAN. Ongoing approval is conditional upon the submission of annual reports failure to provide an annual report may result in Ethics approval being withdrawn.

Final reports are due within six months of the project expiring or as soon as possible after your research project has concluded.

The annual/final reports forms can be found at:
www.rmit.edu.au/staff/research/human-research-ethics

Yours faithfully,

Associate Professor Barbara Polus Chair,
Science Engineering & Health College
Human Ethics Advisory Network

Cc	Student Investigator/s:	Mr Akvan Gajanayake, School of Engineering, RMIT University
	Other Investigator/s:	Dr Tehmina Khan, School of Accounting, RMIT University Dr Hessam Mohseni, School of Engineering, RMIT University Dr Yew-Chin Koay, VicRoads Asset Services

Appendix B – Participant Information Sheet and Consent Form

Participant Information Sheet/Consent Form

End User Interviews

Title	Measuring social, environmental and economic impacts of road structure failure due to natural disasters
Chief Investigator/Senior Supervisor	Professor Kevin Zhang
Associate Investigator(s)/Associate Supervisor(s)	Dr. Tehmina Khan Dr. Hessam Mohseni Dr. Yew-Chin Koay
Principal Research Student(s)	Mr. Akvan Gajanayake

What does my participation involve?

1 Introduction

You are invited to take part in this research project, which is called "Measuring social, environmental and economic impacts of road structure failure due to natural disasters". You have been invited because the researchers would like to understand what specific factors are considered by your organisation in post-disaster road infrastructure reconstruction decision making. Your contact details were obtained through your previous interaction with RMIT University on disaster reconstruction projects.

This Participant Information Sheet tells you about the research project. It explains the processes involved with taking part. Knowing what is involved will help you decide if you want to take part in the research.

Please read this information carefully. Ask questions about anything that you don't understand or want to know more about.

Participation in this research is voluntary. If you don't wish to take part, you don't have to.

If you decide you want to take part in the research project, you will be asked to sign the consent section. By signing it you are telling us that you:

- Understand what you have read
- Consent to take part in the research project

You will be given a copy of this Participant Information and Consent Form to keep.

2 What is the purpose of this research?

The aim of the project is to measure the social, environmental and economic impacts of road failure due to natural disasters in order to build a framework that can be used by local government and road authorities for infrastructure decision making purposes. Current research in this area has mainly focussed on understanding the structural and financial aspects of disaster related road failure and has overlooked wider social and economic impacts it can cause. The outcome of this project will help authorities make more informed decisions relating to reconstruction of post disaster infrastructure.

The results of this research will be used by the researcher Akvan Gajanayake to obtain a PhD, Civil Engineering degree.

3 What does participation in this research involve?

The participation in the study involves you taking part in an interview conducted by the research team to obtain information on the factors that are considered by your organisation when making decisions regarding post-disaster road infrastructure reconstruction. You may be invited to take part in a follow-up session to obtain your feedback on the framework that will be developed as part of this research. A typical interview will take 1.5 hours and will be conducted at the RMIT University. However you may choose another location (e.g. your office) for the interview to be conducted if it is convenient for you, given that the chosen location is suitable for such a discussion.

There are no costs associated with participating in this research project, nor will you be paid. However, you may be reimbursed for any reasonable travel, parking, meals and other expenses associated with the research project visit.

4 Other relevant information about the research project

The project will also collect information from a disaster affected community in Lockyer Valley, Queensland regarding how damage to a road structure impacted their daily lives. This information will be collected through a questionnaire survey and will be used as input in to the framework that will be developed by this project.

5 Do I have to take part in this research project?

Participation in any research project is voluntary. If you do not wish to take part, you do not have to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage.

If you do decide to take part, you will be given this Participant Information and Consent Form to sign and you will be given a copy to keep.

Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your relationship with the researchers or with RMIT University.

You may stop the interview at any time. Unless you say that you want us to keep them, any recordings will be erased and information you have provided will not be included in the study results. You may also refuse to answer any questions that you do not wish to answer during the interview.

6 What are the possible benefits of taking part?

We cannot guarantee or promise that you will receive any benefits from this research; however, you may appreciate contributing to knowledge. Possible benefits may include the development of a more relevant framework that can be used to take into consideration the social, environmental and economic impacts of road failure for post disaster decision making purposes.

However there will be no clear benefit to you, individually, from your participation in this research.

7 What are the risks and disadvantages of taking part?

The research team does not foresee any risks or disadvantages of taking part in this project. However if you do not wish to answer a particular question, you may skip it and go to the next question, or you may stop immediately.

Whilst all care will be taken to maintain privacy and confidentiality, you may experience embarrassment if one of the group members were to repeat things said in a confidential group meeting. It is advisable that you do not reveal anything too personal or that you may regret later on.

8 What if I withdraw from this research project?

If you do consent to participate, you may withdraw at any time. If you decide to withdraw from the project, please notify a member of the research team.

9 What happens when the research project ends?

The research project is expected to be completed in 2020. The findings of the project will be shared with you / your organisation.

How is the research project being conducted?

