School of Design and Built Environment

Developing Sustainable Road Maintenance Strategies by Integrating Carbon Footprint and Road User Costs

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Abstract

Infrastructure assets require large capital investment and ongoing operation and maintenance. As the number of newly constructed roads is limited in recent years, and most road projects have moved to the operational stage in Australia, it is imperative to consider the impact of operation and maintenance activities of roads, especially on a variety of sustainability indicators, such as social and environmental ones.

Road user cost, including vehicle operating cost, value of time and accident cost, has been commonly adopted as an indicator to measure the impact of road development to road users. Although this indicator has been commonly used in the planning and design stage, its implementation in the maintenance stage is limited. In addition, as global climate change is one of the most significant environmental impacts, the carbon footprint of maintenance activities should also be integrated into the decision making process.

This research aims to develop an innovative framework to evaluate the social and environmental impacts of road maintenance activities and integrate these impacts to enable sustainable road maintenance decision making in Australia.

Firstly, a review of the current decision making process in road maintenance is conducted by identifying all indicators that are relevant to maintenance. A total of 19 factors are identified, from budget limitation, onsite construction cost to energy consumption. A questionnaire survey is adopted to evaluate the importance of these factors to the selection of maintenance activities and it is found that budget and direct cost are the most important indicators and road user cost and environmental factors are less important in the current decision making process, although both social and environmental impacts are identified as highly important for the sustainable development of road projects.

Secondly, innovative and improved models to accurately calculate the environmental cost and road user cost of roads in Australia are developed. This thesis analyses 6,304 cases of road maintenance activities in Western Australia, encompassing a total treated area of 55,330,752 m^2 in order to estimate the environmental impacts of eight maintenance strategies based on the Life Cycle Assessment (LCA) method. The results show that structural asphalt work (ASRS) has the highest emissions value of 43.96 kg CO_2e/m^2, while chip shape sprayed seal (CS) has the lowest emissions value of 2.41 kg CO_2e/m^2.

In addition, the road user cost of 6,174 cases of road maintenance treatment cases, encompassing a total of 54,201,382 m^2 treatment area, is analysed based on the data provided by Main Roads Western Australia, using a modified calculation method from the Australian Transport Assessment and Planning method. Based on the results, the road user cost of the same eight maintenance strategies is evaluated and their impact on road users during construction and after construction is also estimated.

Finally, this thesis innovatively integrates the social and environmental impacts into the decision making process using three scenarios: (1) the Life Cycle Cost Analysis (LCCA) of maintenance decisions over 20 years; (2) the appropriate budget allocation for road maintenance (rehabilitation), considering the impact of the maintenance to the whole community; and (3) the true cost of road maintenance activities for easy assessment of maintenance activities in practice.

This thesis makes valuable contribution to theory and practice in road maintenance area. It proposes an innovative framework to integrate social and environmental impacts of maintenance activities into the decision making process. The usefulness of the framework, including the indicators, their calculations and potential implementations, is also presented in this thesis, using real-life scenarios. It is believed that road agencies can usefully adopt the results of this study for developing sustainable maintenance activities, such as selecting truly sustainable maintenance activities.

Keywords: Sustainable Development, Road Maintenance, Environmental Cost, Road User Cost.

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number HRE2017-0602 (Appendix 2)

Signature: ____________________

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List of Abbreviations

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Accident Cost
AHP	Analytic Hierarchy Process
ARRB	Australian Road Research Board Group
ATAP	Australian Transport Assessment and Planning
CBA	Cost–Benefit Analysis
CH_4	Methane
CO_2	Carbon Dioxide
CS	Chip Seal
GCWR	Gross Combined Weight Rating
GHG	Greenhouse Gas
GVM	Gross Vehicle Mass
GVWR	Gross Vehicle Weight Rating
GWP	Global Warming Potential
HDM	Highway Development and Management
IEA	International Energy Agency
IRI	International Roughness Index
KMO	Kaiser-Meyer-Olkin
LCA	Lifecycle Assessment
LCC	Lifecycle Costing
LCCA	Lifecycle Cost Analysis
LCCB	Lifecycle Cost–Benefit
LCI	Lifecycle Inventory
MRWA	Main Roads Western Australia
N_2O	Nitrous Oxide
NAASRA	National Association of Australian State Road Authorities
NPV	Net Present Value
PPI	Producer Price Index
RAP	Reclaimed Asphalt Pavement
RUC	Road User Cost

SD	Standard Deviation
TRDF	Texas Research and Development Foundation
UK	United Kingdom
UN	United Nations
US	United States
VOC	Vehicle Operating Cost
VOT	Value of Time

Chapter 1: Introduction

1.1 Introduction

Roads comprise one of the most expensive and comprehensive infrastructure assets in the global construction environment. Therefore, it is important to ensure that the road asset management plan represents the reality of the current situation, and that the road performance forecast matches the true behaviour of the asset in various circumstances, such as during economic downturns (SBEnrc 2017). An infrastructure asset requires a large capital investment and then requires ongoing operation and maintenance, including improvement and removal of roads. According to Main Roads Western Australia (MRWA) (2016), the Australian Government spends more than AUD$7 billion every year on maintaining and renewing roads. In Western Australia, MRWA manages a network of around 18,000 kilometres of national highways and major roads across the state, covering an area of some 2.5 million square kilometres, which accounts for 32.9% of the total roads in Australia (Main Roads Annual Report 2017). To maintain the existing road network by maximising asset life and minimising whole-of-life cost, approximately 126,000 kilometres of local roads and 30,000 kilometres of roads through national parks and forests require funding for maintenance. This significant public asset operates throughout the state’s diverse landscapes and climates in the service of all road users. Although the cost of maintaining and rehabilitating roads is the largest item of expenditure for many local governments, roads are important contributors to national wealth and are a key component of social structure, as a significant aspect of national infrastructure capital.

The sustainability of a project considers the interaction between the given project and the social, environmental and economic dimensions of the system enclosing it. Brundtland (1987) defined sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs. The sustainable development of road projects can generate significant benefits associated with these projects, such as cost-effectiveness, reduced material consumption, improved community quality of life, enhanced protection of finite environmental resources, improved lifecycle approaches, and enhanced innovation and knowledge transfer (The World Bank 2015). Additionally, sustainable construction means that the creation, construction, maintenance and operation of infrastructure helps build a community in a way that maintains the environment, creates long-term wealth and improves quality of life (Greenwood 2008). Thus, sustainable roads are constructed to reduce environmental impacts and are designed to optimise the alignment; be resilient to future pressures; and be adaptable to changing use, including increased travel volume and changes in demand for road users (SBEnrc 2012). Thus, while considering budgeting and cost benefits from an economic viewpoint, it is also necessary to consider social effects, such as road user effects and environmental impacts.

The sustainability of road networks involves upgrading and maintaining existing road spaces to improve safety, accessibility, convenience and traffic flow. Population and economic growth have increased the need for road network expansion, rehabilitation and maintenance in the region. However, current road maintenance decision making processes do not seriously consider environmental impacts. It is important to consider the direct and indirect environmental impacts of the road through end use as a strategic direction for road maintenance. Sustainable development is becoming increasingly important because of climate change, resource depletion and energy constraints, and it is essential to optimise resources and energy consumption and minimise greenhouse gas (GHG) emissions (Alam et al. 2013). MRWA has expanded its focus on emissions reduction to manage the emissions generated by projects and maintenance activities through reducing emissions from activity via energy efficiency, the use of renewable or alternate energy sources, and the use of materials with lower embodied energy.

Road user costs (RUCs) and benefits can be used for infrastructure asset management and decision making. RUCs can have monetary and non-monetary effects. The monetary effects include vehicle operating cost (VOC), value of time (VOT), accident cost (AC) and emissions cost. The non-monetary effects can include negative effects on the environment and ecology or local businesses caused by construction activities (Qin and Cutler 2013). By understanding the major factors influencing user cost, analysts can take steps to minimise the effects of planned future rehabilitation activities on users. RUCs can be used in cost–benefit analysis (CBA), lifecycle cost analysis (LCCA) and other analyses to help determine the most appropriate delivery method of maintenance work. RUC is a necessary component when conducting LCCA or CBA related to future system designs, preventative strategies, safety or capacity improvements, and operation selections. LCCA seeks to optimise the cost of allocating, owning and operating physical assets over their useful existence by seeking to quantify and identify all significant costs involved in that lifecycle, using the present value technique (SBEnrc 2017). Costs are evaluated over the lifecycle of a road, including different materials and construction procedures, following a standard price list for road materials and construction. The existing lifecycle costing (LCC) method is mainly based on an evaluation of the present worth cost or equivalent uniform annual cost of asset management strategies.

Although the LCC method can help evaluate the lifecycle economic performance of assets, it does have limitations, as many studies have reported that the user benefits and costs—an element not included in the LCC method—account for a significant portion of the lifecycle cost (Sieglinde 2010). Similarly, the current lifecycle cost is often minimised when not considering the often-significant cost for users of the asset or the long-term effects of the decision (Heralova et al. 2014). Lifecycle cost–benefit (LCCB) analysis is an extended LCC analysis that includes all indirect costs, such as user costs and benefits, as well as externalities. Thoft-Christensen (2009) found that the main factor leading to the non-adoption of LCCB in infrastructure projects is that engineers generally do not understand or appreciate the probabilistic concepts behind LCCB analysis. This situation highlights the need for an in-depth understanding of all critical cost factors and their mathematical representation, as well as a comprehensive evaluation of these factors and their application in asset management.

In Australia, especially Western Australia, road agencies usually do not consider social or environmental benefits when making maintenance decisions, even though social impacts are considered a key factor for decision making and infrastructure asset management. Further, the guidance provided by road agencies to calculate RUC only covers limited cost indicators. Parameter values for calculating RUCs are not structurally provided and information data are isolated. Therefore, RUC is not considered a factor for making decisions on road maintenance, although it has a strong influence on the economic, environmental and social aspects of road infrastructure. For example, previous decision making models focused on financial performance related to the direct cost of maintenance, and did not consider multiple factors (Haapasalo et al. 2015; Kalb 2014; Meneses et al. 2012; Sadasivam et al. 2015).

1.2 Problem Statement

The number of newly constructed roads has been limited in recent years, and most road projects have moved to the operational stage; thus, it is imperative to consider operation and maintenance activities. Maintenance of a road consists of routine maintenance, specific maintenance, restoration maintenance and pavement rehabilitation, all of which have a crucial influence on the related economic, social and environmental aspects (Sally et al. 2005).

The cost of the road can be categorised as agency cost, user cost and non-user cost. Agency cost includes the initial costs of construction, future maintenance costs (such as overlays) and reconstruction costs. Additionally, agency cost includes salvage cost, cost of investments and engineering cost. Meanwhile, user costs generally encompass travel time delays, vehicle operation costs, accidents and discomfort. Finally, non-user costs can include air pollution, noise pollution and neighbourhood disruption. Traditionally, RUC has only been applied in limited areas of the management of highway structures, such as pavements and bridges (Arviddson 2017; Binu et al. 2014; Kann et al. 2015; Khan et al. 2016; Pakrashi et al. 2006). RUC is not a direct cost to the road agency department’s budget and there is no apparent uniformity in applying RUC to certain areas, such as defining the cost components, the driving unit costs for VOT, VOC computations, estimating lane capacity values, and travel delay and queuing algorithms; thus, the uptake of RUC in the maintenance of roads is limited.

When making maintenance decisions, the important categories of cost and benefit that must be considered include: (1) agency cost, such as design fee, construction and future maintenance; (2) user costs and benefits associated with the work zone; (3) user costs and benefits associated with facility operations; and (4) externalities, such as emissions and noise (ATAP 2016; Austroads 2011; FHWA 2011; NJDOT Road User Cost Manual 2001; Xiao et al. 2013). However, the current analysis of road maintenance decisions has several problems. During maintenance, agencies rarely consider the quantitative evaluation of user cost. In other words, the current status of creating road maintenance strategies does not consider the true cost of road projects. Thus, to assist agencies to make sustainable management decisions, an innovative method of evaluating the true cost of road maintenance strategies should be developed, covering various cost and benefit factors, including agency cost, RUC and environmental cost.

In particular, social and environmental effects are considered less important than economic effects. This derives from the difficulty in recognising the importance of social and environmental sustainability and identifying the elements of sustainability. Another reason for this oversight is the lack of clear initial cost evidence and lack of clear benefits of implementing social and environmental sustainability, given that the vast majority of benefits are intangible and difficult to quantify. Therefore, further research is required to promote the implementation of social and environmental sustainability in road maintenance. However, most previous research was undertaken to focus on a single aspect of sustainability, rather than integrating the three elements into one comprehensive model. In other words, most studies focused on addressing economic aspects (Anand et al. 2000; Goerner et al. 2009; Isaksson 2005; Spangenberg 2005), social aspects (Chan et al. 2008; Dempsey et al. 2011; Dillard et al. 2008; Hutchins et al. 2008; Valdes et al. 2010) or environmental aspects (Ding et al. 2008; Gangolells et al. 2009; Garzon et al. 2008; Lam et al. 2011; Muga et al. 2008; Peters et al. 2009).

Issues related to the effects of road maintenance on the environment, government, industry and community represent a major challenge facing Australia (Garnaut 2011). The Commonwealth of Australia (2011) announced that road transport contributes 87% to the total GHG emissions produced in Australia. Thus, transportation should be considered a high-impact emissions component in Australia. Given the large quantities of materials required for road treatment, the transport of materials forms a significant part of the total GHG emissions. Additionally, the distance of transport has a high influence on the transportation. The transportation component includes transportation of materials from the source to the production plant, and then from the production plant to the site. Unlike in smaller countries, such as Singapore or South Korea, Western Australia alone has a transport distance of up to 4,000 km. This research will carefully analyse each of these transportation components.

1.3 Research Aim and Objectives

The main aim of this research is to develop an innovative framework to identify important cost indicators in road maintenance, and integrate these indicators to enable sustainable road maintenance decisions in Australia. To achieve this aim, four objectives were established, as follows:

- **Objective 1: To investigate the current decision making process in road maintenance by identifying all relevant cost indicators.**

  Objective 1 focuses on investigating the current decision making process in the maintenance stage of road infrastructure. This research seeks to identify the influencing impact factors in road maintenance and investigate the important concerns regarding these factors. Additionally, this study will investigate the underlying factors leading to the implementation pattern of RUCs and environmental assessment in Australia. Previous studies from the Australian Road Research Board Group (ARRB) found that the implementation of social impacts when making maintenance decisions varies significantly across Australia. For example, the Australian Transport Research Forum (Naude et al. 2015) found that, while RUC is usually considered when making maintenance decisions in Queensland, it is not a consideration in Western Australia. As such, it is useful to understand and investigate the underlying reasons leading to this difference, which may include budget, governance structure and the availability of relevant data.

- **Objective 2: To develop an innovative and improved model to accurately calculate the environmental cost of road maintenance in Western Australia.**

  Global climate change is recognised as one of the greatest threats to human development. To address this challenge, environmental considerations—especially GHG emissions—must be integrated into decision making processes SBEnrc 2012). Road maintenance and rehabilitation activities can be resource intensive; thus, it is important to calculate the emissions from maintenance and rehabilitation activities. LCA has been widely adopted to assess the environmental impacts of the manufacturing and construction sectors (Harris 1999). LCA assigns potential environmental impacts and underlying flows to the primary production flow. This study will analyse the detailed processes of eight pavement treatment strategies adopted by MRWA. Additionally, the emissions values will be calculated using a LCA approach. The emissions values will be converted to emissions cost using the carbon tax value to enable decision makers to make relevant decisions. Therefore, this research aims to analyse the pavement strategy process in detail, including raw materials, manufacturing, placement and transportation. Australia-specific data and detailed information of the components will provide an accurate determination of the environmental cost.

- **Objective 3: To develop an innovative and improved mathematical model to accurately calculate the RUC of roads in Australia.**
  The Transport and Infrastructure Council (2016) published the Australian Transport Assessment and Planning (ATAP) Guidelines to help road agencies calculate RUC. However, the model has been criticised on several levels. The model provides accurate calculation at a micro-level to estimate VOCs, which is an integral part of RUC. However, travel time values and crash costs are only provided as parameter values. The international approach to calculating RUC can provide useful insight regarding the ways in which RUC can be calculated and used at a network level. Thus, a systematic evaluation of RUC in road maintenance is necessary.

- **Objective 4: To innovatively integrate environmental cost and RUC into making maintenance decisions for road projects.**
  RUC has been traditionally applied in the construction stage of roads. However, the number of newly constructed roads has been limited in recent years, and most road projects have moved to the operational stage; thus, it is imperative and useful to understand how environmental considerations (emissions, in this thesis) and social considerations (RUC, in this thesis) can be integrated into making maintenance decisions.

1.4 Scope of the Study

This research was driven by the rising need to integrate environmental and social impacts to identify the true cost of road maintenance. To achieve the aim and objectives of this research, several specific boundaries are identified, as follows.

Road deterioration is a significant factor that needs to be considered when making maintenance decisions. As such, civil engineers have developed various models to predict road deterioration. For example, the United Kingdom (UK) has developed sustainable rating systems for infrastructure, such as CEEQUAL (2013) and ICSA (2013). In the United States (US), the Green Roads (2011) and Green Lites (NYSDOT 2009) framework were designed to rate sustainability. In Australia, sustainability initiatives from VicRoads

(2010), IPWEA (2013), ISCA (2013), RTA New South Wales (2012), ARRB (Houghton 1998), IRF (2011), MAV (2013), Austroads (2012) and WALGA (2008) have laid the basis for reducing resource consumption, GHG emissions, waste generation and the costs of road construction and maintenance. However, it should be noted that, while this is an important factor when making maintenance decisions, this factor is not included in this study because this study aims to identify the cost indicators related to road maintenance. When these cost indicators are identified and evaluated, they can be easily integrated with road deterioration models to provide a more comprehensive evaluation of road maintenance decisions. As such, this research focuses on investigating the environmental and social impacts of maintenance activities, with the expectation that these can be integrated with other considerations to generate sustainable maintenance decisions.

These boundaries also directly influenced the methodology of this study. To achieve optimal results from integrating social and environmental impacts in the decision making processes of road maintenance, critical factors and variables must be defined at the beginning of the study. Analysis of cost and benefits and understanding the relationships between variables will be achieved by developing mathematical models. Moreover, this study will investigate the current implementation factors and underlying reasons leading to the implementation pattern of influencing factors in Australia. Through the literature review and survey, defined problems will be solved with an improved model. These models and structure system will be integrated into making maintenance decisions for road infrastructure projects. Finally, case studies to evaluate the effectiveness and accuracy of the proposed model will be provided with different conditions.

The three primary components of RUC are VOC, VOT and AC; however, this study limits the boundaries to VOC and VOT because of the difficulty in generalising specific accident cases. In addition, this study limits the boundaries to carbon emissions in terms of sustainable development, which consists of economic, social and environmental sustainability. Figure 1.1 presents the scope of this study.

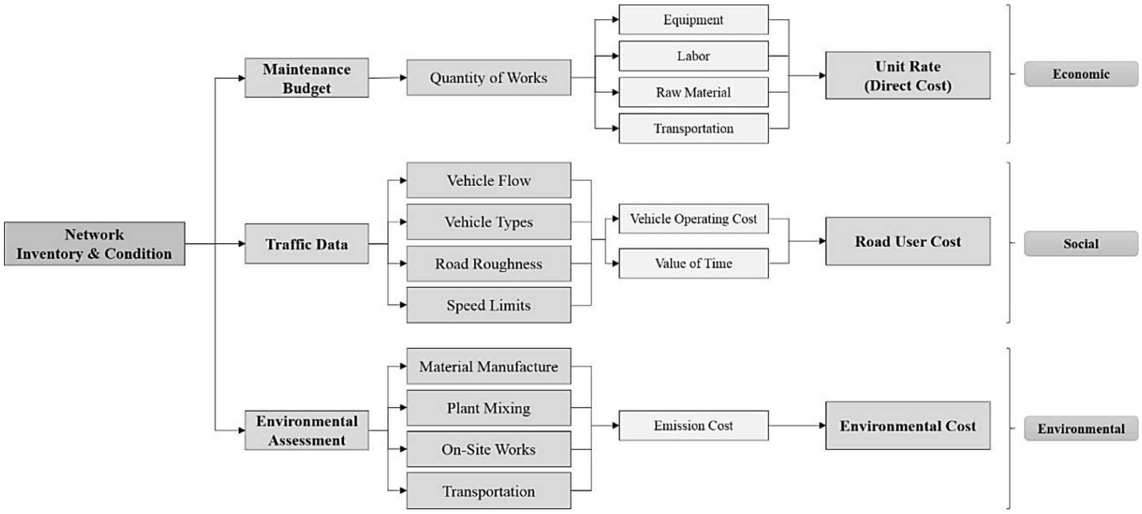


Figure 1.1: Scope of the Study

1.5 Significance and Contribution of the Research

Between the 1950s and 1970s, many new roads were built in Western Australia (MRWA 2017). As these roads reach the end of their lifespan, the state will have to devote large amounts from the budget to replace them in the future. The Western Australian road system is steadily ageing, which increases the need to fully understand the decision making process in establishing road maintenance decisions. Although it is recognised that this is an emerging issue, the implications are not fully understood. Moreover, as traffic volumes and truck axle loads increase, the rate of deterioration can be expected to accelerate.