10 What will happen to information about me?

By signing the consent form you consent to the research team collecting and using information from you for the research project. Any information obtained in connection with this research project that can identify you will remain confidential. The information you provide will be recorded as comments / feedback from the organisation and department you represent and not as individual comments, unless explicitly specified.

The data collected will be saved on the RMIT University network drive which will be password protected and will only be accessible to the project team. The data will be stored on the RMIT University network for a period of 5 years after the project and will be destroyed thereafter.

It is anticipated that the results of this research project will be published and/or presented in a variety of forums. In any publication and/or presentation, information will be provided in such a way that you cannot be identified, except with your express permission.

In accordance with relevant Australian and/or Victorian privacy and other relevant laws, you have the right to request access to the information about you that is collected and stored by the research team. You also have the right to request that any information with which you disagree be corrected. Please inform the research team member named at the end of this document if you would like to access your information.

11 Who is organising and funding the research?

This research project is being conducted by Akvan Gajanayake as a part of his PhD studies and in conjunction with the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC) of Australia.

12 Who has reviewed the research project?

All research in Australia involving humans is reviewed by an independent group of people called a Human Research Ethics Committee (HREC). This research project has been approved by the RMIT University HREC.

This project will be carried out according to the *National Statement on Ethical Conduct in Human Research* (2007). This statement has been developed to protect the interests of people who agree to participate in human research studies.

13 Further information and who to contact

If you want any further information concerning this project, you can contact the researcher on 03 9925 3821 or any of the following people:

Research contact person

Name	Professor Kevin Zhang
Position	Chief investigator / Senior supervisor
Telephone	
Email	

14 Complaints

Should you have any concerns or questions about this research project, which you do not wish to discuss with the researchers listed in this document, then you may contact:

Reviewing HREC name	RMIT University
HREC Secretary	Peter Burke
Telephone	
Email	
Mailing address	Research Ethics Co-ordinator Research Integrity Governance and Systems RMIT University GPO Box 2476 MELBOURNE VIC 3001

Consent Form

Title	Measuring social, environmental and economic consequences of road structure failure due to natural disasters
Chief Investigator/Senior Supervisor	Professor Kevin Zhang
Associate Investigator(s)/Associate Supervisors	Dr. Tehmina Khan Dr. Hessam Mohseni Dr. Yew-Chin Koay
Research Student(s)	Mr. Akvan Gajanayake

Acknowledgement by Participant

I have read and understood the Participant Information Sheet.

I understand the purposes, procedures and risks of the research described in the project.

I have had an opportunity to ask questions and I am satisfied with the answers I have received.

I freely agree to participate in this research project as described and understand that I am free to withdraw at any time during the project without affecting my relationship with RMIT.

I understand that I will be given a signed copy of this document to keep.

Name of Participant (please print) ______________________________

Signature ____________________ Date ____________________

Declaration by Researcher†

I have given a verbal explanation of the research project, its procedures and risks and I believe that the participant has understood that explanation.

Name of Researcher† (please print) Akvan Gajanayake

Signature ____________________ Date ____________________

† An appropriately qualified member of the research team must provide the explanation of, and information concerning, the research project.

Note: All parties signing the consent section must date their own signature.

Appendix C – End-user Interview Questions

1. Name of organisation and department:

2. What are the key objectives/deliverables of your department?

3. Please explain your department's involvement in post-disaster reconstruction of road infrastructure.
    - 2.1 Level of involvement: Scale of 1-5
    - 2.2 Type of involvement: Operational/Technical/Financial/Consultatve

4. Does your department conduct any type of prioritisation in disaster recovery situations?
    - 4.1 What processes are followed during PDR
    - 4.2 Do the methods change according to
        - 4.2.1 Type of disaster
        - 4.2.2 Type of infrastructure
        - 4.2.3 Method of reconstruction
        - 4.2.4 Scale or extent of disaster

5. What aspects/factors are considered by your department in post-disaster reconstruction situations?
    - 5.1 Social factors
    - 5.2 Economic factors
    - 5.3 Environmental factors

6. Are there any additional factors/impact categories that should be considered during PDR?
    - 6.1 Why aren't these factors considered currently?

7. Are there any set methods used to measure/assess the factors identified in Q4?
    - 7.1 If yes, what are these methods and how are they used?
    - 7.2 If no, how are such measurements/assessments carried out?

8. Do you think a framework that measures the social, environmental and economic impacts of road structure failure will be useful for your department? Please explain.

9. What type of information should be captured through such a process?

10. What types of impacts/factors should be considered in such a framework?
    - 10.1 Social factors
    - 10.2 Environmental factors

10.3 Economic factors

11. What are the most critical factors/ impacts that you would like included in such a framework?

12. What is the optimal form of output you require from such a framework that will help meet your department's objectives during PDR?
    12.1 What are the basic objectives it should meet?
    12.2 What are the characteristics of performance that it should meet?
    12.3 What are the operating conditions it should meet?