Meanwhile, through improving energy efficiency, MRWA has a target of reducing the 2010 level of carbon emissions by 5% by 2020, with a stretch target reduction of 15%. The total emissions across facilities from 2016 to 2017 were 23,894 tonnes CO_2. As part of a collaboration with MRWA, this research will develop an innovative methodology to assess the emissions of road projects. The concept of developing an innovative framework to integrate social and environmental impacts in the decision making process of road maintenance in Australia will play a significant role in the economics of future infrastructure projects.

The specific contributions of this project are as follows. First, current maintenance decisions are based on two factors: direct cost and improvement to the overall road network health. This study focuses on developing an innovative framework to provide strategies for road maintenance decision making by considering RUC, which is an integral part of the lifecycle cost of the road. This RUC considers vehicle types and road conditions, and will guide road agencies to develop truly low-cost maintenance strategies (Research Objective 4). Second, the current status of RUC calculation is not fully implemented for asset management. The anticipated results of this study, including the mathematical calculation tool, will benefit the industry practical roles. The developed model will be validated through various road segments provided by industry partners. With these case studies, organisations will understand why RUC has not been adopted and how RUC can be integrated into their decision making (Research Objective 1). Finally, this study will provide a well-documented calculation tool that includes every road user effect, combined with a systematic approach. The developed methodology will be evaluated for application using case studies and considering the maintenance stage of the project. Alongside gathering the isolated information and using software tools to calculate automatically will provide emission values and RUC estimation method for practical uses (Research Objectives 2 and 3).

This research demonstrates that the indirect costs—the social impacts—can be measured quantitatively to be integrated into decision making. Previous studies encountered the challenge of concluding the macro-level analysis and using specific data of that region. However, this research will provide both macro-level true data and specific micro-level data. This research will identify various factors related to road maintenance and social impacts, including detailed analysis of the maintenance treatment strategy process.

This research will demonstrate the ways in which the methodology and tools developed in this study can be implemented in practical cases. This will enable capture of the ever-changing requirements for economic performance and environmental considerations. The proposed innovative model is expected to achieve a new maintenance paradigm that will enable development of treatments tailored to the actual behaviour and conditions of the road, achieve cost-effective maintenance and provide environmental benefits. The approach developed in this study will largely address by supporting asset management that can be performed while lowering lifecycle costs.

1.6 Description of Chapters

This thesis is organised into eight chapters in the following sequence, as displayed in Figure 1.2.

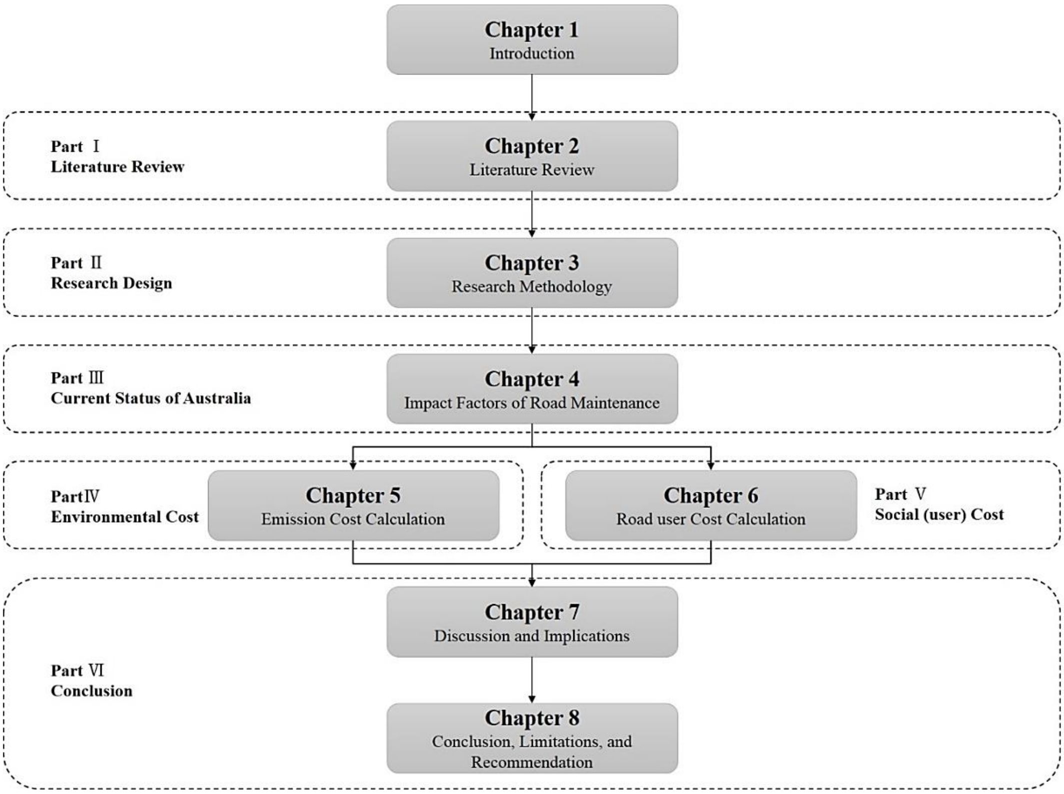


Figure 1.2: Structure of the Thesis

Chapter 1 has been an introductory chapter that explained the aim and objectives of this research, and the basic structure of the study. Chapter 2 presents a review of the literature, including maintenance of roads from a management view and pavement technical view, RUC theory, and emissions cost theory. Chapter 3 provides the research methodology, including the data collection and analysis methods. Chapter 4 presents the influencing factors when making maintenance decisions in Australia. Chapter 5 analyses eight road maintenance strategies in terms of emissions, which is considered one of the most important environmental indicators. Chapter 6 provides an estimation of RUC in Australia-specific conditions, which will serve to indicate the social impacts of road maintenance. Chapter 7 presents the discussion and implications of this study. Finally, Chapter 8 discusses the conclusions of this research, including summaries and theoretical and practical contributions for road maintenance. This chapter also provides the study limitations and suggestions for future research.

Chapter 2: Literature Review

2.1 Introduction

Roads are essential to the wellbeing and economic health of society (Ken 1996). Transport efficiency, public safety, social equity and environmental integrity related to roads should all be considered to ensure roads are effectively managed. Therefore, it is important to ensure appropriate decision making when managing roads, with clear strategies to achieve sustainability. This can include economic considerations, given that the cost of maintaining the road network represents a significant amount of public funds. This may also require considerations of social impacts, such as the influence of road activities on the community. Moreover, environmental impacts—including considerations of global climate change and solid waste—should be included in the decision making process.

Roads have a limited lifecycle and must be upgraded or replaced when their general condition falls below certain standards. The average life of a sealed road in Western Australia is about 40 years (MRWA 1996). Road maintenance encompasses all the activities needed to ensure that a road remains serviceable for its full design life. Failure to maintain the road soon leads to marked deterioration of the system and results in increased costs. Thus, it is necessary to ensure that road maintenance activities are appropriately assessed, so that their effects—economic, social and environmental impacts—are clearly understood and can lead to informed decisions. It should be noted that, because of the rising recognition of the need for sustainable development, road agencies, including MRWA, are expected to satisfy a variety of customer-defined service criteria, including indicating traffic density and type, road function, environmental and use requirements, road safety and the availability of funds in the future. However, they do not directly report the social and environmental impacts of their operational activities.

This chapter presents a comprehensive review of the existing literature on the sustainability concept, road maintenance principles and practices, and environmental and social impacts on roads, which are all integral to this thesis.

2.2 Concept of Sustainable Development

Road systems provide a significant function in creating and maintaining a desirable quality of human life (The World Bank 2015). Thus, well-planned road networks—including the lifecycle of road planning, construction, maintenance and renovation—support the national economy and contribute to human wellbeing. In this sense, sustainable development is becoming increasingly important, with its focus on the interaction between infrastructure projects and economic, environmental and social sustainability. Sustainability is defined as the requirement of a generation to manage the resource base so that future generations can share the same average quality of life. Development can continue if the average quality of life does not deteriorate (Asheim 1994). The concept of sustainable development was first defined by the United Nations (UN) Division for Sustainable Development (1987) in the Brundtland Report as being development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Additionally, while the Brundtland Report (1987) and UN Agenda 21 (1992) emphasised the importance of sustainability, the UK Government (1999) established four goals to recognise the needs of all people, effectively protect the environment, use prudent natural resources, and maintain social progress at a stable level. The World Summit on Social Development (2005) and previous studies (Giddings et al. 2002; Van der Vorst et al. 1999) identified three key areas that contribute to the philosophy of sustainable development and social science: economic, environmental and social sustainability. In particular, Goodland (1995) first argued that sustainable development differs from sustainability because development involves increasing, improving and growing. In summary, sustainable development is development compatible with maintaining the resources necessary for the lives of humans and other organisms (Corriere and Rizzo 2012).

2.2.1 Economic Sustainability

The general definition of economic sustainability is the ability of an economy to indefinitely support a defined level of economic production. Economic sustainability is closely linked to environmental and social sustainability because of growth limitations. Sudhir and Amartya (2000) explored the relationship between distributional equity, sustainable development, optimal growth, and pure time preference to insist that economical sustainability is a specification of what is to be sustained and not a matter of intergenerational equity. Meadows et al. (2004) argued that human demand has exceeded natural supply since the 1980s, and special measures should be taken or the increased consumption will lead to environmental and economic collapse. Moreover, previous studies (Gilding 2011; Jones et al. 2013; Thompson 2013) indicated that society has reached the limits of long-term growth and resource depletion. Sustainable economic development should provide for humans' desires without sacrificing quality of life—particularly focusing on reducing the financial burden in developing countries.

2.2.2 Environmental Sustainability

The basic global definition of environmental sustainability refers to sustainable development, which is sustainable economic growth. Environmental sustainability refers to the rate of renewable resource harvest, pollution creation and non-renewable resource depletion that can be continued indefinitely (Daly 1990). The *Commonwealth Environmental Protection and Biodiversity Act 1999* developed certain principles to follow for ecologically sustainable development. It insists the following. First, decision-making processes must effectively integrate economic, environmental and social considerations. Second, in the event of a threat of significant or irreversible environmental damage, a lack of complete scientific certainty should not be used as a reason to postpone measures to prevent environmental degradation. Third, the principle of equality across generations should ensure that the current generation is maintained or improved in terms of the health, diversity and productivity of the environment for the benefit of future generations. Four, preservation of biodiversity and ecological integrity should be a fundamental consideration in decision making. Five, evaluation, pricing and incentive mechanisms need to be improved. In contrast, the Commonwealth Government defined ecologically sustainable development in Australia as using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased (Department of Environmental and Heritage).

Meanwhile, environmental effects deeply influence human life, especially in terms of climate change. The Intergovernmental Panel on Climate Change (2015) reported that the warming of the climate system is unclear, and there are many unprecedented changes for decades to millennia of years observed since the 1950s. Climate change is affecting biodiversity because of the warming of the atmosphere and oceans, decreased ice levels, sea level rise, and increased ocean acidification and GHGs (Reddy and Thomson 2015). Therefore, environmental sustainability is the primary pillar of sustainable development that contributes to the future of human life. It defines how humans should protect the ecosystem, air quality, and integrity and sustainability of human resources, with a focus on factors that stress the environment.

It is clear that environmental benefits are important not only because of the inherent value of preserving the world in which we live, but also because these benefits are economically important to the community. Therefore, these environmental benefits should be quantitatively quantified and considered part of a truly meaningful evaluation of possible alternatives to economic and social impacts.

2.2.3 Social Sustainability

Social development refers to the improvement of individual welfare and overall social welfare because of the increase in social capital. A general definition of social sustainability is the ability of a social system, such as a country, to function indefinitely at the defined social welfare level. However, there are universal differences in the quality of life goals, with differences between countries and political, religious, cultural, class and activist groups. In particular, the most important difference lies in awareness and legislative protection of human health from pollution and other harmful activities caused by businesses and organisations. Research reports (The World Bank 2014; UN Report 2011) indicated that the global financial crisis was not just a crisis of markets, but also a social crisis, which emphasises the relationship between economic and social sustainability. Previous studies identified different aspects of social sustainability and connecting them to sustainable development more generally (Vallance et al. 2011; Godschalk 2004; Chiu 2002 and 2003; Sachs 1999). These studies support the belief that poverty and underdevelopment are barriers to better social and environmental outcomes.

2.2.4 Sustainability of Roads

To ensure that transport is supported by the principles of sustainability, transport policy should focus on improving the transport system through considering the economic, social and environmental development of wellbeing. Sustainable practice is leading engineering to reflect on both the economic and safety aspects of a solution, while also focusing on social and environmental improvements. The Sustainable Built Environmental National

Research Centre (SBEnrc 2012) defined a sustainable road as being: (1) constructed to reduce environmental impacts and designed to optimise the alignment; (2) resilient to future pressures, such as climate change and resource scarcity; and (3) adaptable to changing uses, including increased travel volumes, changes in demand for public transport, cycling and walking which can power vehicle, harvest energy and measure its own performance. In addition, Austroads (2007) suggested that sustainable pavements should ensure: (1) good quality construction to minimise future maintenance, rehabilitation needs and associated disruptions to traffic; (2) a smooth, quiet wearing surface to minimise energy consumption by traffic and environmental impacts; and (3) construction using sustainable materials wherever possible. Sustainability in pavement construction over the lifecycle is achieved by reducing waste, subsequent use, energy consumption, pollution, material transport and use of raw materials; reusing materials; and respecting society members and the environment. Based on these definitions and suggestions, a sustainable road should interact sustainably throughout its whole lifecycle by considering effects such as regulations, energy efficiency, transport capacity, maintenance and social and business effects.

2.3 Road Maintenance Principles

The National Association of Australian State Road Authorities (NAASRA) (1973) defined road maintenance as all work required for the preservation and upkeep of a road, its associated works, or both to prevent the deterioration of the road’s quality and efficiency to a noticeable extent after construction. Road maintenance is essential to keep roads in an as-constructed condition; protect adjacent resources; and provide efficient, convenient and safe travel. Minor repairs and improvements to eliminate the cause of defects are included to avoid excessive repetition of maintenance efforts.

2.3.1 Maintenance Strategy

To manage road maintenance, it is necessary to consider all works that contribute to the preservation and upkeep of the functional capabilities of roads. Road maintenance comprises a multitude of tasks that vary in nature and size. Specific maintenance tasks are developed based on the specific road authority’s needs. The World Bank (2005) categorised road maintenance as routine maintenance, periodic maintenance and urgent maintenance for management and operation convenience. Routine maintenance refers to small-scale works conducted regularly to ensure the daily pass ability and safety of the road, and to prevent premature deterioration of the road (World Road Association 1994). Periodic maintenance is regular and a relatively long-interval activity to preserve the integrity of the road. Urgent maintenance refers to unpredictable repairs that require immediate attention, such as collapsed drains or landslides that block roads.

The NAASRA and Department of Transport and Main Roads of Queensland divided maintenance into three types: routine maintenance, specific maintenance and restoration work. Routine maintenance encompasses activities that—because of their extent, location, time of occurrence or means of execution—are not amenable to planning in detail. Specific maintenance encompasses activities that can normally be predicted and planned for by extent, location and nature, and are thus amenable to more rigorous management techniques, as is the case with routine maintenance works. Restoration works are performed to restore the roadway following damage or disturbance by events beyond the control of the road authority.

The primary aim of road maintenance is to provide safe driving conditions and a uniform road surface, and to minimise the rate of deterioration of the pavement. To ensure the preservation of the asset and the convenience of road users, road maintenance focuses on activities related to the repair of defects and attention to the road structure and associated facilities (Austroads 2009). Austroads divided maintenance into routine maintenance, preventative periodic maintenance and rehabilitation. Routine maintenance includes activities that address minor defects on the carriageway and structures, off-carriageway works (including grass cutting and drain clearing) and essential activities to remove obstacles from the road and ensure a base level of road safety. These works are usually unplanned or planned with a short lead time, and undertaken with minimal light equipment and small quantities of materials. Preventative periodic or specific maintenance includes works that are intended to reduce future deterioration by timely surface interventions to limit the need for expensive rehabilitation, and to ensure minimum skid resistance and that the general safety level does not fall below minimum acceptable levels. These works are usually planned with lead times generally greater than one month. Rehabilitation includes works that target roads whose ride quality has deteriorated significantly, or that display inadequate structural capacity for current or future traffic loading. These works are planned with lead times generally greater than one month and are often planned as part of an annual program.

2.3.2 Management System

It is important to recognise the value of road assets and the strategic importance of road networks. As the road network is formed and matured, increasing resources must be dedicated to its maintenance (Austroads 2011). Figure 2.1 describes the typical process of identifying a project for detailed design as part of the overall asset management system. As a result of limited data in the management system, network-level and program-level analysis performed as part of that system can generate a wide range of treatment types. Therefore, the cause of pavement distress and the choice of treatment at the project level, based on engineering assessments, often lead to other treatments being implemented in a wide range of treatment types generated by network- and program-level analysis.

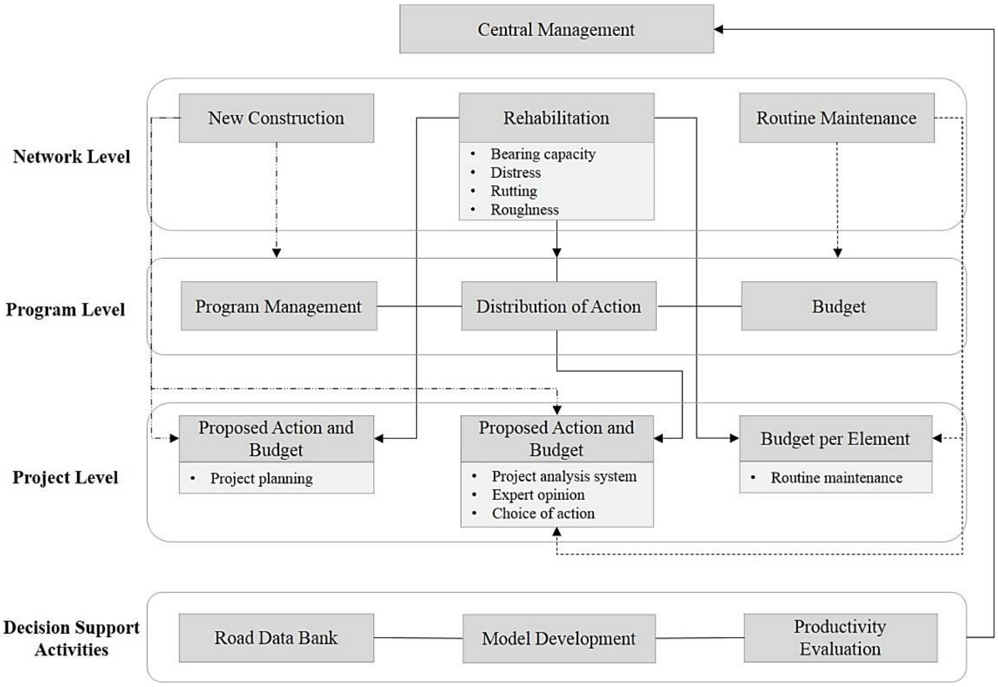


Figure 2.1: Overall Asset Management Process (Source: OECD 1994)

Previous research focused on the limited resources available for road infrastructure, given that road authorities face resource challenges, especially in terms of funding availability. Parche (2007) argued that there are insufficient funding sources to support the increased need for new road infrastructure. Further, there are increased demands for safety, accessibility and use of advanced traffic management systems to reduce socioeconomic costs. The cost of a road project over its service life is a function of design standards, construction quality control, maintenance strategies and maintenance quality (Hawzheen 2011). Free-Hewis (1986) developed a maintenance workload framework that presents a few considerations related to the evaluation of road maintenance throughout the road's lifecycle.