Appendix D – Participant information Sheet for Questionnaire Survey

RMIT UNIVERSITY

Participant Information Sheet

Community adaptation to cope with post-disaster road failure

Title	Measuring social, environmental and economic impacts of road structure failure due to natural disasters
Chief Investigator/Senior Supervisor	Professor Kevin Zhang
Associate Investigator(s)/Associate Supervisor(s)	Dr. Tehmina Khan Dr. Hessam Mohseni Dr. Yew-Chin Koay
Principal Research Student(s)	Mr. Akvan Gajanayake

What does my participation involve?

1 Introduction

You are invited to take part in this research project, which is called "Measuring social, environmental and economic impacts of road structure failure due to natural disasters". You have been invited because the researchers would like to understand how your day to day life was affected as a result of the failure of roads and bridges due to flooding. You have received this survey as the research team believes that you would have been affected by 2013 flood events.

This Participant Information Sheet tells you about the research project. It explains the processes involved with taking part. Knowing what is involved will help you decide if you want to take part in the research.

Please read this information carefully. Ask questions about anything that you don't understand or want to know more about. Before deciding whether or not to take part, you might want to talk about it with a relative or friend.

Participation in this research is voluntary. If you don't wish to take part, you don't have to. Filling out the questionnaire and submitting it to the research team will be taken as consent to participate in the project.

You can keep a copy of this Participant Information Sheet if you wish to do so.

2 What is the purpose of this research?

The aim of the project is to measure the social, environmental and economic impacts of road failure due to natural disasters in order to build a framework that can be used by local government and road authorities for infrastructure decision making purposes. Current research in this area has mainly focussed on understating the structural and financial aspects of disaster related road failure and has overlooked wider social and economic impacts it can cause. The outcome of this project will help authorities make more informed decisions relating to reconstruction of post disaster infrastructure.

The results of this research will be used by the researcher Akvan Gajanayake to obtain a PhD, Civil Engineering degree.

3 What does participation in this research involve?

The participation in the study involves you completing a questionnaire to provide details regarding how the damage of a particular road structure affected your daily lives during a recent flood event. The details include changes to your travel patterns before and after the event, types of routes used, effects on business activities and work lives and changes to general social mobility.

The questionnaire (attached herewith) can be completed by you and mailed back using the stamped return addressed envelope provided for this purpose. Alternatively you could complete the questionnaire online by using the following web link; linktosurvey.com

The questionnaire will take approximately 10-15 minutes to complete.

There are no costs associated with participating in this research project, nor will you be paid.

4 Other relevant information about the research project

The project aims to collect information from around 200 participants all of whom are residents of the Lockyer Valley Regional Council area or travel to the area.

This research will also include a focus group discussion with relevant disaster and road authorities to get their feedback on the framework that will be developed by using the data gathered through this survey.

5 Do I have to take part in this research project?

Participation in any research project is voluntary. If you do not wish to take part, you do not have to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage.

Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your relationship with the researchers or with RMIT University.

Submitting your completed questionnaire is an indication of your consent to participate in the study. You can withdraw your responses any time before you have submitted the questionnaire. Once you have submitted it, your responses cannot be withdrawn because they are non-identifiable and therefore we will not be able to tell which one is yours.

6 What are the possible benefits of taking part?

We cannot guarantee or promise that you will receive any benefits from this research; however, you may appreciate contributing to knowledge. Possible benefits may include the better understanding of the wider social and economic costs associated with road infrastructure failure which may help relevant authorities make more informed decisions in the future.

A draw prize will be conducted for all fully submitted questionnaires, with the chance to win a $100 Coles Myer Gift Card. If you wish for your name to be submitted to this draw, you would need to fill out the attached slip with your personal details and post it together with the completed questionnaire.

7 What are the risks and disadvantages of taking part?

The research team does not foresee any risks or disadvantages of taking part in this project. However if you do not wish to answer a particular question, you may skip it and go to the next question, or you may stop immediately.

This project will use an external site to create, collect and analyse data collected in a survey format. The site we are using is www.qualtrics.com. If you agree to participate in this survey, the responses you provide will be stored on their host server. No personal information will be collected in the survey so none will be stored as data. Once we have completed our data collection and analysis, we will import the data to the RMIT server where it will be stored securely for five years. The data on the host server will then be deleted and expunged.

8 What if I withdraw from this research project?

You can withdraw your responses any time before you have submitted the questionnaire. Once you have submitted it, your responses cannot be withdrawn because they are non-identifiable and therefore we will not be able to tell which one is yours.

9 What happens when the research project ends?

The research project is expected to be completed in 2020. The findings of the project will be shared with the Lockyer Valley Regional Council.

How is the research project being conducted?

10 What will happen to information about me?

The data collected will not be individually identifiable and cannot be used to identify the respondent.

The data collected will be saved on the RMIT University network drive which will be password protected and will only be accessible to the project team. The data will be stored on the RMIT University network for a period of 5 years after the project and will be destroyed thereafter.

By signing the consent form you consent to the research team collecting and using information from you for the research project.

It is anticipated that the results of this research project will be published and/or presented in a variety of forums. In any publication and/or presentation, information will be provided in such a way that you cannot be identified, except with your express permission.