In Australia, road authorities are seeking to implement a maintenance management system and pavement management system to allocate and use resources in the most efficient and effective manner. The maintenance management system plays an important role in the performance evaluation of all assets within the road reserve, including planning, programming, budgeting, costing, scheduling and so forth. A pavement management system provides a systematic structure for the process of managing pavements (Austroads 2009) and optimises pavement performance and user benefits.

In summary, given that roads are the most important public asset, road maintenance plays an important role in many countries. Road improvements bring significant benefits to road users in both direct and indirect ways. The World Bank (Burningham and Stankevich 2005) argued that repair costs increase to six times the maintenance cost after three years of neglect, and to 18 times the cost after five years of neglect (SANRAL 2004). These figures indicate that postponing road maintenance activities causes a high risk of indirect costs of road construction. Moreover, road conditions affect users via operating costs, such as repair and fuel costs, and most seriously in terms of safety by increasing the accident rate. Overall, roads contribute to economic development and growth, and offer important social benefits; therefore, effective and appropriate road maintenance management is required to preserve this asset. Figure 2.2 displays the maintenance management flowchart of elements relationship. The line between elements indicates the relationship, while the arrowheads designate the direction of flow. The elements are discussed in detail in the next section.

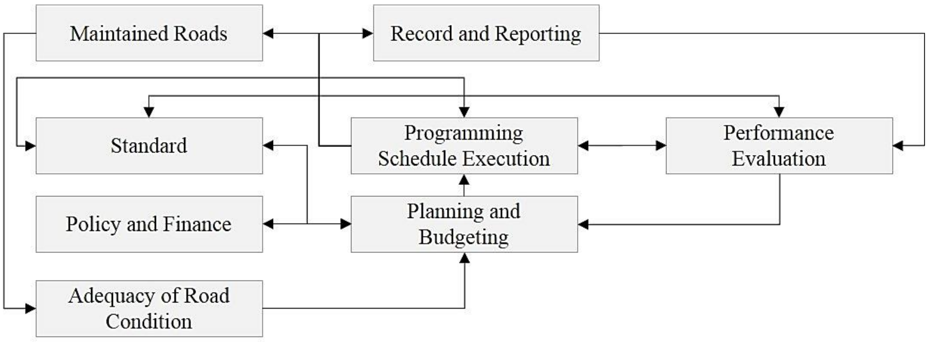


Figure 2.2: Maintenance Management Flowchart

2.3.3 Maintenance and Preservation Process

Maintenance-related works pertain to the preservation, upkeep and renewal of a road, such as rehabilitation, as distinct from the improvement of strengthening. Although the management process for each type of maintenance may vary in detail, four principal phases of maintenance management are common: the determination of maintenance funds, resource direction, recording and reporting, and performance evaluation. Figure 2.3 displays the four phases of maintenance management, including the elements in each phase and the relationship between each phase.

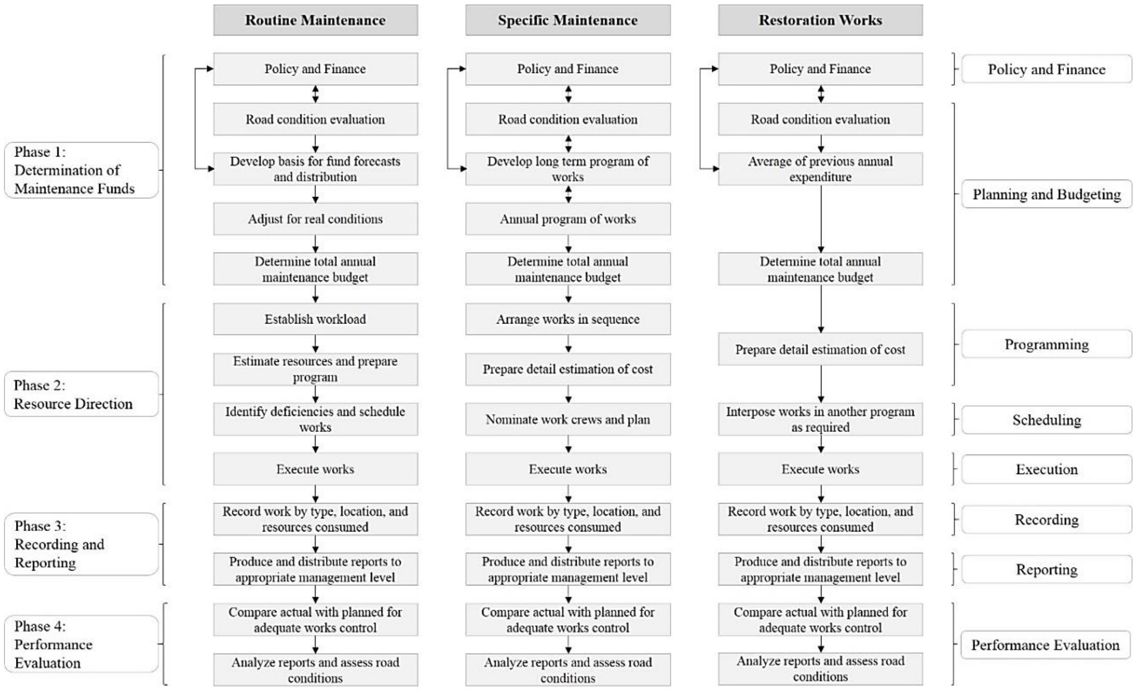


Figure 2.3: Road Maintenance Work Process (Modified from NAASRA 1980)

Phase 1 involves determining maintenance funds, including policy, finance, planning and budgeting. Management must base the maintenance policy on economic assessment and the goals and objectives of the road authority. In this manner, maintenance policy can be determined with regard to the priorities of other works, stated in terms of maintenance levels or strategies, and supported by financial planning. Techniques for developing policy and finance strategies are managed as part of the planning and budgeting elements. In planning and budgeting, the present and future maintenance needs of the road network are determined and plans are developed to accomplish these needs. This usually results in the preparation of a program of works for several years into the future. The plans are used to develop policy and budget submissions to establish the magnitude of the annual workload and distribute funds in accordance with the adopted budget. While the budget provides an authority for works programming and scheduling, this element must be responsive to standards, performance evaluation and the adequacy of road conditions.

Phase 2 involves resource direction, including programming, scheduling and execution. This element constitutes the resource direction phase. Programs define and document the type, amount and sequence of work estimated to be required. Schedules assign resources at the time when the works are to be executed. Maintained roads are the physical result of this resource direction and work execution. The annual maintenance program is derived from a survey of needs based on standard and budget strategies. District management determines the extent and type of maintenance to be performed, and arranges the works to remove peak demands in resource requirements.

Phase 3 involves recording and reporting. In this element, the resources employed in the execution of maintenance works are recorded, so that all levels of management can be provided with sufficient reported information upon which to make decisions, and with permanent records of costs and accomplishment.

Phase 4 is the performance evaluation. This element involves a comparison of actual performance—as indicated by the recording and reporting elements—and the planned objectives established by the budget, annual program and standards for road condition and workmanship. Monitoring comprises both an immediate and direct evaluation and a long-term analysis of expenditure trends and the cost-effectiveness of maintenance works. Performance evaluation provides a means to exercise control over planning and budgeting, standards and resource directions.

Additionally, central management contains senior management and a maintenance service. Senior management establishes maintenance policy, monitors progressive expenditure with respect to the maintenance budget, and directs district management. The maintenance service involves managing the method, planning and performance evaluation, and providing information for both central and district management.

On the other hand, the pavement lifecycle consists of material production, design, (new) construction, preservation, maintenance, rehabilitation, road usage and end-of-life stages. Figure 2.4 displays the processes of the maintenance and preservation stage, modified from the Pavement Lifecycle Assessment Workshop (University of California Pavement Research Center 2010).

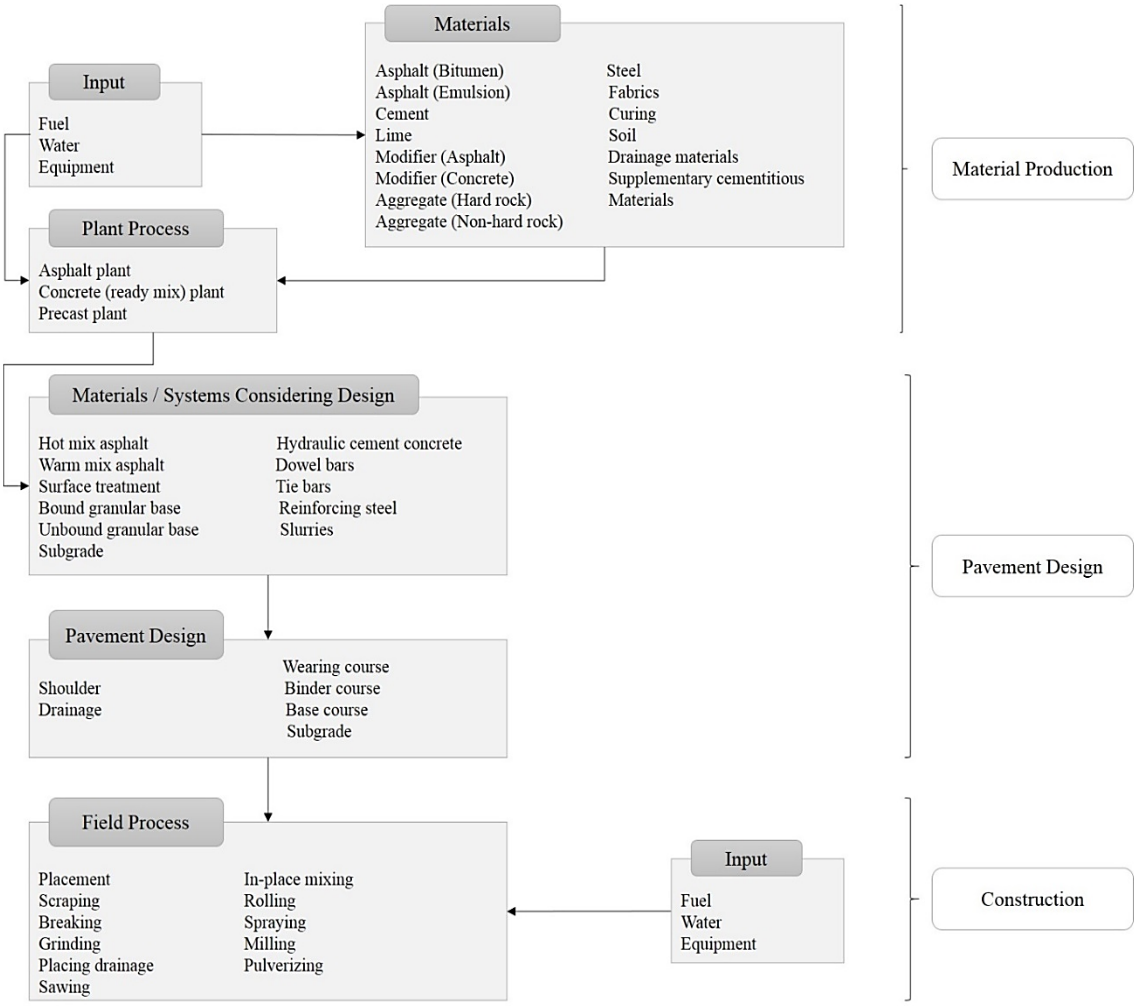


Figure 2.4: Production Process of Road Maintenance (Modified from University of California Pavement Research Center 2010)

As can be seen in Figure 2.4, there are three processes (FHWA 2015). First, the process of pavement materials production refers to all processes involved in pavement materials acquisition, such as mining and crude oil extraction. It also includes the processes of refining, manufacturing and mixing, and plant processes, including mixing plants. Materials production affects sustainability factors, such as air and water quality, ecosystem health, human health and safety, depletion of non-renewable resources and lifecycle costs.

Second, the pavement design process refers to the process of identifying the structural and functional requirements of a pavement for given site conditions, and then determining the pavement structural composition and accompanying materials. Included in this phase are the design processes for both new pavement design and for those processes associated with pavement rehabilitation. Structural design affects sustainability factors, such as performance life, durability, lifecycle costs, construction and materials use.

Third, the pavement construction process refers to all processes and equipment associated with the construction of pavement systems. Generally, construction activities are associated with initial construction, as well as subsequent maintenance and rehabilitation efforts. Construction activities affect sustainability factors, such as air and water quality, human health and safety, durability, and work zone traffic delay, as well as project costs and time. Thus, the process of maintenance in pavement lifecycle indicates that the lifecycle assessment approach is required, including lifecycle inventories (LCIs). Details will be explained in Section 2.5 on assessment methods.

2.4 Road Maintenance Practice

A pavement surface protects the underlying courses of pavement and provides a hard, uniform, dust-free, wearing surface, which contributes to the safety and comfort of the public. It is designed primarily to resist abrasion from traffic and to prevent penetration by moisture. The continuous maintenance of a bituminous surface is an important phase of road work because any break or weakness can cause rapid deterioration of both the surface and pavement. Prompt attention to minor weakness may prevent major repairs at a later date. It may also prevent the development of conditions that are likely to be hazardous or inconvenient to the road user. However, it is necessary to identify the type of pavement before attempting corrective work (NAASRA 1970).

2.4.1 Pavement Types

Pavement can be divided into flexible pavement, which contains unbound granular material or asphalt, and rigid pavement, which is a concrete pavement with joints of steel reinforcement. The types of surface treatment make the pavement suitable for a particular set of service conditions, and are classified as spray treatment, asphalt, bituminous slurry surfacing and concrete. Figure 2.5 displays the detailed classifications of pavement.

A flexible pavement refers to all pavement structures other than rigid pavement. A rigid pavement consists of a relatively high-strength concrete base and one of a range of subbase materials (such as lean mix concrete, cement stabilised crushed rock and unbound granular materials) (Austroads 2009). Flexible pavement activities are simpler than rigid pavement construction; thus, decision making needs to consider construction constraints, materials availability, cost and so forth.

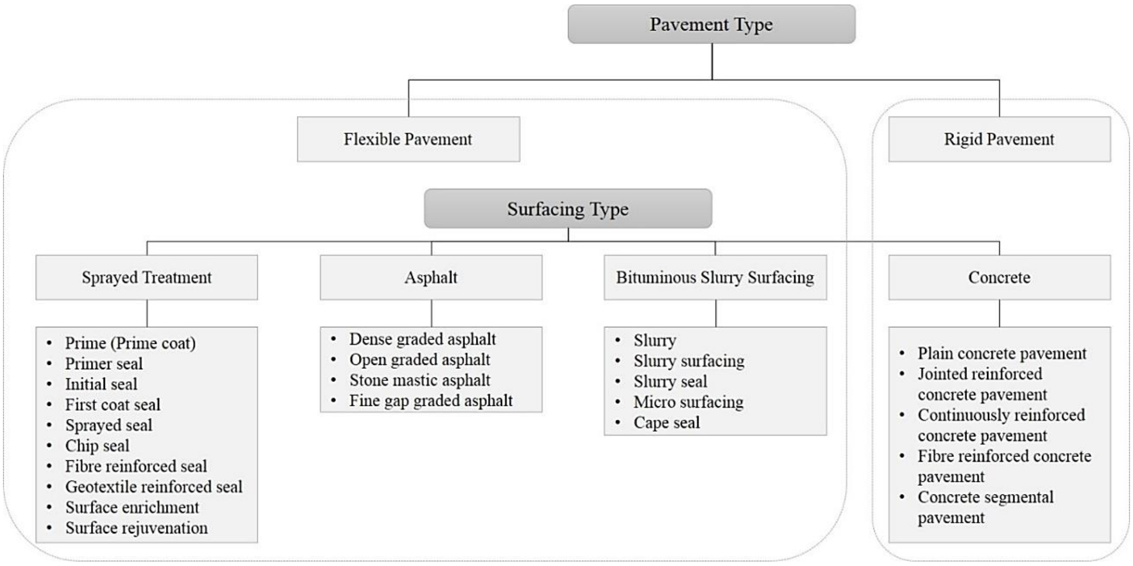


Figure 2.5: Types of Pavement and Surfacing (Source: Austroads 2009)

Sprayed treatment involves a thin layer of binder sprayed onto a pavement surface with a layer of aggregate incorporated (Austroads 2008). The prime coat is a preliminary treatment to a more permanent bituminous surfacing. It involves application of a primer to a base without cover aggregate to provide penetration of the surface, enable temporary waterproofing and obtain a bond between the pavement and subsequent seal or asphalt. The primer seal intends to carry traffic for a longer period than with a prime. It involves the application of a primer binder with a fine cover aggregate to a prepared base to provide penetration of the surface and retain a light cover of aggregate, which is used as a preliminary treatment to a more permanent bituminous surfacing. The initial seal is placed on a prepared base course that has not been primed, and spray seals (which are similar to chip seals) contain a small surface layer of bituminous material with aggregates, and are immune to water. A fibre-reinforced seal consists of a specifically formulated polymer-modified binder with chopped glass fibre. Geotextile-reinforced seal involves application of a bituminous binder, into which both geotextile and aggregate are incorporated to provide a durable wearing surface. A layer of binder is applied first, followed by a layer of geotextile fabric, and then the second coat of binder, followed by the aggregate. Surface enrichment involves a light application of bituminous binder over an existing seal without aggregate. It is used to increase the binder content and extend the life of a bituminous road surfacing. Surface rejuvenation involves a light application of an emulsified fraction of a bituminous binder. It is used to extend the life of a bituminous road surfacing (SBEnrc 2017).

Asphalt is a structural layer in pavement that is a mixture of bituminous binder and aggregate. The most common types are dense-graded asphalt, open-graded asphalt, stone mastic asphalt and fine-gap-graded asphalt (Austroads 2009). Dense-graded asphalt is a mixture of coarse aggregate, fine aggregate, filler and bitumen that is placed hot and compacted to a dense state as a pavement layer or resurfacing. Open-graded asphalt is a mix containing only a small amount of fine material, which provides a high percentage of air voids. Stone mastic asphalt is a gap-graded wearing course mix with a high proportion of coarse aggregate, which interlocks to form a skeletal structure to resist permanent deformation. Fine-gap-graded asphalt is a mix in which gar aggregate is used. A fine-gap-graded mix contains a large proportion of fine aggregate and a lesser proportion of coarse aggregate (SBEnrc 2017).

Bituminous slurry surfacing is slurry, slurry surfacing, slurry seal, micro-surfacing and cape seal, which is a combination with a sprayed seal. The slurry is a stable suspension of aggregate and filler in a less dense and liquid bitumen emulsion. Slurry surfacing is a general term for slurry seal and micro-surfacing. Slurry seal is a thin layer of bituminous slurry surfacing, usually without a polymer modifier. Micro-surfacing is a bituminous slurry surfacing usually containing a polymer that is capable of being spread in layer up to 30 mm thick for rut filling and correction course, and for wearing course application where the good surface texture is required to be maintained through the service life (MRWA 1996).

Concrete is a mixture of fine and coarse aggregate, water, cementitious binder and admixture (Austroads 2009). Plain concrete pavement is a concrete pavement that is unreinforced. Joint-reinforced concrete pavement is a concrete pavement that is typically (mesh-reinforced with square dowelled joints at a spacing of 8 to 12 m. Continuously reinforced concrete pavement is a concrete pavement containing relatively heavy longitudinal reinforcement and no transverse joint. Fibre-reinforced concrete pavement is a concrete pavement reinforced with steel fibre. Concrete segmental pavement is a pavement consisting of a surfacing of interlocking precast concrete pavers.

These surfacing of roads provide a riding surface with suitable smoothness; a safe, economical, durable and well-drained all-weather surface; the necessary skid resistance; and a dust-free surface. In addition, they provide suitable properties for the local environment, such as noise reduction and surface texture. Additionally, road surfacing minimises vehicle operating and maintenance costs, the rate of pavement wear and pavement maintenance costs (Austroads 2009).

2.4.2 Pavement Materials

The choice of road pavement material is an essential feature in the development of pavement with the desired performance characteristics and low overall lifecycle cost. The selection process depends on the evaluation of several criteria, such as material testing, environmental impact assessments, financial considerations, legacy issues, past performance and engineering judgement (Austroads 2007). Figure 2.6 presents the evaluation framework for pavement material selection. This framework indicates the primary consideration and components for selection of pavement materials through the lifecycle of materials.

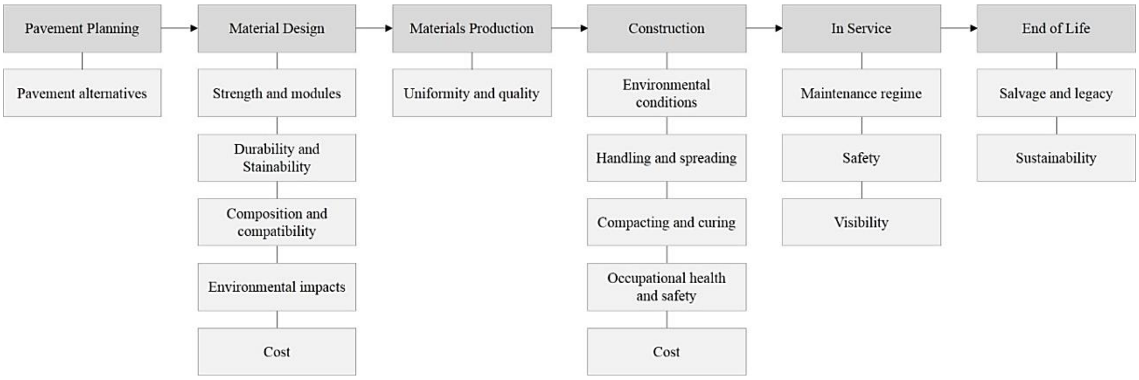


Figure 2.6: Pavement Material Selection Framework (Modified from Austroads 2007)

A road essentially consists of four layers: sub-grade, subbase course, base course and surface course. Pavement materials are categorised based on their position in the pavement structure and the properties of the materials. Figure 2.7 presents the components and distress modes of flexible and rigid pavements.

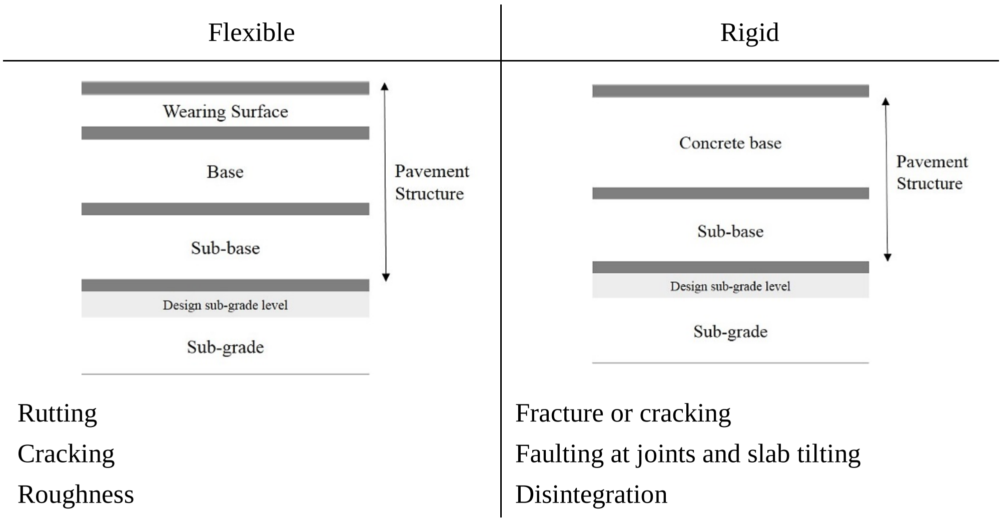


Figure 2.7: Components and Distress Types of Flexible and Rigid Pavement Structures

The sub-grade is the naturally occurring material upon which the pavement is constructed. An imported sub-grade or selected sub-grade may be placed over the natural sub-grade. The subbase provides a stable platform for the construction of the base and wearing surfaces. It assists in providing adequate pavement thickness so that the strains in the sub-grade are kept within design limits and provide adequate erosion resistance to prevent pumping and erosion upon moisture entry into the pavement structure. The base and concrete base provide the bulk of the structural capacity in terms of load-spreading ability by means of shear strength and cohesion. They minimise changes in strength with time by having low moisture susceptibility, and minimise the ingress of moisture into the pavement by having adequate shrinkage and fatigue properties. They also assist with providing a smooth riding surface by having volume stability with time and under load. The wearing surface provides a smooth riding surface with a safe and economical aspect (Austroads 2009). However, pavement distress occurs in a number of different ways, depending on pavement type, material type and quality, traffic loading, environmental impact, pavement composition and maintenance regime. In summary, a flexible pavement has lower construction cost, yet deteriorates rapidly, compared with a rigid pavement, which has a higher initial cost of construction.

2.4.3 Asphalt Manufacture

Hot mix type is a mixture of dense-graded aggregates and bitumen that is produced at about 150°C and is laid and compacted while hot (Vicroads 2010). The hot mix usually has slightly less bitumen and mineral filler, and consequently slightly higher air voids, than does asphaltic concrete. It is used for road pavements and is particularly suited for base courses and thick applications. As a result of the lower filler content, hot mix type is more workable than asphaltic concrete, and fine-graded mixes can produce smooth, even-textured surfaces, particularly where hand-placing methods are required.

Open-graded mix type is made from graded aggregates and bitumen, yet with less fine aggregate than a dense-graded mix. This type of mix presents an open-textured appearance and is used for high-porosity surface courses to prevent hydroplaning or provide drainage under an impermeable asphalt layer.

Cold mix type (premix) is made from semi-dense graded aggregates with a total binder content similar to hot mix type. It is normally produced at about 100°C using bitumen fluxed with approximately 20% of flux oil to produce mixes that are workable at ambient temperatures. Cold mix type is used mainly for patching, temporary patching of road opening and service trenches. It can also be produced using a slow-breaking bitumen emulsion as the binder.

The manufacture of asphalt can be produced in two types of plants, including batch plants and continuous plants (FHWA 2010). Figure 2.8 presents the process of the typical batch plant. The aggregates are taken from storage in controlled amounts and passed through a rotary dryer, where they are dried and heated. The aggregates then pass over a screening unit that separates them into differently sized fractions and deposits them into bins for hot storage. The aggregates, mineral filler and bitumen are then proportioned by weight on sets of scales on a batch basis, and thoroughly mixed in a twin-shaft pug mill. The mix is then discharged into either a hot surge or directly into trucks, and transported to the paving site. Batch plants are designed around flexibility, and can be operated intermittently and changed from one mix to another quite readily.

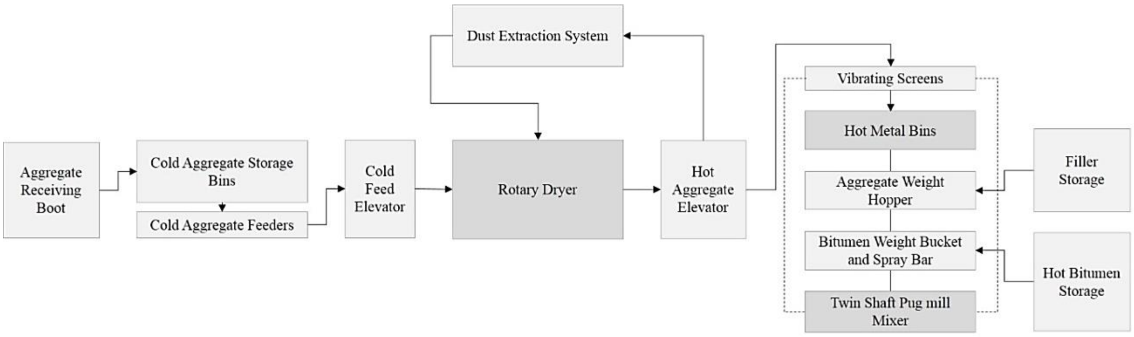


Figure 2.8: Process of the Batch Plant

Continuous plants produce asphalt in a continuous process. Figure 2.9 presents the process of a drum mixing plant, which is one special type of continuous plant. These plants differ from batch plants in that the aggregates are proportioned by accurately calibrated feeders that feed the desired aggregate grading into the dryer mixer drum, and hot bitumen is proportioned by a calibrated pump and delivered into the drum by a separate pipe. Thus, the aggregates are dried, heated and mixed with the bitumen binder in the drum dryer in one operation. The mixed materials are transferred to a hot surge or storage bin for subsequent loading into trucks. The operation is continuous, as opposed to batch, and is subsequently more suited to the continuous production of one type of mix.

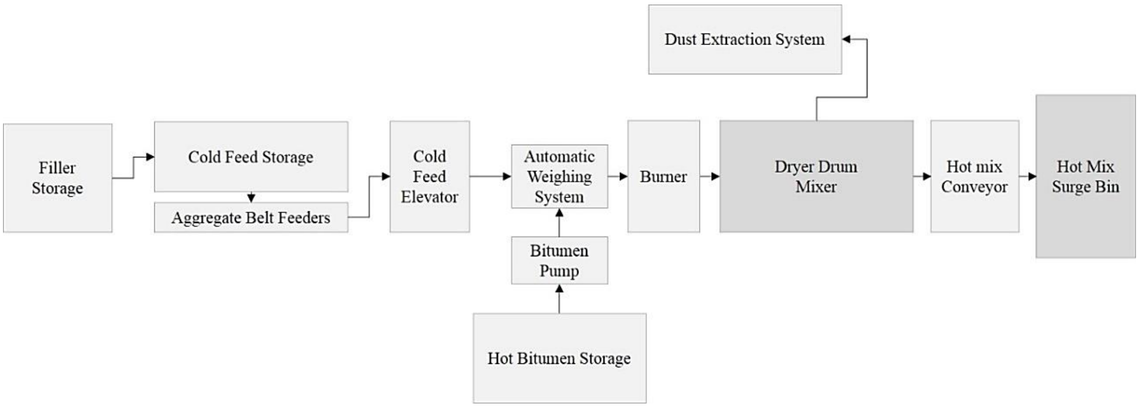


Figure 2.9: Process of Drum Mixing Plant

2.4.4 Plant Mix Work and Sprayed Work

As discussed in the previous section, road surfacing consists of sprayed seal, asphalt, slurry and concrete. However, a thin protective wearing surface is applied to a pavement or base course for maintenance purposes. This protective wearing is usually referred to as bituminous surfacing. It provides a waterproof layer to protect the underlying pavement and increase skid resistance, as a filler for existing cracks or ravelled surfaces, as an anti-glare surface during wet weather, and as an increased reflective surface for night driving (Highway Research Board 1970). Bituminous surfacing can be divided into two types: plant mix work and sprayed work. Figure 2.10 presents a comparison of the typical process of plant mix work and sprayed work.

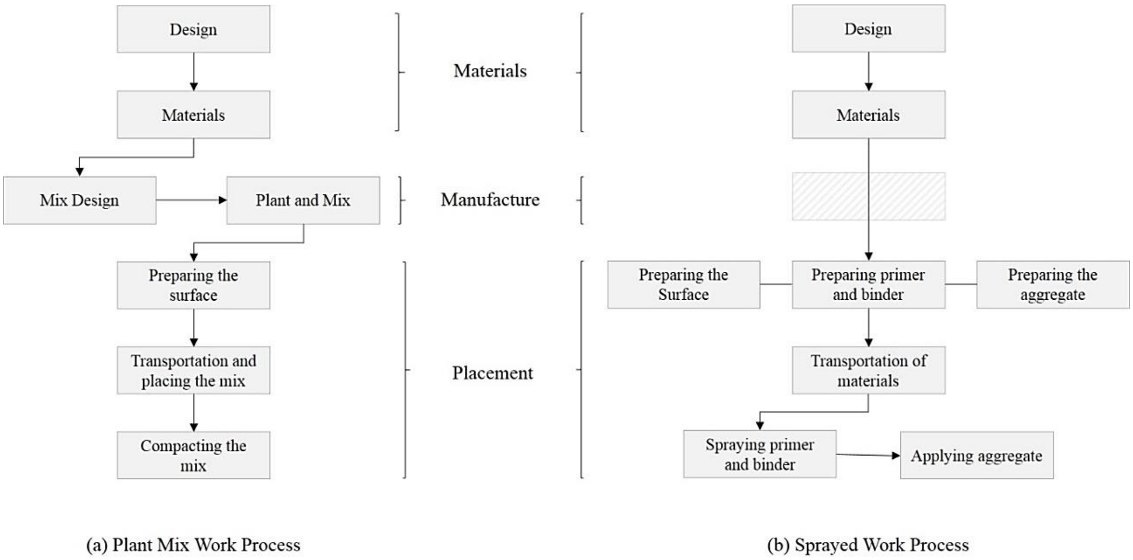


Figure 2.10: Typical Process of Plant Mix Work and Sprayed Work

Plant mix works typically use asphalt, which is a mixture of grade aggregates and bitumen binder. The actual composition varies according to the proposed use, and is based on a combination of different field tests (The Australian Asphalt Pavement Association 2018). The greatest difference between sprayed works is the asphalt manufacture. Asphalt is produced by drying and heating aggregates, and then mixing them with a bitumen binder in carefully controlled proportions and within a narrow temperature band that depends on mixing type, as explained in Section 2.4.3. Plant mix work involves the mixing, spreading and compacting of a blend of bituminous binder and aggregate. The mixed material, either open graded or dense graded, is usually prepared at a mixing plant, and then transported, spread mechanically on the road and compacted.

The sprayed seal may consist of a primer seal, a prime and seal, or a seal. A primer seal is a treatment in which the primer binder will hold small-sized aggregate and provide temporary protection to the surface. A prime and seal involves the application of a primer, followed by the application of a binder and cover aggregate. A seal involves the application of a binder and cover aggregate. The aggregate is spread uniformly upon the sprayed binder, and broomed and rolled until it forms a tight mat that completely covers the surface.

Slurry seal involves the application, by squeegee or spreading box, of a thin layer of a carefully proportioned mixture of bitumen emulsion, water and fine aggregate to an existing bituminous surface. An important factor to note is that slurry sealing mixing may be either a batch or continuous process.

2.4.4.1 Plant Mix Work

The plant mix is a mixture of aggregate and bituminous binder produced in a mixing plant for use in a road pavement. Plant mix may be used in the construction of a new pavement, to strengthen an existing pavement, to correct irregularities in the surface of an existing pavement, or to provide a new wearing surface. Plant mix usually entails a higher initial cost than sprayed work. However, because plant mix is suitably designed and laid on an adequate base, it can normally provide greater resistance to traffic stresses and enable a more regular running surface. It also has the advantage that traffic passing over newly laid work does not dislodge pieces of aggregate to the extent that may occur on sprayed work. Types of plant mix include dense graded (bituminous concrete), open graded (bituminous macadam) and intermediate between these two types. The dense grade and open grade can be a hot laid mix; however, a cold laid mix should only be open graded to promote curing of the binder (NAASRA 1968). Table 2.1 presents the critical processes and details of plant mix work.

Table 2.1: Plant Mix Work Process

Critical operations processes	Items	Specific details	
1. Materials	Material available	• Coarse aggregate • Filler • Fluxes and cutters • Task coat	• Fine aggregate • Binders (bitumen) • Adhesion agents
2. Mix design	Laboratory investigation	• Prepare trial mixes • Test density and voids	• Compact specimens • Compare desirable mix proportion
	Preparation of specimens	• Determine the grading and solid densities of the aggregates (including filler) • Combine a heated mixture of aggregates with bitumen	• Combine in proportions (maximum density grading) • Compact into a cylindrical specimen
	Calculation of void contents	• Air void content calculation ○ The measured bulk specific gravity of the compacted specimen ○ The maximum theoretical density calculated from the proportions and specific gravities of its components	• Compacted aggregates occupied by the bitumen void content calculation ○ The bulk specific gravity of the specimen ○ The maximum specific gravity of its aggregate components ○ The specific gravity of the bitumen
	Alternative methods of laboratory investigation	• The Marshall method • The Hubbard-Field method	• The Hveem method
	Compliance with design criteria and workability	• Determine the optimum bitumen content for a particular aggregate combination	• Qualitatively assess the workability of the mix during its handling and compacting
	Mechanical testing of specimens	• Mechanical test at 60ºC (140ºF) of compacted specimens	
3. Plant and mix	Mixing plants (batch and continuous flow mixers)	• Proportion cold aggregates • Screen aggregate into separate sizes • Add filler and binder in the required proportions • Discharge mix	• Heat and dry aggregates • Re-combine aggregates in required proportions • Mix materials intimately

	Mix production	• Temperature control • Cold aggregate feeding • Screening of hot aggregate • Aggregate proportioning • Binder feeding system • Pugmill operation • Plant control	• Aggregate supply and storage • Aggregate heating and drying • Hot aggregate storage • Binder storing, heating and circulating • Filler feeding • Sampling and testing • Permissible variations from the job mix
4. Preparing the surface	Traffic control	• Avoid inconvenience, delay or damage to property	• People controlling (STOP/SLOW)
	Preparing for new work	• Sweep off any loose stones, dust or dirt	• Remove adherent material to uncover the surface of the pavement
	Preparing for resurfacing	• Inspect the condition • Sweep and clean, and remove any shoulder material encroaching on the pavement	• Repair fatty areas, potholes and breaks along the edge of the existing surface
	Application of tack coat	• Tack coat by mechanical sprayer	• Paint with a thin, uniform tack coat of all contact surface of kerbside and structures, and all joints
5. Transporting and placing the mix	Transporting mixed materials	• Haulage trucks	• Limit loss of heat, segregation of the mix, and contact with any other material detrimental to the mix
	Spreading plant	• Self-propelled pavers or spreaders • Another spreading plant	• Drag spreaders
6. Compacting the mix	Compacting plant	• Self-propelled steel wheel rollers • Drawn rollers	• Self-propelled pneumatic tyred rollers
	Rolling	• Breakdown or initial rolling • Finishing rolling	• Secondary rolling

2.4.4.2 Sprayed Works

Sprayed work can be divided into priming, primer sealing, sealing, resealing, dust laying and surface enrichment. Priming is the application of a bituminous material of suitable viscosity to a prepared pavement as a preliminary treatment to the application of a seal coat. A primer sealing is an application of a suitable primer binder with fine aggregate cover intended to carry traffic for a longer period than a normal primer. Sealing is the application of a thin surface layer of the bituminous binder into which aggregate is incorporated. Resealing is the application of a seal to an existing sealed surface. Dust laying is the application to a dust road surface of a low-viscosity, slow-curing oil or bituminous material. Finally, surface enrichment is the correct application of bituminous material to an existing sealed surface to increase the binder content (NAASRA 1968). Table 2.2 presents the principles and practices of sprayed work. The main processes include surface preparation, asphalt material application, aggregate application and aggregate embedding. First, surface defects, such as potholes, are repaired and the existing surface is cleaned by a street sweeper. Second, the asphalt material is applied, in which an asphalt emulsion is typically applied from a spray truck to the surface of the existing pavement. Third, the aggregation is applied, which expands onto the asphalt material before the thin aggregate cover is set. Aggregates usually have a uniform gradation. Finally, rollers are used to push the aggregate into the asphalt material and secure it to the underlying pavement (Minnesota Handbook 2007).