11 Who is organising and funding the research?

This research project is being conducted by Akvan Gajanayake a PhD Researcher at RMIT University under the Australian Government funded Bushfire and Natural Hazards Cooperative Research Council (BNHCRC) project.

12 Who has reviewed the research project?

All research in Australia involving humans is reviewed by an independent group of people called a Human Research Ethics Committee (HREC). This research project has been approved by the RMIT University HREC.

This project will be carried out according to the *National Statement on Ethical Conduct in Human Research* (2007). This statement has been developed to protect the interests of people who agree to participate in human research studies.

13 Further information and who to contact

If you want any further information concerning this project, you can contact any of the following people:

Research contact persons

Name	Mr. Akvan Gajanayake
Position	Research student
Telephone	
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Name	Prof. Kevin Zhang
Position	Chief investigator / Senior supervisor
Telephone	
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14 Complaints

Should you have any concerns or questions about this research project, which you do not wish to discuss with the researchers listed in this document, then you may contact:

Reviewing HREC name	RMIT University
HREC Secretary	Peter Burke
Telephone	
Email	
Mailing address	Research Ethics Co-ordinator Research Integrity Governance and Systems RMIT University GPO Box 2476 MELBOURNE VIC 3001

Appendix E –Questionnaire Survey

RMIT UNIVERSITY

Survey on community adaptation to cope with post-disaster bridge failure

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Thank you for taking part in this survey conducted as part of a student research project at the RMIT University, Melbourne, funded through the Bushfire and Natural Hazards Cooperative Research Centre of Australia. This questionnaire aims to understand how individuals and businesses in the Lockyer Valley region responded to the damage of bridges due to the flooding events in 2013.

Participation in this survey is voluntary and your decision to take part or not, will not affect your relationship with RMIT University. The responses are not individually identifiable and will not be used to identify any of the respondents.

Completing the questionnaire will take 10-15 minutes. Participants who fully complete the questionnaire can submit their details for a draw prize and stand a chance to win a Coles / Myer Gift Card worth $100. If you wish your name to be submitted for the draw please fill in the slip with your contact details and post it along with the completed questionnaire.

This questionnaire needs to be completed by you and mailed back using the reply paid envelope provided for this purpose. Alternatively you could complete the questionnaire online by using the following web link;
https://rmit.au1.qualtrics.com/jfe/form/SV_b1KCUEO09fyOdPT

Further information on this research is available through the Participant Information Sheet attached.

Section 1: General Information

1. 1 Do you live in the Lockyer Valley Region?

- ☐ Yes
- ☐ No (Please proceed to section 1.4)

1.2 If yes, which suburb did you live in 2013?

- ☐ Grantham
- ☐ Veradilla
- ☐ Winwill
- ☐ Townson
- ☐ Other ....
- ☐ Carpendale
- ☐ Lilydale
- ☐ Thornton

1.3 Number of people who were residing at your residence in 2013;

Adults: .... Children (under 18): ....

1.4 Were your routine travel patterns affected by the damage to the Thistlethwaite Bridge (on the Grantham – Winwill Road) during 2013?

☐ Yes
☐ No

Section 2: General travel patterns

2.1 How often did you use the Thistlethwaite Bridge before the 2013 floods?

☐ Couple of times a day
☐ Once a day
☐ Couple of days a week
☐ Once a week
☐ Couple of days a month
☐ Very rarely

2.1.1 If you used the bridge at least once a week before the 2013 floods, please provide the following information;

Time of use	Purpose / Destination	Duration of trip (Minutes)	Number of trips per week	Number of people travelling in the vehicle	Type of vehicle used
Week day morning					
Week day evening					
Weekend					

2.1.2 Please mention the extent and duration of disruption

☐ Bridge could not be used at all……. Days …. Weeks …..Months
☐ Bridge could be used partially……...Days …. Weeks …..Months

2.2 Did you make any of the following changes because the bridge was damaged? (tick all that is applicable)

☐ Cancelling trips
☐ Combining trips / travelling less often
☐ Changing the time of the trip
☐ Selecting an alternative route
☐ Using a different mode of transport (vehicle type, walking, cycling etc.)
☐ Other (Please specify) …………………….…………

2.3 When the Thistlethwaite Bridge was unusable what alternative routes did you use?

☐ Route A: Grantham Scrub Road and Gatton Clifton Road
☐ Route B: Gatton Helidon Road passing Stanbroke Meats
☐ Other route ……………….…………….………..
☐ Other route ……………….…………….………..