Table 2.2: Surfacing Sprayed Work Process

Critical operation processes	Specific details		
1. Investigate the factors	• Existing surface conditions • Pavement strength • Shape • Surface drainage	• Alignment and grades • Road life • Availability of materials • Economy	• Traffic • Stage construction • Climate
2. Design	• Priming • Dust laying	• Primer sealing • Surface enrichment	• Sealing and resealing
3. Materials	• Aggregate • Tar • Precoating materials	• Bitumen • Bitumen emulsion • Rubber	• Flux and cutter • Adhesion agents
4. Adhesion of binder to aggregate	• Factors affecting adhesion	• Methods of promoting adhesion	• Adhesion test
5. Skid resistance	• Factors affecting skid resistance	• Measurement of skid	• Improving skid resistance
6. Preparing for work	• Typical bituminous surfacing unit • Fire precautions • Instructions	• Preliminary inspection • First aid	• Heating site • Aggregate stockpile site
7. Preparing the surface	• Pavement condition	• Sweeping	• Rotary road brooms
8. Preparing primer and binder	• Distribution • Preparing bitumen emulsion	• Storage and heating • Incorporating adhesion agent	• Fluxing and cutting back bitumen • Incorporating rubber
9. Preparing aggregate	• Supply and stockpiling	• Precoating	
10. Spraying primer and binder	• Bitumen sprayers • Sprayer personnel • Preparation for sprayer run	• Atmospheric conditions • Loading the sprayer • Sprayer run	• Setting out • Calculation of spraying rates • Hand spraying
11. Applying aggregate	• Loading and hauling • Rolling	• Spreaders • Drag brooming	• Spreading • Loose aggregates
12. Traffic control			

2.5 Assessment Methods

This research adopted three principal assessment methods which is distinct from approaching: lifecycle assessment (LCA), LCI and LCCA. Although all these assessment methods consider the lifecycle of the pavement, LCA and LCI should not be confused with LCCA. LCCA is a lifecycle approach that considers the direct monetary costs involved with a product, while LCA and LCI consider the environmental impact.

2.5.1 Lifecycle Assessment of Environmental Impacts

LCA is adapted to assess the environmental impacts of products from both the manufacturing and construction industries (Harris 1999). This includes estimation of the environmental impacts of raw material extraction and material production, processing, manufacturing, distribution, transportation, maintenance, disposal and recycling (International Organization for Standardization 1997). The International Organization for Standardization established four steps for conducting LCA study, as displayed in Figure 2.11.

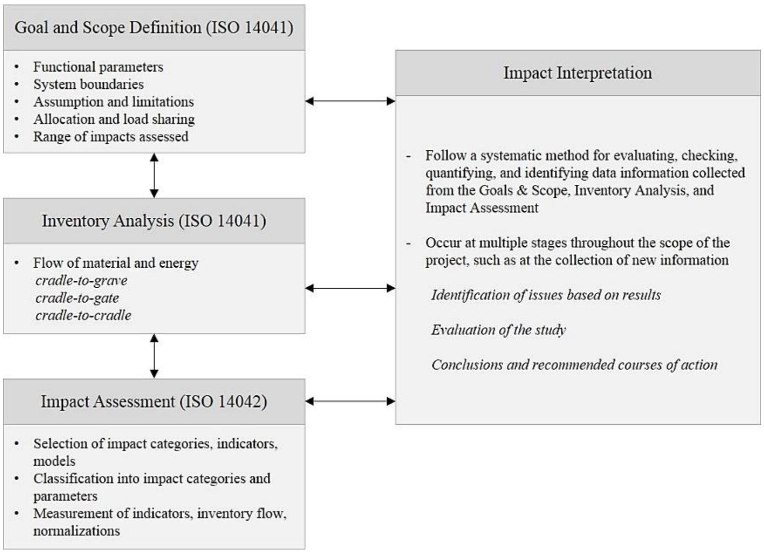


Figure 2.11: LCA Stages (Penn State 2017)

The first step is defining the goals and scope of the process. In all processes for LCA consideration, the goal is to quantify and characterise the flow of all materials involved in the process to help identify the environmental impact of the materials and determine alternative approaches to mitigate their effects. LCA has emerged as a widely executed process to reduce harmful environmental impacts, and offers many beneficial results.

Defining the goals of all processes is considered the most important step in initiating a LCA. The goal is to define the question to answer and then select the scope of the assessment. The scope includes defining how the entire process will be described and which alternatives should be defined. This step includes approaches to define system boundaries, assumptions and limitations.

The next step involved in defining goals and scope is inventory analysis, which refers to LCI. Inventory analysis is the inventory flow analysis of a product or process from the cradle to the final stage. This includes inputs such as water, soil, energy and raw materials. The inventory model consists of a flowchart containing the input and output data for the system under consideration, and the flow model is created using data from the technical system. These data are made up of raw materials that reach the end-of-life/recycling stage. Data are directly related to the goals defined in the LCA.

An LCA impact assessment constitutes the effects of an activity on the specific aspect of the environment, and the relative severity of changes in the environmental characteristics affected. An environmental impact assessment of a process can be performed using relationships between elements and the environment. The relationship between the environment and the elements that place stress on the system can be developed by combining LCA inventory results and their effects. This step assesses the effects of products and processes on the environment and human health. Assessment items may include global warming potential, acidification, eutrophication, baseline air pollutants, photochemical smog and so forth.

Thus, for a pavement, the LCA approach requires the input of materials from the LCI, including raw material acquisition, raw material production, mixed processes and transportations. Pavement design has a significant role in determining the materials used, the pavement structure, future preservation of the pavement, and maintenance and rehabilitation activities. The construction, preservation, maintenance and rehabilitation should consider the equipment transport; equipment usage at the site; material transportation to the site; transport of materials from the site for final disposal, reuse or recycling; and energy usage at the site.

2.5.2 Lifecycle Assessment Study Review

The previous studies conducted using LCA for pavements began with analysing the inventory data (Aurangzeb et al. 2014; Celauro et al. 2015; Chen et al. 2015; Qian et al. 2013; Reza et al. 2013; Zang et al. 2010). Butt et al. (2014) calculated the energy of bitumen material, while Araujo et al. (2014) and Yu et al. (2013) estimated the LCA effect of the materials. Wayman et al. (2012) conducted a cradle-to-grave study to determine the main impact on the process of pavement, while Tatari et al. (2012) studied resource consumption during the construction phase. Several studies analysed the influence on maintenance considering environmental impacts (Azarijafari et al. 2016; Gschosser and Wallbaum 2013; Wayman et al. 2012) and concluded that material production has the greatest effect on the lifecycle (Cass and Mukherjee 2011; Giani et al. 2015; Gschosser et al. 2014). Further studies estimated emissions (Barandica et al. 2013; Liu et al. 2014; Santero et al. 2011; Thiel and Len 2014); however, Noshadravan et al. (2013) and Swei et al. (2013) putted uncertainties to the case to overcome limitations of previous studies.

In contrast, Yu and Lu (2012) compared the LCA of concrete and asphalt pavement, while Anastasiou et al. (2015) conducted LCA on concrete pavement only. Most previous studies focused on the LCA of asphalt pavement (Celauro et al. 2015; Rodrigues et al. 2015; Santos et al. 2015; Turk et al. 2014; Vidal et al. 2013). However, several studies (Chen et al. 2015; Giustozzi et al. 2012; Liu et al. 2015) argued that LCA should be integrated with LCCA to attain accurate analysis results. In addition, several studies adopted LCA to assess social impacts throughout the pavement lifecycle (Gatti et al. 2012; Thorpe 2013; Zhao et al. 2012).

2.5.3 Lifecycle Cost Analysis of Social Impacts

LCCA is mostly used to convert the initial and future cost to the present or annual cost of direct construction cost, maintenance cost and social cost, such as user cost. LCCA is an analytic method to evaluate alternative decisions on long-term options. Previous studies conducted LCCA (Habbouche et al. 2016; Flannery et al. 2016; Ozbay et al. 2004; Rangaraju et al. 2008; Zimmerman et al. 2000) and proposed a LCCA model for pavement (Wilde et al. 1999). Meanwhile, studies assessing the social impact of pavements with LCCA seemed to focus on RUC. Flannery et al. (2016) and Ozbay et al. (2004) investigated the current situation of RUC implementation, while several studies examined the problem of implementing RUC into LCA (Habbouche et al. 2016; Flannery et al. 2016; Morgado and Neves 2014; Papagiannakis and Delwar 2001; Yu et al. 2010). However, further studies implemented LCCA into a decision-making model to provide a framework for economic evaluation (Lee et al. 2011; Yu et al. 2010; Zheng et al. 2010). Further explanation will be presented in Section 2.7 on social impacts.

2.6 Environmental Impacts of Road Maintenance

Global climate change is a significant impact factor for the transport sector to achieve sustainability. To assess the environmental sustainability of maintenance activities, the carbon dioxide (CO_2) emissions value is used as a proxy indicator. Thus, calculating the emissions produced by maintenance activities is important for transport authorities. In recent years, decision making in road maintenance has included considerations of environmental aspects when selecting alternative treatment methods or planning new road construction.

Climate scientists argue that a significant increase of CO_2 has occurred over the past century, with an average growth of 2 ppm/year (IEA 2017). The average concentration of CO_2 was 403 ppm in 2016, which was 40% higher than the level in the mid-1800s. According to World Energy Outlook (IEA 2017), in 2015, transport was the second-highest sector for total emissions, as displayed in Figure 2.12.

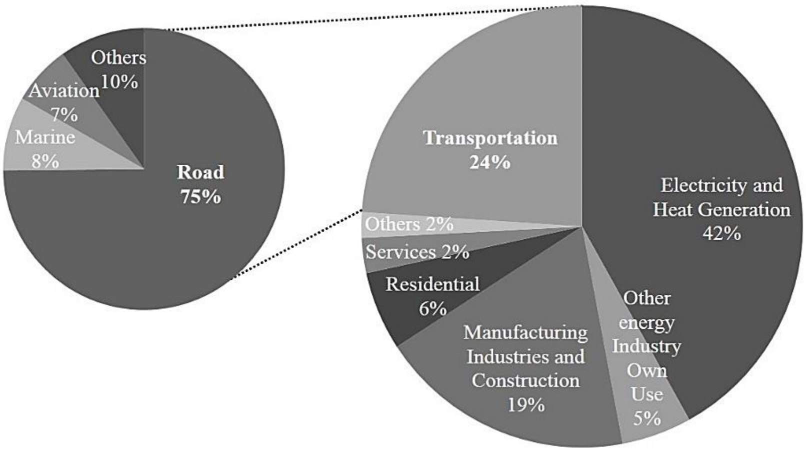


Figure 2.12: CO_2 Emissions by Sector in 2015 (Source: OECD/IEA 2017)

In the global transport sector, road transport accounts for about 75% of the sector's overall emissions, as a result of fuel combustion. Additionally, the 68% increase in emissions since 1990 was led by increasing emissions from the road sector, which accounted for three-quarters of transport emissions in 2015.

2.6.1 Environmental Requirement

According to the International Energy Agency (IEA) (2017), the road transport sector requires mitigation efforts in all countries, as with the energy sector (which accounts for around two-thirds of global GHG emissions) to decarbonise the energy supply of developed countries and move developing countries onto a low carbon development path. Figure 2.13 indicates a million tonnes of CO_2 emissions change in transport factors from 1990 to 2015. The road sector comprises the largest portion of this, and is increasing rapidly.

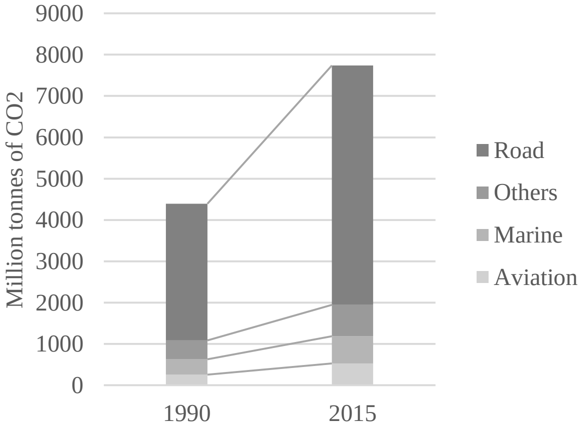


Figure 2.13: CO_2 Emissions from Transport, 1990 to 2015 (IEA 201)

Under the Kyoto Protocol, Australia is aiming to reduce its GHGs in 2020 by 5%, compared with the levels in 2000, as indicated in Table 2.3. In Australia in 2015, CO_2 emissions from fuel combustion comprised 380.9 million tonnes (Table 2.4), which is a 47% increase compared with 1990 (259.7 million tonnes of CO_2). Of this, the emissions from road transport comprised 79.7 million tonnes, representing 84.16% of the total emissions from the transport sector (94.7 million tonnes). This high percentage emphasises the importance of road transport achieving sustainability.

Table 2.3: Australia's 2020 GHG Reduction Target (Million Tonnes of CO_2)

1990	2005	2015	2020 GHG target	Base year level	2015 level	Change %
260	372	381	5% reduction relative to 2000	335 Mt	381Mt	+14%

Table 2.4: Australia's CO_2 Emissions by Sector in 2015

Sectors	Million tonnes of CO_2
Total CO_2 emissions from fuel combustion	380.9
Electricity and heat production	190.5
Other energy industry own use	32.7
Manufacturing industries and construction	41.9
Transport	94.7
Of which: road	79.7
Other sectors	21.1

The Kyoto Protocol (1997) indicated six significant sources of GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (SF_6). The calculation of a GHGs account (E_{GHG}) can be obtained through the use of activity data (*AD*) and emissions factor (*EF*), as shown in Equation (2.1):

$$E_{GHG} = AD \times EF \qquad \text{Equation 2.1}$$

Emissions factors for calculating direct emissions are generally expressed in the form of the quantity of GHGs emitted per unit of energy ($kgCO_2$-e/GJ), fuel (t CH_4/t coal) or a similar measure. While CO_2 is the GHG that has received the greatest concern, there are several other GHGs. Thus, conversion coefficients are used to convert the emissions of other GHGs into CO_2 equivalents (CO_2e). According to the Intergovernmental Panel on Climate Change (2006), global warming potential (GWP) is the integral of the global warming effect of GHGs compared with that of CO in the same time interval, commonly using a time horizon of 100 years. The 100-year GWPs of CO_2, CH_4 and N_2O are 1, 23, and 296, respectively. The definition of CO_2e is presented in Equation (2.2):

$$CO_2e = AD \times EF \times GWP \qquad \text{Equation 2.2}$$

The GHG emissions of road pavements are the sum of all relevant emission sources. Therefore, the final expression of the road pavement's carbon footprint can be obtained through Equation (2.3):

$$\sum_{i=1}^{n}(CO_2e)i = \sum_{i=1}^{n}(AD_i \times EF_i \times GWP_i) \qquad \text{Equation 2.3}$$

where $(CO_2e)_i$ refers to the GHG emissions from a source in road pavement treatment.

Most pavement construction activities are undertaken with heavy machinery and equipment. The GHG emissions of road pavements derive from the machines and equipment used in the placement process. They are calculated by multiplying the energy consumption data (*AD*) by the emissions factor (*EF*) of each energy type (fuel or electricity). This study adopted emissions factors for typical construction equipment and machinery in Australia from the National Greenhouse Accounts Factors (Australian National Greenhouse Accounts 2015). For example, Table 2.5 presents the indirect emissions factors for the consumption of purchased electricity.

Table 2.5: Indirect Emissions Factors for Consumption of Purchased Electricity in Australia

State or territory	Emissions factor (kg CO_2-e/kWh)
New South Wales and Australian Capital Territory	0.84
Victoria	1.13
Queensland	0.79
South Australia	0.56
South West Interconnected System in Western Australia	0.76
North Western Interconnected System in the Northern Territory	0.66
Darwin Katherine Interconnected System in the Northern Territory	0.57
Tasmania	0.12
Northern Territory	0.67

Although this study prefers Australia-specific emission data, international data were adopted when Australia-specific data were unavailable. The sources of emissions data included:

- National Greenhouse Accounts Factors (Australian Greenhouse Accounts 2015)
- *Greenhouse Gas Assessment Workbook for Road Projects* (Transport Authorities Greenhouse Group 2013)
- *Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation* (The World Bank 2010)

- *Life Cycle Assessment of Road—A Pilot Study for Inventory Analysis* (IVL Swedish Environmental Research Institute 2001)
- *Life Cycle Inventory: Bitumen* (Eurobitume 2012).

2.6.2 Treatment Process of Strategies

To assess environmental impact with LCA, the process of treatment strategies must be identified accurately. This research investigated eight surface treatment types that have been adopted in Western Australia. The names of these treatment strategies are slightly different from the terms used in other countries, depending on the specific methods and treatments. However, similar methods can be found in these treatment strategies. All surface treatments seal existing surfaces with asphalt. If more friction is necessary, an aggregate is applied on top of the pavement. The most common surface treatments are similar and tend to vary based on the type and amount of aggregate placed on top of the asphalt emulsion to seal the pavement. Surface pavements—such as asphalt concrete overlay, fog seal, seal coat, chip seal and slurry seal—help pavements last longer.

To calculate the activities following the LCA method, it is necessary to determine the material components and manufacturing process information for each pavement treatment. For most treatment activities, raw materials contain bitumen, crushed aggregate, gravel, sand, cement and water. Manufacturing of materials includes handling, drying, mixing and preparation of material for placement. Calculation of transportation to the construction site for placement is also required. Materials and equipment usage depends on treatment types and specific project requirements. In this study, a total of eight pavement treatment strategies adopted by Main Road WA were investigated, including:

1. ASDG: dense-graded asphalt overlay/replacement
2. ASIM: intersection mix asphalt overlay/replacement
3. ASOG: open-graded asphalt replacement
4. ASRS: structural asphalt work
5. GrOL: heavy rehabilitation—gravel overlay/stabilisation
6. RipSeal: light rehabilitation treatment for strong pavements
7. Slurry: rutting smoothing treatment with slurry
8. Chip Seal (CS): chip shape sprayed seal.

Figure 2.14 presents the details of the system boundary. The eight strategies extract appropriate activities for each process within the overall scope of road maintenance treatment.

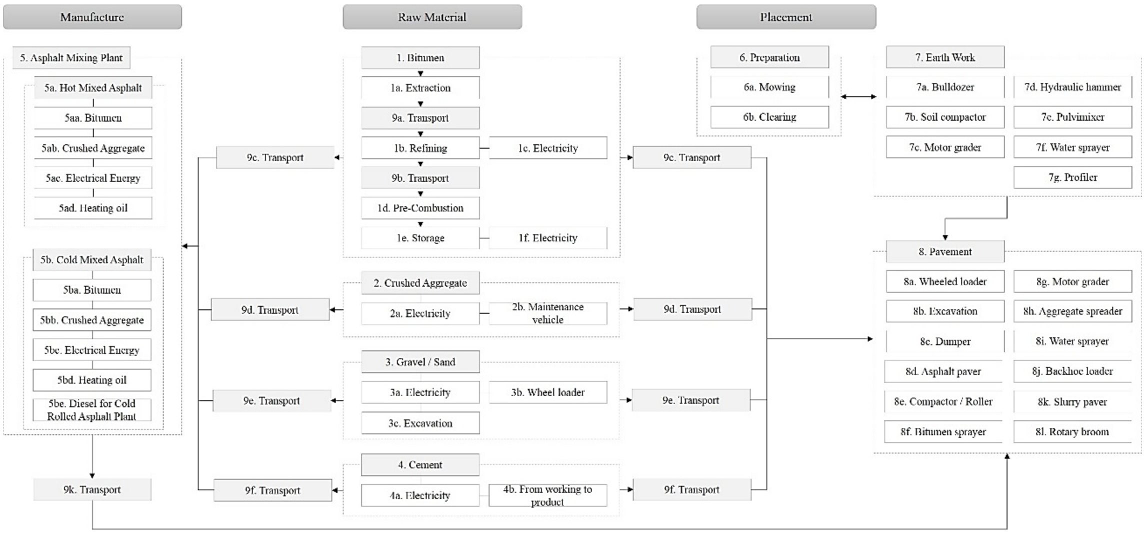


Figure 2.14: Evaluation of System Boundary and Critical Factors of Road Pavement

2.6.2.1 ASDG, ASIM and ASOG

ASDG, ASIM and ASOG are plant mix works related to asphalt replacement. The main activities of these three types of pavement treatment strategies include asphalt mixing, paving and compacting. Figure 2.15 displays the process of these three strategies. Specific details of equipment and assumptions are described in Chapter 5.

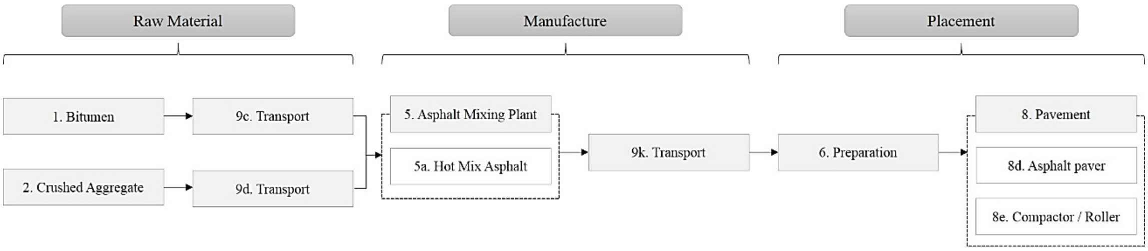


Figure 2.15: Process of ASDG, ASIM and ASOG

Asphalt concrete consists of mineral aggregate bound together with asphalt, laid in layers and compacted. The most common type used for roads is hot mix asphalt. Hot mix asphalt overlay is regarded by most road departments as a standard for road maintenance and restoration. This form of sealant is made from aggregate and asphalt cement. These types of surface treatment are used to enhance the functional conditions of pavement, with a thickness ranging from 0.75 to 1.5 inches (AASHTO 2003). Mixes are often combined with polymers to accommodate the need for higher performance.

2.6.2.2 ASRS

Structural asphalt work aims to increase the structural capacity of the pavement, as well as providing a surfacing with adequate properties. Figure 2.16 displays the process of ASRS.

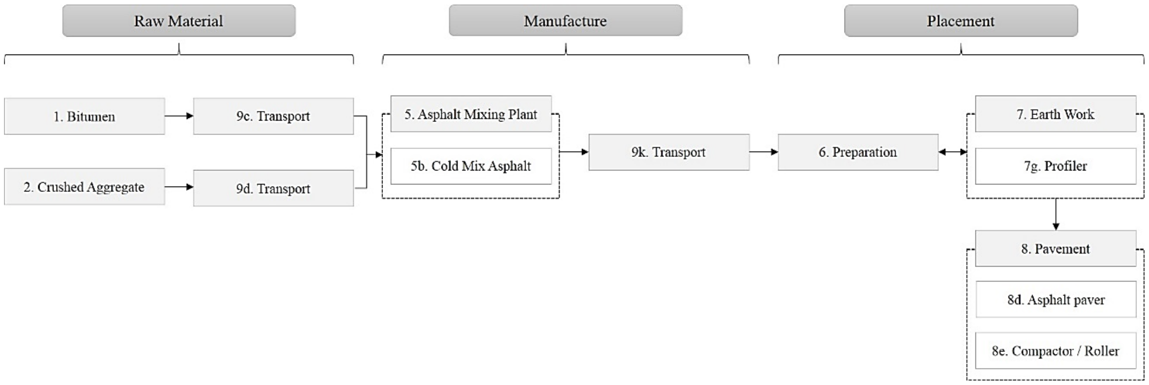


Figure 2.16: Process of ASRS

2.6.2.3 GrOL and RipSeal

GrOL is heavy rehabilitation, which includes gravel overlay and stabilisation. RipSeal is a treatment for strong pavement and is light rehabilitation that is mainly used for roughness reduction. It includes cement stabilisation, gravel placement and seal. The process is displayed in Figure 2.17.

A fog seal is a light application of a diluted slow-setting asphalt emulsion to the surface of an aged pavement surface. It is an inexpensive diluted asphalt emulsion that does not include a cover aggregate. It is used to seal and enhance surfaces, fix minor cracks, reduce risks for ravelling and deliver shoulder delineation. Fog seals are commonly used on high-volume roads, as well as low-traffic roads. The frequency of the application depends on the original thickness of the existing asphalt mixture.

A seal coat includes a coat of asphalt followed by an aggregate cover. Seal coats are used to waterproof surfaces, seal minor cracks and rehabilitate surface friction. Pavement may be sealed with this type of treatment at any time of its life; however, this method is especially beneficial for dry and ravelled pavements. Even if roads are in good condition, this is a great way to revitalise and reduce the need for maintenance. No vehicles can drive over roadways until the rolling is completed and bituminous materials are set; otherwise, materials will transfer to tyres. The detailed process of these two treatment strategies is displayed in Figure 2.17.

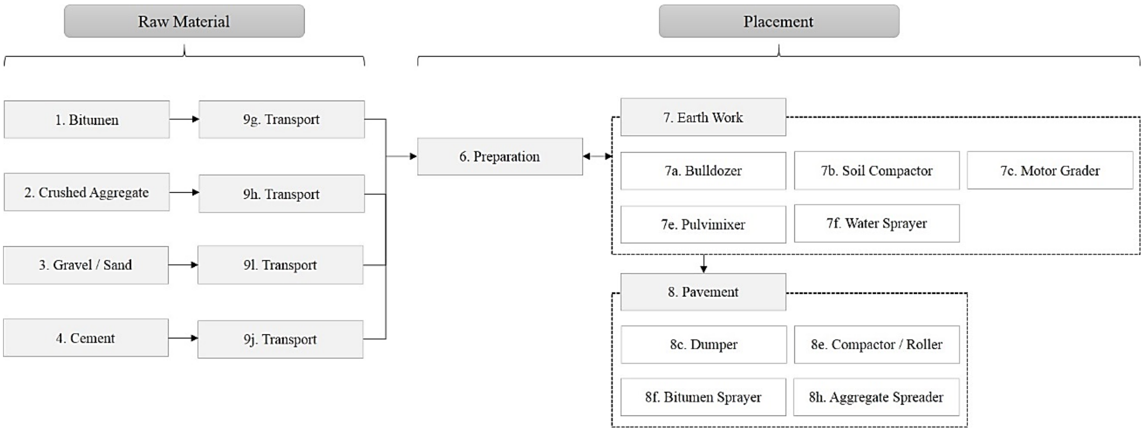


Figure 2.17: Process of GrOL and RipSeal

2.6.2.4 Slurry

Slurry refers to slurry/micro-surfacing. Bitumen, crushed aggregate and water are mixed in a mixer, and the spreader is attached to the surface of the slurry mixing unit. The process of the slurry seal is displayed in Figure 2.18. A slurry seal is the application of a mixture of water, asphalt emulsion, aggregate and additive to an existing asphalt pavement surface. It differs from fog seal because slurry seal has aggregates as part of the mixture. This type of sealant is commonly used to seal pavement, reduce surface ravelling, seal minor cracks and enhance surface friction.

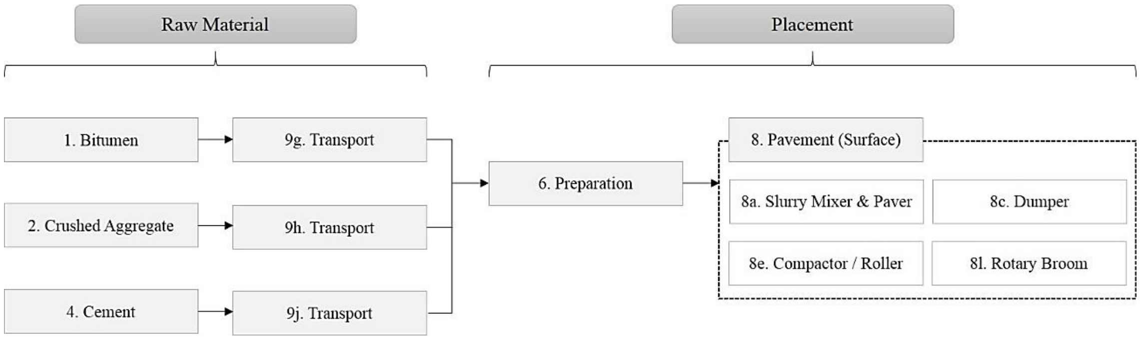


Figure 2.18: Process of Slurry

2.6.2.5 Chip Seal

CS refers to surface dressing. The asphalt emulsion is spread over the surface, and then aggregate is laid. Figure 2.19 displays the process of CSs. A CS refers to liquid asphalt being sprayed onto the pavement, followed immediately by spreading a thin layer of uniformly sized aggregate chips. It is similar to a seal coat, yet includes two single seal coats, instead of one. The second coat is applied directly following the first coat, which includes 60% of the total asphalt binder with large aggregate. The second coat includes 40% of the total asphalt binder with aggregates half as large as the first layer. This type of sealant is applied to older asphalt. CSs are relatively inexpensive, compared with conventional hot mix asphalt overlays, and CS involves a fast and easy process.

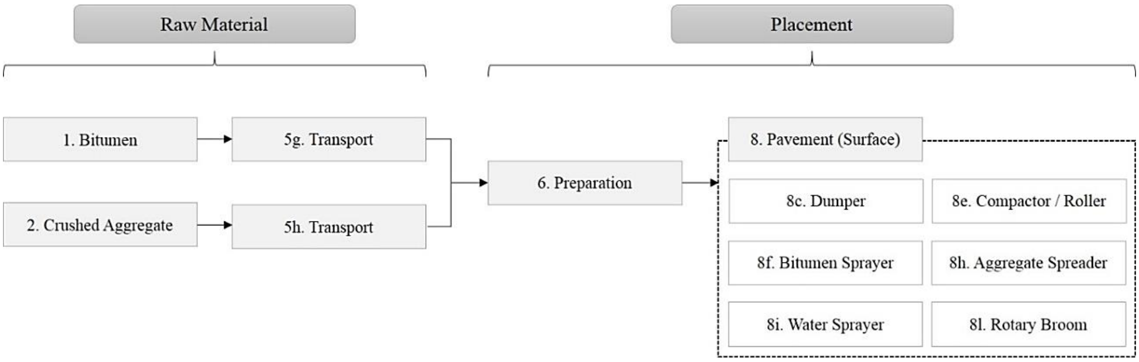


Figure 2.19: Process of CS

There are other types of road pavement treatment, such as micro-surfacing, cold-in-place recycling, bonded wearing course and full-depth reclamation. However, these treatment methods are not included in this study because they are not adopted in Western Australia.

2.7 Social Effects of Road Maintenance

Recently, some research has applied the LCC model for road infrastructure with a focus on delivering the most cost-effective strategies for planning, designing and maintaining road projects. LCCA converts the initial construction and future costs to present costs or average annual costs, including the various construction, maintenance and social costs (such as user costs). The calculated results of transferred costs can be used for different strategies. However, some cost factors have not been considered, while other cost factors are either overestimated or underestimated, especially in the road maintenance stage. The results presented in Chapter 4 of this thesis indicate that Australian road agencies do not currently consider RUC in the evaluation of road design, maintenance or rehabilitation.

Therefore, the estimation of road lifecycle cost does not include important aspects. This situation exists because agencies have very limited resources, and maintenance decisions are often political decisions that are not easy to accept for the community. Thus, it is necessary to convince decision makers that the cost of the user should be considered when making major decisions. However, RUC is always very uncertain, is difficult to quantify, and requires much research work, as it depends on numerous factors with considerable variations. It is difficult to support because of the wide range of data requirements, and road expenditures must consider total lifecycle agency adding unit costs (Sparks 1991; Watanatada 1987; Winfrey 1969).

Currently, there are many methods used by different international agencies to estimate and calculate user costs. Numerous studies have been undertaken by academics and commercial researchers to establish improved models. Through these investigations, this study identified a variety of models established and studied internationally. Several represented methods are the World Bank's Highway Development and Management (HDM), Australia's NIMPAC VOC module (2002), the Texas Research and Development Foundation's (TRDF's) model, the Micro BENCOST module, the British COBA module, the Swedish VETO, the ARFCOM model and New Zealand's NZVOC.

2.7.1 Previous Studies

Although several studies included insufficient consideration of maintenance aspects (Mattingly et al. 2002; Thorsman and Magnusson 2004; Wolford et al. 1997) and LCCA (Adams and Kang 2004; Bajaj et al. 2002; Gransberg et al. 2004; Stenbeck 2004), a few studies have considered both road authorities' costs and socioeconomic costs. Agencies can use RUC to compare the economic benefits of future projects over a lifecycle, based partly on the user cost. These methods include CBA or LCCA, which include the construction and maintenance costs through the life of the project. Kim et al. (2015) developed the LCCA procedure to automate cost calculation, while Kendall et al. (2008) integrated the LCA and LCC model. During new construction or maintenance activities, RUCs are used to refine the preferred design alternatives and estimate the additional costs from work zone activities. However, few agencies have integrated social impacts into maintenance decisions because these costs are insignificant compared with other cost components, and are difficult to quantify. Studies related to quantification include the work by Sadasivam et al. (2015), who calculated incentive through RUC; Zang et al.

(2012), who optimised road maintenance; Zhu et al. (2009), who developed a procedure for RUC calculation; and Palle (2009), who studied LCCB analysis from a user's perspective. Additionally, Hartmann et al. (2013) investigated satisfaction in road maintenance, while Zhang et al. (2010) studied pavement system impact.

Road authorities seldom consider social costs, such as RUC and environmental costs, during road planning, design, construction, maintenance and rehabilitation. Studies of the lifecycle cost model—including investment, maintenance and user costs—indicate (Holmvik and Wallin 2007; Huvstig 1998) that none of the available models can be used as a standard model without considerable improvements, as they are developed for specific road projects. The absence of reliable lifecycle cost methods derives from the lack of accurate road deterioration models or models to calculate social costs (Hawzheen 2011; Huvstig 2004). Therefore, several case studies of network calculation of social costs and RUC have been undertaken (Jing et al. 2016; Santos et al. 2011; Velmurugan et al. 2009), and calculation methods and parameters have been reviewed (Abelson 1973; Berthlot et al. 1996; Naude et al. 2015; Santos et al. 2014; Watts et al. 2012). Additionally, Morgado et al. (2014) integrated user cost into a computer model to calculate the cost.

The successful implementation of road maintenance strategies will need to be underlined by the retention and ongoing development of key skills and expertise in many areas. Several studies have been conducted in terms of these strategies in different areas. For example, Arviddson (2017) studied winter maintenance strategies, Khan et al. (2016) studied pre-flood and post-flood road maintenance strategies (2015), and Binu et al. (2014) optimised maintenance strategies and conducted a case study. Likewise, Haapasalo et al. (2015) investigated contract types for road maintenance, Kalb (2014) determined cost efficiency, Partha et al. (2012) optimised a tool for a healthy road network, and Meneses et al. (2012) adopted a multi-objective decision-aid tool.

2.7.2 Road User Cost Components

Three fundamental components of RUC are VOC, VOT and AC, as well as additional parameters (such as comfort and convenience cost, and environmental impact cost). RUC calculation can consist of monetary and non-monetary effects (Mallela and Sadasivam 2011). Monetary effects include VOCs, VOT, AC and emissions cost. Non-monetary effects encompass negative influences on the environment and ecology or local businesses caused by construction activities. Figure 2.20 displays the components of RUCs and the main factors that contribute to them.

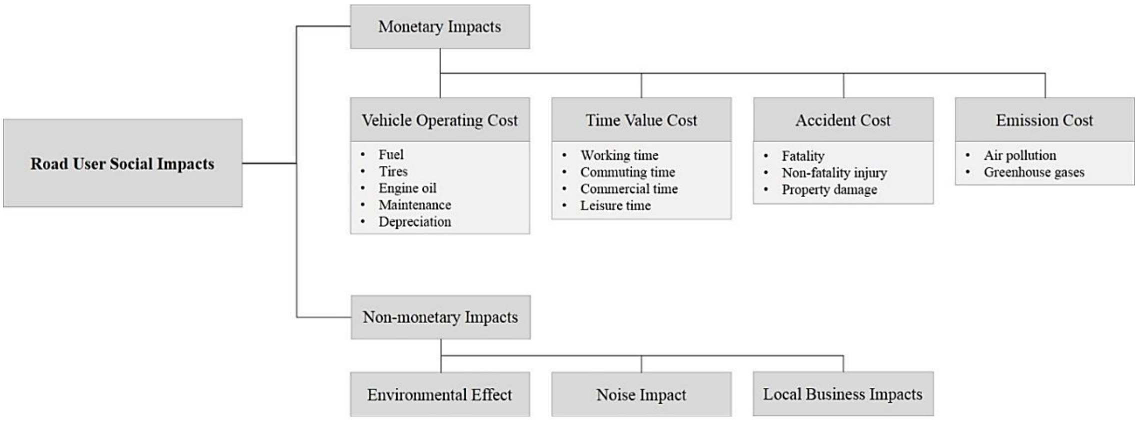


Figure 2.20: Road User Effects

Previous studies and manuals from agencies defined VOC components as consisting of fuel consumption, repairs and maintenance, tyre use, lubricating oil and vehicle depreciation (BTCE, AASHTO, FHWA and ATAP). VOC is a major component of RUC and can be categorised by variables and fixed costs (Velmurugan et al. 2009). VOC is a composite of the costs associated with operating and owning a vehicle over the project analysis (such as fuel, oil, tyre wear, vehicle maintenance and repairs, ownership cost, insurance, license and registration fees, taxes, economic depreciation and finance charges). VOCs can increase because of speed changes around work zones (causing excess fuel use, oil use, tyre wear and vehicle maintenance because of deceleration when entering work zones and acceleration when exiting) and vehicles travelling further because of detours or alternative routes. In addition, several issues can be caused by project construction factors, such as a change in fuel costs because of the speed change with and without, or before and after a project (lower speed during a work zone or higher speed after an improvement project), extra distance because of a detour route (if there is one) and additional operating costs because of vehicle deceleration when entering a work zone and acceleration when exiting (Xiao et al. 2013).

The calculation of travel time delay cost should include the travel delay time, unit cost data for each mode of transportation, number and type of vehicles per hour using the work area and vehicle occupancy rates. Moreover, it may include elements to discount personal travel time and the time depreciation of related vehicles (Xiao et al. 2013).

To calculate the VOT, delays related to the length of a detour or choices of alternative routes are a basic situation and concept to understand. Therefore, this study examined three different situations with the same route distance and different route distance, considering speed changes based on the route detour, road speed reduction and alternate route caused by construction conditions.

2.7.3 Road User Cost Calculation

There are programs with various algorithms to calculate the user cost. Queue and User Cost Evaluation of Work Zones (QUEWZ) is a program to calculate highway work zone capacity using a linear model. MicroBENCOST also evaluates the effect on capacity caused by lane closures and delays from work zones during construction works. QuickZone is network-based model that estimates user delays and traffic effects with hourly traffic flow information. Jiang and Adeli (2004) developed IntelliZone software, which is a work zone capacity estimator based on pattern recognition and a neural network model. It has 17 variables as input information, and compares 20 different scenarios to analyse the results. Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) is a strategy method to plan and design the work schedule and estimate delays and the cost of the project.

Most of the previous studies in the US followed the American Association of State Highway and Transportation Officials' (AASHTO's) *The Red Book*, McFarland's benefits analysis, Winfrey's economic analysis and the TRDF study. One of the represented manuals is the Texas Department of Transport methodology used for contract purposes, which was the first incentive-based system for road construction. Another method is the New Jersey Department of Transportation's (2001) *Road User Cost Manual*. This manual divides 10 potential work zones to calculate user costs, yet only considers reduced speed delay, queue delay, queue idling VOC, detour delay and circuitry VOC. Moreover, it has the limitation that the estimated methodologies of these five components are only based on a spreadsheet. Sam Salem (Ohio DOT 2008) improved models for user cost analysis by selecting delay factors, and then conducting a survey to identify the role of RUC in the pavement type selection process.