2.3.1 Please provide the following information regarding all alternative routes used

	Route A	Route B	Other	Type of vehicle used
How long did the typical journey take **before the floods** (mins)				
How often did you use each route **before the floods** (per week)				
How long did the typical journey take **after the floods** (mins)				
How often did you use each route **after the floods** (per week)				

2.4 Did you have to cancel any trips, which you would have normally made, due to the damage to the Thistlethwaite Bridge?
☐Yes ☐ No

2.4.1 If yes, How many trips did you cancel (per week)? …………………………..……
what would have been the purpose / destination of these trips?
…………..……………………….………..…………..……….……….………

Section 3: Impacts to business and work

3.1 Were you unable to commute to work as a result of the damage to the Thistlethwaite Bridge?
☐ Yes, often ☐ Yes, occasionally ☐ Never

3.1.1 If yes, Place or region of work ………………….
Type of industry you work in …………………
Self-employed ☐Yes ☐ No
Number of days unable to commute to work ………………….
Were you paid any type of compensation for not being able to attend work? (Please give details) ………………………………..…

3.2 Are you a business owner?

☐ Yes

☐ No (Please proceed to section 4)

3.2.1 If yes, type of industry / sector …………………………….

Location of business ……………………………….

Expected average weekly earnings during February ($/week) ……………………..

3.3 Were your routine business activities impacted by the floods?

☐ Yes

☐ May be

☐ No

3.4 Did any of the following factors affect your business?

☐ Shipping delays

☐ Customer access to business location

☐ Employee access to business location

☐ Change in demand for goods / service provided

☐ Other ………………………………..

3.4.1 Please mention how each of these factors affected your business;

Factor	Influence on operations	Impact on profits (per week)	Impact on profits (per week)
Goods transport from business location	☐ Could not meet demand ☐ Stock expired due to delays in shipping ☐ Increase in cost of transportation ☐ Increase transportation times	Increase $ ……. Decrease $ ……..	Increase % ……. Decrease % ……..
Goods transport to business location	☐ Delayed production ☐ Ran out of stock ☐ Increase in cost of transportation	Increase $ ……. Decrease $ ……..	Increase % ……. Decrease % ……..
Customer access to business location	☐ Increase in sales ☐ Decrease in sales ☐ Increase in cost of transportation	Increase $ ……. Decrease $ ……..	Increase % ……. Decrease % ……..
Employee access to business location	☐ Decrease in production ☐ Extra cost of bringing employees to work ☐ Increase in cost of transportation	Increase $ ……. Decrease $ ……..	Increase % ……. Decrease % ……..

Change in demand for the goods / services	☐ Increase in sales ☐ Decrease in sales	Increase $ ……. Decrease $ ……..	Increase % ……. Decrease % ……..

3.5 Did your business adopt any actions to reduce the impacts of any of these factors?

☐ Yes
☐ No

3.5.1 If yes, please provide details of such actions

……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………

Section 4: Social impacts

4.1 Did you have any children living with you during 2013?

☐ Yes
☐ No (please proceed to section 4.2)

4.1.1 If yes, were their attendance at pre-school / school / university affected due to the damage to the bridge?

☐ Yes
☐ No (Please proceed to Section 4.2)

4.1.2 If yes, Duration of days not attending school

☐ Less than a week
☐ One week
☐ 1 – 3 weeks
☐ One month
☐ One month to 3 months
☐ More than 3 months

4.2 Did you find it hard to access markets / shops due to the damage to the bridge?

☐ Yes
☐ No (Please proceed to section 4.3)

4.2.1 If yes, How did you overcome this problem?

☐ Managed with extra stocks at home

☐ Got friends / family to deliver
☐ Other……………….

4.2.2 If these actions were not taken how often would you have had to travel to the market / shops? …………………………………….…….

4.3 Did you have reduced access to any of the following?

☐ Friends and family
☐ Medical facilities (hospital, chemists, doctors etc.)
☐ Recreational facilities (parks, library etc.)
☐ Essential services (banks, insurance companies, council offices etc.)
☐ Delivery of essential services (garbage collection, mail etc.)
☐ Other ……………………………...
☐ None of the above

4.3.1 If you ticked any of the above please mention how many times you have liked to take such trips but was not able to, during the disruption.

	Times you would have liked to access (per week)	Number of times accessed during the time the bridge was damaged	How did you overcome these issues?
Visiting friends and family			
Access to medical facilities			
Access to recreational facilities (parks, library etc.)			
Access to essential services			
Delivery of essential services			

4.4 How did the damage to the bridge affect the following factors? (Please select the most appropriate box for each factor)

Factor affected	Not at all affected	Somewhat affected	Affected to a great degree	Very severely affected
Travel to work	☐	☐	☐	☐
General mobility	☐	☐	☐	☐
Access to medical facilities	☐	☐	☐	☐
Access to recreational activities	☐	☐	☐	☐
Access to shops and markets	☐	☐	☐	☐
Access to friends and family	☐	☐	☐	☐
Life satisfaction	☐	☐	☐	☐

4.5 Please provide any other details relating to the reduction in your routine activities due to the damage to the Thistlethwaite Bridge. Mention how you were impacted and how you overcame such problems;

……
……
……
……
……
……

Thank you for completing the survey. Please post this questionnaire using the reply paid envelope provided.