In Australia, the Transport and Infrastructure Council (2016) published the ATAP Guidelines, which provide parameter values for a full range of road user effect components. VOC unit processes are provided for fuel, oil, tyres, repairs and maintenance, and depreciation. The guidelines consist of applicable coefficients and appropriate vehicle classification, based on the relation to Australasian conditions of transferrable mechanistic-empirical model adoption and calibration. VOCs and fuel consumption are categorised based on uninterrupted flow (e.g., rural areas) and interrupted flow (e.g., urban areas) models, and travel time values are provided for vehicle occupants and freight. Vehicle classifications appropriate to Australia have been reviewed, and a 20-vehicle classification was selected for both unit values and VOC modelling throughout the documents. The classification's relationship with the Austroads 12-vehicle classification is also explained. Additionally, average crash costs by injury severity across jurisdictions are provided (ATAP 2016).

Thoresen and Ronald (2002) upgraded the 20-vehicle classification used in HDM into the Austroads 12-vehicle classification. The Austroads 12-vehicle classification was developed in 1994, with the most recent description of vehicles in terms of mass and length appearing in Austroads (2013), which also contains references to other vehicle classifications used by the Australian Bureau of Statistics and by state and territory road agencies.

This research adopted the ATAP parameter value used in HDM-4 in Australia. Designations based on axle numbers have also been used, while selected vehicle types (eight-vehicle classification) have been used in NIMPAC models (Austroads 2005). Table 2.6 presents the vehicle classification in Australia.

Table 2.6: Vehicle Class Types in Australia

Vehicle class	Vehicle name	Vehicle category
1	01. Small car	Small car
	02. Medium car	Medium car
	03. Large car	Large car
	04. Courier van utility	Light commercial (2 axle, 4 tyre)
	05. 4WD mid-size petrol	4WD mid-size SUV, petrol
3	06. Light rigid	Light truck (2 axle, 6 tyre), petrol
		Light truck (2 axle, 6 tyre), diesel
	07. Medium rigid	Medium truck (2 axle, 6 tyre)
		Small bus
		Route bus (including school bus)
4	09. Heavy bus	Large bus (coach)
	08. Heavy rigid	Large truck (3 axle)
6		Articulated truck (3 axle)
7	10. Artic 4 axle	Articulated truck (4 axle)
8	11. Artic 5 axle	Articulated truck (5 axle)
9	12. Artic 6 axle	Articulated truck (6 axle)
10	13. Rigid + 5 axle dog	Large truck (rigid 3 axle) + 5 axle dog trailer
	14. B-double	B-double (tri-tandem)
		B-double (tri-tri)
		Twin steer truck + 4 axle dog trailer
	15. Twin steer + 5 axle dog	Twin steer truck + 5 axle dog trailer
11	16. A-double	Road train (double)
	17. B-triple	B-triple
	18. A–B combination	A–B combination
12	19. A-triple	Road train (triple)
	20. Double B-double	Double B-double

Source: Austroads Vehicle Classification Scheme (1990, 1994, 2002, 2013), ARRB Report RC2062 (2002) and Austroads Report AP-R264-05 (2005).

2.7.4 Road User Cost Parameter

This research adopted parameter values provided by the Transport and Infrastructure Council (2016). The ATAP Guidelines provide updated parameter values for the full range of road user effects. They consider direct road user effect components (such as fuel, oil, tyres, repairs and maintenance, and depreciation) and travel time components (such as vehicle occupants and freight per vehicle type). VOC models are categorised with state of a rural area, which indicates a free and uninterrupted flow speed, and urban models, which indicates interrupted flow speed. Vehicle classification appropriate to Australia has been adopted, including a 20-vehicle classification to apply parameter values. Therefore, 12 classifications outlined in MRWA were undertaken, as they are broadly consistent with the vehicle classification and provide a sufficiently broad range of vehicle types from which agencies can select the vehicle most appropriate to their local vehicle fleets. The overall equation for calculating RUC is:

$$RUC = VOT + VOC + AC$$

where RUC is the road user cost, VOT is the value of time, VOC is the vehicle operating cost and AC is the accident cost. However, as mentioned in Section 1.4 on the scope of this study, this research sought to limit the boundaries to VOT and VOC because of the difficulty in generalising specific accident cases. The details of the calculation method will be presented in the following Chapter 3.

2.7.4.1 Vehicle Operating Cost Components

VOCs consist of fuel, oil, tyres, repairs and maintenance, and estimation of new vehicle depreciation. Fuel price data were collected from all over Australia, based on the type of petrol (unleaded and premium), diesel, liquid petroleum gas (LPG) and ethanol fuels. Table 2.7 presents an example of the weighted average fuel price (cents per litre) based on each Australian state or territory’s capital city as of 30 June 2013.

Table 2.7: Fuel Cost in Australia

Capital city	**Fuel type (cents/litre)**			
	Petrol (weighted average by volume)	**Diesel**	**Liquid petroleum gas**	**Ethanol**
Sydney	96.5	96.0	46.3	117.9
Melbourne	94.5	93.3	40.1	113.8
Brisbane	99.4	96.9	46.3	121.7
Adelaide	94.5	96.2	49.3	–
Perth	97.0	96.1	50.5	–
Hobart	101.4	100.5	68.3	–
Darwin	109.5	108.7	83.8	–
Average (weighted)	96.7	95.7	45.5	118.3

Source: Commonwealth Department of Infrastructure and Regional Development (Fueltrac).

The oil was investigated through the retail outlets for volumes of petrol engines to large containers of diesel engine oil for road freight transport. For instance, in June 2013, the petrol market price was AUD$7.66 per litre and the resource price was AUD$6.96 per litre. Likewise, the diesel market price was AUD$4.64 per litre and the resource price was AUD$4.22 per litre.

Information on tyres, repair and maintenance, and vehicle prices was adopted from ARRB Group Ltd. The tyre data collection was undertaken through a sample of retail outlets and companies. Data are presented for market prices and resource prices per vehicle type. For passenger cars and light vehicles, the repairs and maintenance costs used in previous Austroads (2012) unit values were updated using an average of the Consumer Price Index for vehicle maintenance and repairs and the Consumer Price Index for motor vehicle spares. For a heavy vehicle, repair and maintenance costs were updated using an average of the Producer Price Index (PPI) for road freight and the PPI for auto parts. The estimates were based on a percentage of new vehicle prices, which included estimated time costs for labour, were adopted from HDM-4 models. Additionally, vehicle repair and maintenance costs were based on RACV (2013) data to compare vehicles. The average new vehicle prices for vehicle types were also adopted from ARRB Group Ltd, based on automotive data services, truck sales, freight metrics and so forth. Table 2.8 displays the parameters values of VOC components for 20 vehicle types.

Table 2.8: VOC Component Price

Vehicle type	Tyre prices per vehicle type			Repair and maintenance costs (cents/km)		Vehicle price ($/vehicle)	
	Number of tyres per set	Market price ($/tyre)	Resource price ($/set of new tyres)	PPI	% new vehicle price	Market price	Resource price
Cars							
01. Small car	4	98	356	6.1	7.1	18,770	15,855
02. Medium car	4	128	464	7.1	8.1	29,070	24,645
03. Large car	4	167	604	5.7	9.3	41,467	35,204
Utility vehicles							
04. Courier van—utility	4	171	620	6.7	6.7	34,203	28,919
05. 4WD mid-size, petrol	4	306	1,112	8.2	8.2	57,280	48,357
Rigid trucks							
06. Light rigid	4	247	897	6.1	7.5	56,511	47,913
07. Medium rigid	6	507	2,764	13.1	10.7	139,521	117,726
08. Heavy rigid	10	728	6,618	14.0	16.8	225,004	187,756
Buses							
09. Heavy bus	8	493	3,584	13.1	13.1	322,571	275,000
Articulated							
10. Artic 4 axle	14	676	8,600	19.1	18.9	305,732	255,450
11. Artic 5 axle	18	690	11,291	22.2	19.5	341,347	283,509
12. Artic 6 axle	22	686	13,720	22.8	18.0	373,497	308,840
Combination vehicles							
13. Rigid + 5 axle dog	30	660	18,000	25.2	22.7	340,037	275,668

14. B-double	34	653	20,196	26.5	27.6	436,881	357,110
15. Twin steer + 5 axle dog	32	690	20,064	27.2	30.5	410,015	334,040
16. A-double	42	682	26,796	28.3	37.7	552,824	451,399
17. B-triple	46	689	28,796	35.3	47.1	707,382	582,125
18. A–B combination	54	653	32,076	34.7	45.3	611,048	495,647
19. A-triple	62	688	38,750	36.3	46.2	707,011	571,850
20. Double B-double	66	688	41,250	39.2	47.7	690,398	555,003

Source: PV2 Road Parameter Values (ATAP 2016) and ARRB Group Ltd (2013).

The International Roughness Index (IRI) is used by highway professionals around the world as a standard to quantify road surface roughness. The continuous profile along the road is measured and analysed to summarise the qualities of pavement surface deviations that affect vehicle suspension movement. The IRI is useful for assessing overall pavement ride quality, whereby a higher IRI value indicates a rougher road surface (Michigan Department of Transportation 2017). For MRWA, roughness is a pavement condition parameter that characterises deviations in a road surface from the intended longitudinal profile. Roughness is used to rate the road condition because of its effect on vehicle dynamics, and subsequently on VOCs, driver comfort and dynamic pavement loading. Table 2.9 presents the acceptable maximum roughness values for various MRWA link categories and treatment strategies.

Table 2.9: Minimum Requirement of Roughness

Road type	Roughness	Treatment	Roughness
Freeway (MFF) and MI (heavy traffic roads, metro)	Less than 3.44	ASDG, ASOG, ASIM	Minimum 2.88
AW and AW+ (high standard single carriageway)	Less than 3.82	ASRS	Minimum 2.69
BW and BW+ (medium standard single carriageway)	Less than 4.20	GrOL	Minimum 2.50
CW (basic standard single carriageway)	Less than 5.33	RipSeal	Minimum 2.69
DW (basic standard single carriageway)	Less than 5.33	Slurry	Pre-value * 0.8

The gross vehicle mass (GVM) or gross vehicle weight rating (GVWR) is the maximum operating weight and mass of a vehicle as specified by the manufacturer, including the vehicle’s chassis, body, engine, engine fluids, fuel, accessories, driver, passengers and cargo, yet excluding any trailers (National Highway Traffic Safety Administration 2004). Gross combined weight rating (GCWR) refers to the total mass of a vehicle, including all trailers. GVWR and GCWR both describe a vehicle that is in operation and are used to specify weight limitations and restrictions. MRWA produced guideline mass limit of axle group as single steer 6 tonnes, twin steer 1 tonne, single 9 tonnes, tandem 16.5 tonnes, and triaxle as 20 tonnes. Table 2.10 presents the mass limits of 15 vehicle types.

Table 2.10: GVM in Western Australia

Type	**Configuration**	**Length (m)**	**Mass (tonne)**	**Sample image**	**Type**	**Configuration**	**Length (m)**	**Mass (tonne)**	**Sample image**
2 axle rigid truck	R1-1	12.5	15		6 axle articulated vehicle	A1-2-3	19	42.5	
3 axle rigid truck	R1-2	12.5	22.5		Rigid truck and 4 axle dog trailer	R1-2, T2-2	19	55.5	
4 axle rigid truck	R2-2	12.5	27.5		Rigid truck and 5 axle dog trailer	R1-2, T2-3	25	59	
5 axle articulated vehicle	A1-2-2	19	39		Rigid truck and 5 axle dog trailer	R2-2, T2-3	25	64	
B-double	A1-2-3-3	27.5	62.5		B-double and dog trailer	A1-2-3-3, T2-3	36.5	99	
Double road train	A1-2-3, T2-3	36.5	79		B-triple	A1-2-3-3-3	36.5	82.5	
Double road train	A1-2-2, T2-2	27.5	72		Rigid truck and two dog trailers	R2-2, T2-3, T2-3	36.5	100.5	

Triple road train	A1-2-3, T3-3, T3-3	53.5	122.5	

Source: MRWA (2012).

2.7.4.2 Value of Time Components

Value of travel time can be categorised as: (1) vehicle occupants, (2) travel time for freight and (3) value of travel time for vehicle occupants and freight. The value of travel time for occupants for passenger cars was updated using the average weekly earnings, based on the Australian Bureau of Statistics. The average weekly earnings for full-time workers were calculated by 38 hours per week. The value of travel time for bus drivers was estimated at that of a five-axle articulated vehicle, and for bus passengers as the value of travel time for private passenger car trips (ATAP); however, this research did not consider bus passenger occupancy in average annual daily traffic (AADT) because of lack of information. The value of travel time for the occupants of the commercial vehicle was adopted based on hourly wage rates from the Road Transport and Distribution Award (2013). The weekly wage rates for each transport worker grade were based on the Australian Industrial Relation Commission (2013), as displayed in Table 2.11.

Table 2.11: Wage Rates of Australian Transport Workers by Grade

Transport worker grade	**Minimum weekly wage rate ($)**
Grade 2	676
Grade 3	684
Grade 4	697
Grade 5	705
Grade 6	713
Grade 7	724
Grade 8	745
Grade 9	757
Grade 10	776

Source: Australian Industrial Relations Commission (2013).

The state payroll taxes were calculated from the Australian Bureau of Statistics (2013) and the car occupancy was adopted from Austroads (2013). Table 2.12 presents the results of this investigation.

Table 2.12: Payroll Tax and Car Occupancy in Australia

State	Payroll tax rates (%)	Car occupancy (Austroads 2012)			
		AM peak	PM peak	Off-peak	All day
New South Wales	5.5	1.21	1.25	1.32	1.26
Queensland	4.8	–	1.24	1.24	1.21
Victoria	4.9	1.12	1.22	1.24	1.21
South Australia	5.0	1.0	1.25	1.28	1.26
Western Australia	5.5	–	–	–	–
Australian Capital Territory	6.9	–	–	–	–
Northern Territory	5.5	–	–	–	–
Tasmania	6.1	–	–	–	–

Source: State Revenue Offices, Austroads (2013).

Table 2.13 displays the estimated values of travel time (resource costs) for occupants and freight payload values.

Table 2.13: Occupant and Freight Values

Vehicle type	**Non-urban**			**Urban**		
	Occupancy rate (person/vehicle)	**Value per occupant ($/person-hour)**	**Freight travel time ($ values/vehicle hour)**	**Occupancy rate (person/vehicle)**	**Value per occupant ($/person-hour)**	**Freight travel time ($ values/vehicle hour)**
Cars						
Private	1.7	14.99	–	1.6	14.99	–
Business	1.3	48.63	–	1.4	48.63	–
Utility vehicles						
04. Courier van utility	1.0	25.41	–	1.0	25.41	–
05. 4WD mid-size, petrol	1.5	25.41	–	1.5	25.41	–
Rigid trucks						
06. Light rigid	1.3	25.41	0.78	1.3	25.41	1.53
07. Medium rigid	1.2	25.72	2.11	1.3	25.72	4.15
08. Heavy rigid	1.0	26.19	7.22	1.0	26.19	14.20
Buses 25.72						
09. Heavy bus (driver)	1.0	25.72	0	1.0	25.72	–
09. Heavy bus (passenger)	20.0	14.99	0	20.0	14.99	–
Articulated 1.0						
10. Artic 4 axle	1.0	26.81	15.53	1.0	26.81	30.59
11. Artic 5 axle	1.0	26.81	19.80	1.0	26.81	39.01
12. Artic 6 axle	1.0	26.81	21.36	1.0	26.81	42.06

Combination vehicles						
13. Rigid + 5 axle dog	1.0	27.20	30.53	1.0	27.20	62.99
14. B-double	1.0	27.20	31.46	1.0	27.20	64.91
15. Twin steer + 5 axle dog	1.0	27.20	29.50	1.0	27.98	60.89
16. A-double	1.0	27.98	41.31	1.0	27.98	85.25
17. B-triple	1.0	27.98	42.17	1.0	27.98	87.01
18. A–B combination	1.0	27.98	50.79	1.0	27.98	104.80
19. A-triple	1.0	28.45	60.89	1.0	28.45	125.64
20. Double B-double	1.0	28.45	61.59	1.0	28.45	127.09

2.8 Summary

This chapter has presented an in-depth review of the concept of sustainable development, including economic, environmental and social sustainability. Through the concept of sustainability, this research focuses on the relationship between sustainable development and infrastructure, particularly for road maintenance. Moreover, this chapter has reviewed the road maintenance principles and technical practices. The road maintenance principles include maintenance strategies, management systems and the process of maintenance and preservation. The technical practice section of this chapter explained the basic theory of pavement and surfacing types, based on global methods and especially focusing on Australian approaches.

Further, this chapter discussed the concepts of LCCA, LCA and LCI. The method and process of each assessment indicated the employed research method for this thesis. The following section reviewed the environmental impacts of road maintenance, and the literature review was analysed for both global and Australia-specific data. This study focuses on Australia-specific data. The analysis of maintenance strategies and processes concluded the process of eight maintenance representative strategies.

The review of previous studies indicated that indirect costs considering social impacts can be applied to different purposes during various stages of construction projects. During the planning stage, RUC applies to long-term multi-year analysis, which is for CBA and LCCA comparing alternative decision making. Therefore, RUCs are used to calculate whole-project costs. During the design phase, RUC is used to determine the most appropriate and effective strategies for construction, including maintenance works. Specific plans and treatments can be applied through detailed analysis of alternatives. Finally, during the working stage (e.g., new construction and maintenance works) short-term analysis can be conducted for detailed analysis, such as daily user cost. This is a work zone–specific analysis during construction work.

The previous studies indicated that the latest research trend is to focus more on management strategies, rather than calculating user costs. The first management view of strategies part indicated a similar research pattern of categorising road conditions, and then calculating and optimising the costs by considering RUC. These studies used optimisation algorithms and methods such as genetic algorithm, the Markov-based model and the multiple-criteria decision method (Arviddson 2017; Khan et al. 2016; Meneses et al. 2012; Partha et al. 2012). Further, the current mathematical model to calculate RUC provides accurate calculation at a micro-level (focusing on a specific road section) to estimate RUC. A methodology to calculate RUC at the network level (macro-level) is required to ensure the health of the overall road network.

In summary, the previous studies indicated that considering environmental and social impacts during road maintenance involves focusing on management strategies for specific projects at the micro-level. For this reason, methods and calculations were also investigated and examined for specific case studies. The findings of this chapter emphasise the need to develop methodology to estimate indirect costs at the network level. Further research is required to develop a calculation procedure that also encompasses the macro-level.

Chapter 3: Research Methodology

3.1 Introduction

This chapter introduces this study’s research methodology. This study adopted mixed methods, including a questionnaire survey and case study.

3.2 Research Methodology

The aim of this research was to determine the true cost of road maintenance through considering the direct costs and social impacts. The epistemological part of this research defined the process of knowing, data collection and analysis to determine the correct findings, validate the results and ensure that the research can be adopted by other research using a similar research design and methodology. The axiological commitment of this research related to the ways in which the results can be applied to a government agency and contractors for decision making in road maintenance.

This research was structured to rank the influencing factors of decision making in the transport sector—particularly road maintenance—and assess the effects of maintenance activities in terms of sustainability indicators, including social and environmental ones. In accordance with the objectives of this research, a questionnaire survey and case study were used as the research methodology of this study. The selection of research methodology was closely related to the research aim. This research aimed to integrate the environmental and social impacts of maintenance activities into road maintenance decision making. The research process involved direct observation of current implementations to identify areas for improvement. The research methodology and research design can be categorised into two sections, as shown in Figure 3.1. Four stages were included in the research design, as follows: Stage 1: literature review; Stage 2: survey; Stage 3: case studies; and Stage 4: findings, conclusions and results.