Appendix F – Database Compiled for the Toolkit

Data group	Unique name	Value	Unit	Year	Region	Source
Travel time value	Travel time value private travel cars	14.99	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value business travel cars	48.63	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value utility vehicles	25.41	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Light Rigid trucks	25.41	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Medium Rigid trucks	25.72	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Heavy Rigid trucks	26.19	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Bus Driver	25.72	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Bus Passenger	14.99	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Articulated trucks	26.81	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Rigid + 5 axle dog	27.2	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value B Double	27.2	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Twin steer + 5 Axle Dog	27.2	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value A Double	27.98	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value B Triple	27.98	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value A B Combination	27.98	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value A Triple	28.45	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Travel time value Double B-Double	28.45	$/ person hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Light Rigid trucks Non-urban	0.78	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Medium Rigid trucks Non-urban	2.11	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Heavy Rigid trucks Non-urban	7.22	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Light Rigid trucks Urban	1.53	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines

Travel time value	Freight Travel time value Medium Rigid trucks Urban	4.15	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Heavy Rigid trucks Urban	14.2	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Artic 4 Axle Non-urban	15.53	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Artic 5 Axle Non-urban	19.8	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Artic 6 Axle Non-urban	21.36	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Rigid + 5 axle dog Non-urban	30.53	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value B Double Non-urban	31.46	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Twin steer + 5 Axle Dog Non-urban	29.5	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value A Double Non-urban	41.31	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value B Triple Non-urban	42.17	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value A B Combination Non-urban	50.79	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value A Triple Non-Urban	60.89	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Double B-Double Non-urban	61.59	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Artic 4 Axle Urban	30.59	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Artic 5 Axle Urban	39.01	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Artic 6 Axle Urban	42.06	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Rigid + 5 axle Non Urban	62.99	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value B Double Urban	64.91	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Twin steer + 5 Axle Non Urban	60.89	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	freight Travel time value A Double Urban	85.25	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value B Triple Urban	87.01	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value A B Combination Urban	104.8	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value A Triple Urban	125.64	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines
Travel time value	Freight Travel time value Double B-Double Urban	127.09	$/ vehicle hour	2013	Australia	Australian Transport Assessment and Planning Guidelines

Vehicle Occupancy	Vehicle occupancy rate Bus Passengers	20	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate Bus Driver	1	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate cars private travel Non-urban	1.7	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate cars private travel Urban	1.6	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate cars business travel Non-urban	1.3	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate cars business travel Urban	1.4	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate Courier van - utility	1	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate 4WD mid Size Petrol	1.5	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate Light Rigid Trucks	1.3	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate Medium Rigid Trucks Non-urban	1.2	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate Medium Rigid Trucks Urban	1.3	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate Heavy Rigid Trucks	1	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy rate Artic trucks and Combination vehicles	1	persons / vehicle	2013	Australia	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy cars AM peak	1.12	persons / vehicle	2012	Victoria	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy cars PM peak	1.22	persons / vehicle	2012	Victoria	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy cars Off peak	1.24	persons / vehicle	2012	Victoria	Australian Transport Assessment and Planning Guidelines
Vehicle Occupancy	Vehicle occupancy cars All day	1.21	persons / vehicle	2012	Victoria	Australian Transport Assessment and Planning Guidelines
Vehicle Operating Cost	Privately owned vehicles VOC	16.58	$/ vehicle per 100km	2010	Australia	Bureau of Infrastructure, Transport and Regional Economics
Vehicle Operating Cost	Avg VOC 2-axle rigid truck	144.6	$/ vehicle per 100km	2007	Australia	Bureau of Infrastructure, Transport and Regional Economics
Fuel Consumption	Fuel consumption private cars at 40 km/h	11.41	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption private cars at 50 km/h	10.31	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption private cars at 60 km/h	9.57	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption private cars at 70 km/h	6.94	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption private cars at 80 km/h	7.41	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption private cars at 90 km/h	7.99	litres/ 100 km	2005	Australia	Austroads

Fuel Consumption	Fuel consumption private cars at 100 km/h	8.7	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption light commercial vehicles at 40 km/h	14.8	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption light commercial vehicles at 50 km/h	13.36	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption light commercial vehicles at 60 km/h	12.41	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption light commercial vehicles at 70 km/h	9.07	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption light commercial vehicles at 80 km/h	9.73	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption light commercial vehicles at 90 km/h	10.55	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption light commercial vehicles at 100 km/h	11.55	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Rigid Truck at 40 km/h	34.06	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Rigid Truck at 50 km/h	32.42	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Rigid Truck at 60 km/h	31.33	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Rigid Truck at 70 km/h	18.21	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Rigid Truck at 80 km/h	20.17	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Rigid Truck at 90 km/h	22.46	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Rigid Truck at 100 km/h	25.09	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Artic Truck at 40 km/h	98.22	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Artic Truck at 50 km/h	94.29	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Artic Truck at 60 km/h	91.66	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Artic Truck at 70 km/h	51.18	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Artic Truck at 80 km/h	54.83	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Artic Truck at 90 km/h	59.12	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Artic Truck at 100 km/h	64.06	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Buses at 40 km/h	55.81	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Buses at 50 km/h	52.57	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Buses at 60 km/h	50.41	litres/ 100 km	2005	Australia	Austroads

Fuel Consumption	Fuel consumption Buses at 70 km/h	29.55	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Buses at 80 km/h	32.99	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Buses at 90 km/h	37.05	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Buses at 100 km/h	41.72	litres/ 100 km	2005	Australia	Austroads
Fuel Consumption	Fuel consumption Passenger vehicles Petrol	10.6	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Motor cycles Petrol	5.2	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Light commercial vehicles Petrol	13.6	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Rigid trucks Petrol	24.1	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Non-freight carrying trucks Petrol	14	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Buses Petrol	15.3	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Passenger vehicles Diesel	9.7	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Light commercial vehicles Diesel	10.7	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Rigid trucks Diesel	28.4	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Artic trucks Diesel	53.1	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Non-freight carrying trucks Diesel	29.8	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Buses Diesel	26.3	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Passenger vehicles LPG/other	11.6	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Light commercial vehicles LPG/other	14.4	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Fuel consumption Buses LPG/other	18.8	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Vehicle numbers	Registered passenger vehicles	19129	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered campervans	152	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered light commercial vehicles	7896	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered light rigid trucks	307	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered heavy rigid trucks	957	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered articulated trucks	456	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered non-freight carrying vehicles	28	Number	2013	Lockyer Valley	Australia Bureau of Statistics

Vehicle numbers	Registered buses	221	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered motor cycles	1503	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle numbers	Registered total motor vehicles	30649	Number	2013	Lockyer Valley	Australia Bureau of Statistics
Vehicle use	Total km travelled for business use passenger vehicles	6255	million Km	2012	Queensland	Australia Bureau of Statistics
Vehicle use	Total km travelled to and from work passenger vehicles	10495	million Km	2012	Queensland	Australia Bureau of Statistics
Vehicle use	Total km travelled for personal use passenger vehicles	19103	million Km	2012	Queensland	Australia Bureau of Statistics
Vehicle use	Total km travelled all purposes passenger vehicles	35853	million Km	2012	Queensland	Australia Bureau of Statistics
Energy factor	Energy content factor Petrol	34.2	GJ/kL	2017	Australia	Department of the Environment and Energy
Energy factor	Energy content factor Diesel	38.6	GJ/kL	2017	Australia	Department of the Environment and Energy
Energy factor	Energy content factor Liquified petroleum gas	26.2	GJ/kL	2017	Australia	Department of the Environment and Energy
Energy factor	Energy content factor Ethanol	23.4	GJ/kL	2017	Australia	Department of the Environment and Energy
Emission factor	Co2 emission factor for Petrol	67.4	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	CH4 emission factor for Petrol	0.5	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	N2O emission factor for Petrol	1.8	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	Co2 emission factor for Diesel	69.9	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	CH4 emission factor for Diesel	0.1	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	N2O emission factor for Diesel	0.5	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	Co2 emission factor for LPG	60.2	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	CH4 emission factor for LPG	0.6	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	N2O emission factor for LPG	0.7	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	Co2 emission factor for Ethanol	0	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	CH4 emission factor for Ethanol	0.7	kg/GJ	2017	Australia	Department of the Environment and Energy
Emission factor	N2O emission factor for Ethanol	1.9	kg/GJ	2017	Australia	Department of the Environment and Energy
Fuel Consumption	Average fuel consumption Petrol Vehicles	10.8	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Average fuel consumption Diesel Vehicles	18.7	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Average fuel consumption LPG/other Vehicles	12.5	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics
Fuel Consumption	Average fuel consumption All fuel type Vehicles	12.9	litres/ 100 km	2016	Victoria	Australia Bureau of Statistics

Vehicle numbers	Number of petrol vehicles registered	3,631,515	Number	2016	Victoria	Australia Bureau of Statistics
Vehicle numbers	Number of Diesel vehicles registered	856,594	Number	2016	Victoria	Australia Bureau of Statistics
Vehicle numbers	Number of LPG/dual/other vehicles registered	191,388	Number	2016	Victoria	Australia Bureau of Statistics
Vehicle numbers	Number of Electric vehicles registered	1,437	Number	2016	Victoria	Australia Bureau of Statistics
Environmental values	Average price of Australian carbon credit unit purchased	13.08	$	2017	Australia	Australian Government, Clean Energy Regulator
Environmental values	Total Environmental Externality Cost - Car Urban	20.52	$/1000pkm	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - Car Urban	32.60	$/1000vkt	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - LCV Urban	66.45	$/1000tkm	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - LCV Urban	15.05	$/1000vkt	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - HCV Urban	21.76	$/1000tkm	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - HCV Urban	242.17	$/1000vkt	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - Car Rural	9.86	$/1000pkm	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - Car Rural	15.67	$/1000vkt	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - LCV Rural	24.18	$/1000tkm	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - LCV Rural	5.47	$/1000vkt	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - HCV Rural	7.82	$/1000tkm	2013	Australia	Austroads
Environmental values	Total Environmental Externality Cost - HCV Rural	87.03	$/1000vkt	2013	Australia	Austroads
Construction Cost	Average Project Cost - Class 1 Road	6,450,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost - Class 2 Road	4,130,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost - Class 3 Road	2,860,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost - Class 6 Road	7,760,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost - Class 7 Road	6,440,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council

Construction Cost	Average Project Cost (Excluding land acquisition) - Class 1 Road	6,060,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost (Excluding land acquisition) - Class 2 Road	3,720,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost (Excluding land acquisition) - Class 3 Road	2,700,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost (Excluding land acquisition) - Class 6 Road	5,850,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Project Cost (Excluding land acquisition)- Class 7 Road	4,070,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Construction Cost - Class 1 Road	5,460,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Construction Cost - Class 2 Road	3,400,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Construction Cost - Class 3 Road	2,470,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Construction Cost - Class 6 Road	5,060,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Construction Cost - Class 7 Road	5,110,000.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 1 Road	902,700.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 2 Road	981,900.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 3 Road	230,400.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 6 Road	9,995,300.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 7 Road	891,100.00	$ / lane km	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 1 Road	159.10	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 2 Road	158.50	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 3 Road	79.10	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 6 Road	201.80	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Pavement Cost - Class 7 Road	164.30	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Bridge Costs - Class 1 Road	5,090.00	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Bridge Costs - Class 2 Road	4,150.00	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Bridge Costs - Class 3 Road	3,880.00	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Bridge Costs - Class 6 Road	3,610.00	$ / sq m	2015	Australia	Transport and Infrastructure Council
Construction Cost	Average Bridge Costs - Class 7 Road	3,650.00	$ / sq m	2015	Australia	Transport and Infrastructure Council
Business Revenue	Small Business Annual Turnover	368,000.00	$	2013	Australia	Australian Small Business and Family Enterprise Ombudsman

Business Revenue	Nano Business Annual Turnover	48,000.00	$	2013	Australia	Australian Small Business and Family Enterprise Ombudsman
Life Value	Value of a Statistical Life	4,200,000.00	$	2014	Australia	Department of the Prime Minister and Cabinet
Life Value	Value of a Statistical Life Year	182,000.00	$ / year	2014	Australia	Department of the Prime Minister and Cabinet
Environmental Impact	Agricultural Land Occupation	6.86	m2 × year /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Global Warming Potential	175.53	kg CO2 eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Fossil Fuel Depletion	30.70	kg oil eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Freshwater Ecotoxicity	3.26	kg 1,4-DB eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Freshwater Eutrophication Potential	0.07	kg P eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Human Toxicity Potential	124.46	kg 1,4-DB eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Ionizing Radiation Potential	21.97	kg U235 eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Marine Ecotoxicity	3.24	kg 1,4-DB eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Marine Eutrophication Potential	0.03	kg N eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Metal Depletion	77.63	kg Fe eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Natural Land Transformation	0.02	m2 /m2 of bridge	2011	Spain	Penadés-Plà et al.
Environmental Impact	Ozone-layer Depletion Potential	0.00	kg CFC-11 eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Particulate Matter Formation Potential	0.36	kg PM10 eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Photochemical Oxidant Formation Potential	0.61	kg NMVOC /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Terrestrial Acidification Potential	0.53	kg SO2 eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Terrestrial Ecotoxicity Potential	0.04	kg 1,4-DB eq /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Urban Land Occupation	2.23	m2 × year /m2	2011	Spain	Penadés-Plà et al.
Environmental Impact	Water Depletion	752.22	m3 /m2	2011	Spain	Penadés-Plà et al.
Cost or repair	Initial repairs - Major sealed roads	32000.00	$/km	1999	Victoria	Bureau of Transport Economics
Cost or repair	Initial repairs - Minor sealed roads	10000.00	$/km	1999	Victoria	Bureau of Transport Economics
Cost or repair	Initial repairs - Unsealed roads	4500.00	$/km	1999	Victoria	Bureau of Transport Economics
Cost or repair	Cost of accelorated depreciation - Major sealed roads	16000.00	$/km	1999	Victoria	Bureau of Transport Economics
Cost or repair	Cost of accelorated depreciation - Minor sealed roads	5000.00	$/km	1999	Victoria	Bureau of Transport Economics
Cost or repair	Cost of accelorated depreciation - Unsealed roads	2250.00	$/km	1999	Victoria	Bureau of Transport Economics

Cost or repair	Bridge repairs - Major sealed roads	11000.00	$/km	1999	Victoria	Bureau of Transport Economics
Cost or repair	Bridge repairs - Minor sealed roads	3500.00	$/km	1999	Victoria	Bureau of Transport Economics
Cost or repair	Bridge repairs - Unsealed roads	1600.00	$/km	1999	Victoria	Bureau of Transport Economics
Crash costs	Crash cost on Single Rural Road	0.08	$/VKT	2010	Queensland	Austroads
Crash costs	Crash cost on Divided Rural Road	0.04	$/VKT	2010	Queensland	Austroads
Crash costs	Crash cost on Single Urban Road	0.06	$/VKT	2010	Queensland	Austroads
Crash costs	Crash cost on Divided Urban Road	0.05	$/VKT	2010	Queensland	Austroads