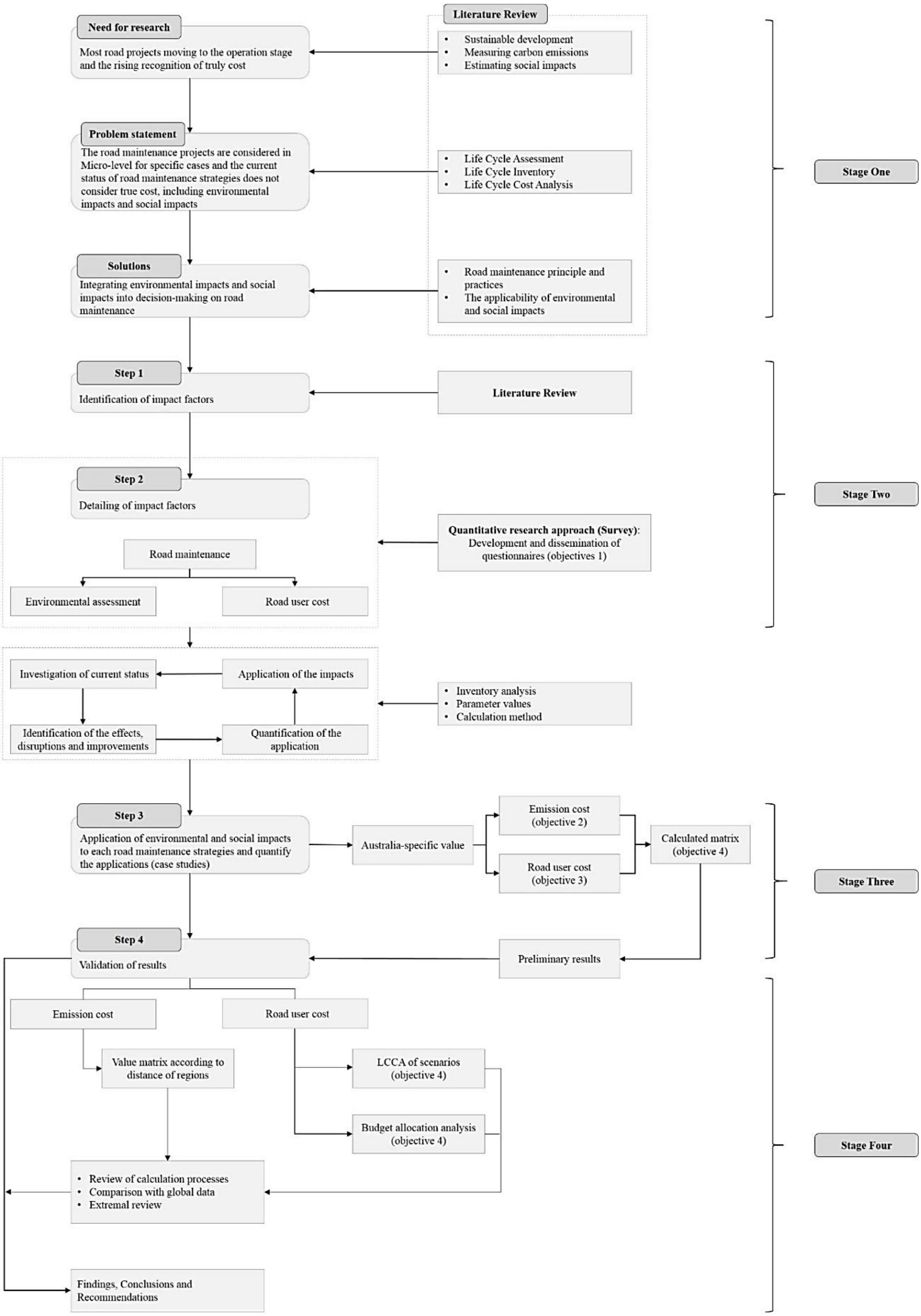


Figure 3.1: Research Methodology

Stage 1 involved a literature review that supported the need for this research and solutions according to the problem identified. The literature review of sustainable development emphasised the importance of road projects focusing on maintenance, and highlighted the possibility of calculating true cost through measuring carbon emissions and estimating social impacts. Review of LCA, LCI and LCCA enables consideration of environmental and social impacts. Review of the road maintenance principles and practices integrates the sustainable development compose for final decision making on road maintenance strategy selections.

Stage 2 involved a survey that approaches quantitatively with questionnaires. A comprehensive literature review was conducted to obtain a list of factors that can affect decision making in road maintenance. Qualitative analysis was employed to improve the internal validation of the list of factors and form the questionnaires. The questionnaire survey was employed to understand the importance of weight between the factors influencing decision making in road maintenance.

Stage 3 involved applying environmental and social impacts to each road maintenance strategy and quantifying the applications in a case study. The emissions cost and RUC were calculated with Australia-specific values.

Stage 4 integrated the previous stages and validated the result to propose the final result of the decision-making framework. Validation of the results included LCCA of the scenarios and budget allocation analysis. The calculation processes and applied data were validated to determine the findings, conclusions and recommendations.

3.3 Identifying and Ranking

3.3.1 Data Collection Method

Figure 3.2 presents the research design of identifying and ranking.

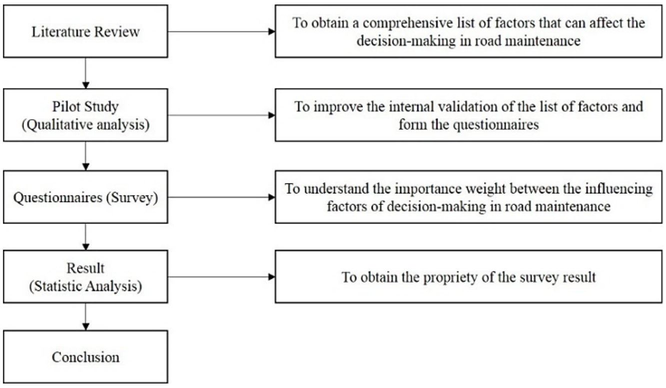


Figure 3.2: Research Methodology of the Survey

A comprehensive literature review was conducted to investigate: (1) previous studies in the area of maintenance strategies evaluation; (2) current methods of evaluation; (3) current standard and guidelines; and (4) most importantly, a list of factors that can influence decision making in road maintenance. Additionally, reports, standards and guidelines were analysed in depth to apply the data as references to calculate the values and refer to identify the influencing factor. Table 3.1 presents the lists that this study adopted and applied directly to calculate the value of factors, while Table 3.2 presents a list of the reports, standards and guidelines adopted to identify the influencing factors on road maintenance.

Table 3.1: Data Used Directly for the Value Calculation

Title	Publication	Country	Adopted data
National Greenhouse Accounts Factors	Australian National Greenhouse Accounts	Australia (2015)	Emissions factors
Greenhouse Gas Assessment Workbook for Road Projects	Transport Authorities Greenhouse Group	Australia (2013)	Emissions factors
Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation	The World Bank	The US (2010)	Emissions factors Capacity data source
PV2 Road Parameter Values	Transport and Infrastructure Council	Australia (2016)	RUC parameter values and equations

Table 3.2: List of Reports, Standards and Guidelines

Title	Publication	Year	Country	Reference
Transport and Main Roads Specifications, MRTS30 Asphalt Pavements	State of Queensland (Department of Transport and Main Roads)	2017	Australia	Asphalt pavement requirements
Sustainable Asset Management Report (Project 3.48)	Sustainable Built Environment National Research Centre	2017	Australia	LCA process, LCCA process
State Roads Infrastructure Asset Management Policy	Tasmanian Government (Department of State Growth)	2017	Australia	Asset management policy
Guide to Pavement Technology	Austroads	2013, 2014, 2016	Australia	Pavement principles and practice
Pavement Rehabilitation Manual	State of Queensland (Department of Transport and Main Roads)	2012	Australia	Pavement principles and technology
Austroads Technical Report	Austroads	2011	Australia	RUC and cost relationship
Austroads Research Report	Austroads	2005	Australia	RUC models
Pavement Life Cycle Assessment Framework	US Department of Transportation	2016	US	LCA process
Rehabilitation Design of Asphalt Concrete Pavements at the North Area Recovery Station (NARS)	Department of Waste Management and Recycling	2015	US	Rehabilitation design
Federal Highway Administration Research and Technology	US Department of Transportation	2015	US	Pavement treatment types
Evaluation of Traffic Flow Analysis and Road User Cost Tools Applied to Work Zones	US Department of Transportation	2015	US	RUC categorised situation cases
Controlling Greenhouse Gas Emissions Generated by the Transport Sector in ECA: Policy Options	The World Bank	2013	US	Regulation and technology of transport sector
Review of Road User Cost and Methods	South Dakota Department of Transportation	2013	US	RUC theory and equation methods

Work Zone Road User Costs	US Department of Transportation	2011	US	RUC parameters
Road User Cost Manual	US Department of Transportation	2001	US	RUC parameters and equation methods
Guidelines for Assessing Pavement Preservation Treatment and Strategies	Alberta Infrastructure and Transportation	2006	Canada	Process of treatment selections
Road Rehabilitation Energy Reduction Guide for Canadian Road Builders	Canadian Construction Association	2005	Canada	Energy use of equipment
Energy Use Generated by Traffic and Pavement Maintenance	Swedish National Road and Transport Research Institute	2012	Europe (Sweden)	Energy calculation
Life Cycle Inventory: Bitumen	Eurobitume	2012	Europe (Belgium)	LCI of material (bitumen)
Life Cycle Assessment of Roads and Pavement	Swedish National Road and Transport Research Institute	2011	Europe (Sweden)	LCA of road pavements
Life Cycle Assessment of Road	IVL Swedish Environmental Research Institute	2001	Europe (Sweden)	Inventory analysis

A questionnaire was designed in accordance with the research aim and Objective 1. The development and dissemination of the questionnaire supported the quantitative analysis of the research. The questionnaire included questions relating to the influencing factors of road maintenance, as displayed in Table 3.3.

Table 3.3: Road Maintenance Decision-making Indicators for This Study

Road maintenance decision-making indicators
M: Assessing the effect of maintenance activities
$\mathbf{M}_{e}$: Economic (cost)
$\mathbf{M}_{c1}$: Construction material cost $\mathbf{M}_{c2}$: Transportation cost $\mathbf{M}_{c3}$: Onsite construction cost $\mathbf{M}_{c4}$: End-of-life cost
$\mathbf{M}_{o}$: Organisational
$\mathbf{M}_{o1}$: Budget limitations $\mathbf{M}_{o2}$: Selection of contractors/sub-contractors $\mathbf{M}_{o3}$: Availability of human resources $\mathbf{M}_{o4}$: Guidelines, regulations, policies $\mathbf{M}_{o5}$: Road conditions
$\mathbf{M}_{s}$: Social
$\mathbf{M}_{s1}$: VOC $\mathbf{M}_{s2}$: VOT $\mathbf{M}_{s3}$: AC $\mathbf{M}_{s4}$: Local business effects
$\mathbf{M}_{e}$: Environmental
$\mathbf{M}_{e1}$: Emissions cost $\mathbf{M}_{e2}$: Waste $\mathbf{M}_{e3}$: Energy
$\mathbf{M}_{w}$: Willingness to improve maintenance practice
$\mathbf{M}_{w1}$: Top management commitment $\mathbf{M}_{w2}$: Availability of relevant resources $\mathbf{M}_{w3}$: Appropriate training
R&E: Factors leading to the low adoption of RUC and environmental considerations
$\mathbf{R}_{o}$ & $\mathbf{E}_{o}$: Organisational
$\mathbf{R}_{o1}$ & $\mathbf{E}_{o1}$: Cost of investment $\mathbf{R}_{o2}$ & $\mathbf{E}_{o2}$: Learning curves to obtain new knowledge $\mathbf{R}_{o3}$ & $\mathbf{E}_{o3}$: Lack of expertise

	$\mathbf{R}_{o4}$ & $\mathbf{E}_{o4}$: Difficulty measuring benefits
	$\mathbf{R}_{k}$ & $\mathbf{E}_{k}$: Knowledge
	$\mathbf{R}_{k1}$ & $\mathbf{E}_{k1}$: Unfamiliar with the assessment methodology $\mathbf{R}_{k2}$ & $\mathbf{E}_{k2}$: Unavailability of a ready-to-use platform $\mathbf{R}_{k3}$ & $\mathbf{E}_{k3}$: Translation to maintenance decision making
	$\mathbf{R}_{l}$ & $\mathbf{E}_{l}$: Legal
	$\mathbf{R}_{l1}$ & $\mathbf{E}_{l1}$: Lack of industry standards $\mathbf{R}_{l2}$ & $\mathbf{E}_{l2}$: Limited successful implementation $\mathbf{R}_{l3}$ & $\mathbf{E}_{l3}$: Lack of incentive $\mathbf{R}_{l4}$ & $\mathbf{E}_{l4}$: Lack of promotion from the government

The importance of the factors was rated using a nine-point Likert scale ranging from 1 to 9, where 1 = not important at all, 5 = moderately important and 9 = extremely important. In addition, based on previous studies on the social impact of maintenance activities, the knowledge level of RUC calculation method was considered to investigate the application status of the current situation, and rated on a scale from 1 to 5, where 1 = extremely low, 3 = moderate and 5 = extremely high. The five-point Likert scale was used in this section because it was not intended to analyse the details, but to identify which methodology was well known and being used. General descriptions of these factors are provided in Chapter 4 and the sample questionnaire is attached in Appendix 1.

3.3.2 Population and Sampling

To identify the current influencing factors of decision making in road maintenance, this study involved government agencies, research organisations (excluding university academics) and private companies (such as engineering consultants and contractors). There were nine national road agencies, two government-owned research centres on road-related research, and 92 companies that were prequalified under the National Prequalification System. The national road agencies included MRWA; the Department of Transport and Main Roads, Queensland; the Department of Planning, Transport and Infrastructure, South Australia; the Department of Infrastructure, Planning and Logistics, Northern Territory; VicRoads, Victoria; Road and Maritime Services, New South Wales; the Department of State Growth, Tasmania; Transport Canberra; and city services. In addition, researchers from road-related research institutions were invited to participate. These institutions included Austroads and ARRB Group. However, academic researchers based in universities were excluded. Additionally, private companies, engineering or consulting, related to road maintenance in design, construction and consulting were invited. Ninety-two companies prequalified under the National Prequalification System and were targeted. Some examples include Clough Project Australia Pty Ltd, Lend Lease Engineering Pty Ltd and BGC Contracting Pty Ltd. These agencies, research centres and contractors formed the population of the study survey.

3.3.3 Data Analysis Method

To identify the current influencing factors and investigate the reasons leading to the limited consideration of social and environmental impacts, this research adopted a weighted scoring model. The results of the respondents' ranking score, in order of importance, indicated the current situation of road maintenance decision making by considering the impact factors. However, to achieve statistical reliability, this research analysed the communalities of all factors and the variance explained by the factors of each variable's variance. Additionally, significance values of Bartlett's test of sphericity, the results of the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, and the Cronbach's alpha coefficient of all the factors were analysed to check data reliability (Nunnally 1978). Table 3.4 summarises the preliminary statistical data analysis method used for factor analysis.

Table 3.4: Preliminary Statistical Data Analysis Method for Factor Analysis

Data analysis method	Objective	Software
Communalities	To explain the factor based on the variable's variance	SPSS
Bartlett's test of sphericity	To provide a minimum standard that should be passed before factor analysis	SPSS
KMO	To measure sampling adequacy	SPSS
Cronbach's alpha coefficient	To assess the reliability and internal consistency	SPSS

3.4 Environmental Impacts of Maintenance Activities

The overall assessment method was adopted from a variety of global standards and guides; however, the detailed calculation methods—including equations and parameter values—were modified to create an Australia-specific method.

The environmental impact analysis was based on LCA, which has been widely adopted to evaluate environmental impacts in both the manufacturing and construction sectors (Harris 1999; Petersen and Solberg 2002). LCA assigns elementary flows and potential environmental impacts to a specific production system. This research evaluated GHG emissions from raw material production to the manufacturing process and placement process. This included emissions from four main components of the raw material (bitumen, crushed aggregate, sand/gravel and cement) extraction and transportation. The emissions sources were calculated based on three major equations: (1) material carbon emissions (kg $CO_{2\text{-}e}$) = quantity (kg) × emissions factors (kg $CO_{2\text{-}e}$/kg); (2) equipment carbon emissions (kg $CO_{2\text{-}e}$) = quantity (litre) × emissions factors (kg $CO_{2\text{-}e}$/Litre); and (3) transportation carbon emissions (kg $CO_{2\text{-}e}$) = distance (km) × emissions factors (kg $CO_{2\text{-}e}$/km). The emissions values of pavement treatment strategies were calculated based on the activities displayed in Figure 3.3.

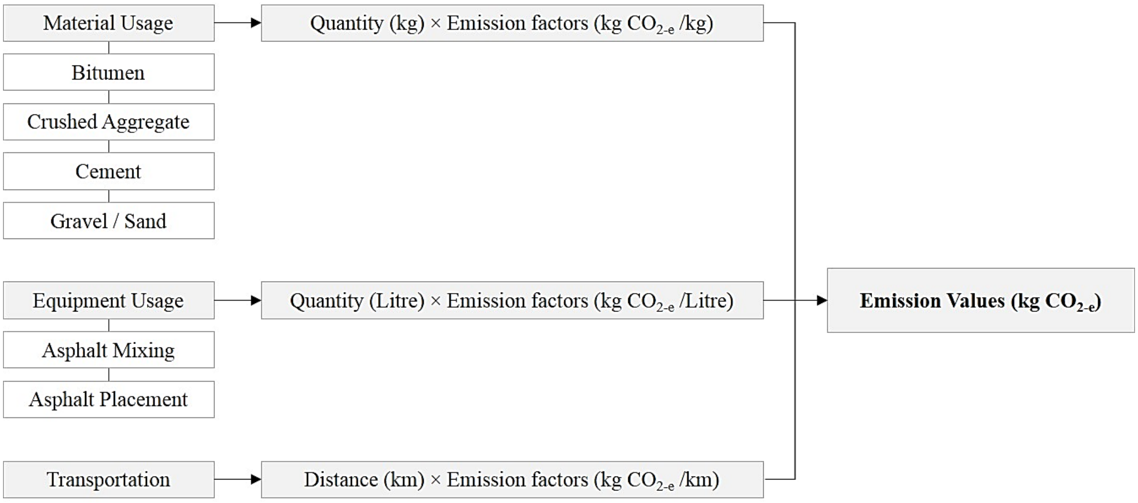


Figure 3.3: Detailed Calculation Activities

This case study aimed to quantify the carbon emissions generated through road maintenance activities. This study analysed 6,304 actual cases of road maintenance extracted from Deighton's Total Infrastructure Management System (provided by MRWA). This encompassed a total treated area of 55,330,752 m^2. To calculate accurate values for different conditions and situations, the data were categorised into eight treatment strategies, eight different regions and four main activities, as described in Figure 3.4. Details of the research assumptions and results will be provided in Chapter 5.

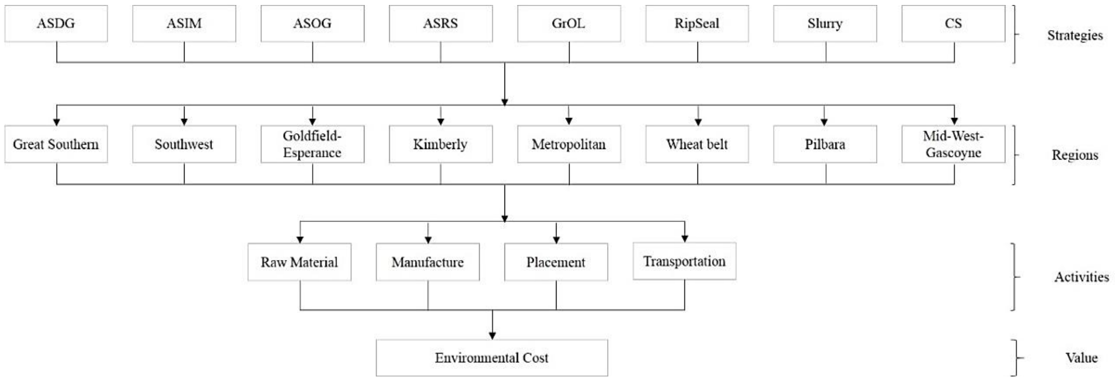


Figure 3.4: Emissions Value Calculation Framework for the Case Study

3.5 Social Impacts of Maintenance Activities

The methodology used in this study was part of the ATAP Guidelines. These guidelines deal with updated parameter (unit) values for use by economic evaluation practitioners in Australia jurisdictions, as of June 2013. This study also used models to estimate VOC and subsequently calculate RUC. This research calculated a total of 6,174 actual cases of VOT and VOC, which encompassed a total of 6,599.88 km and 54,201,382 m^2 in Western Australia. Based on the different calculation methods and equations for different conditions and situations, the data were categorised into eight treatment strategies, eight different regions and five different road types, as displayed in Figure 3.5.

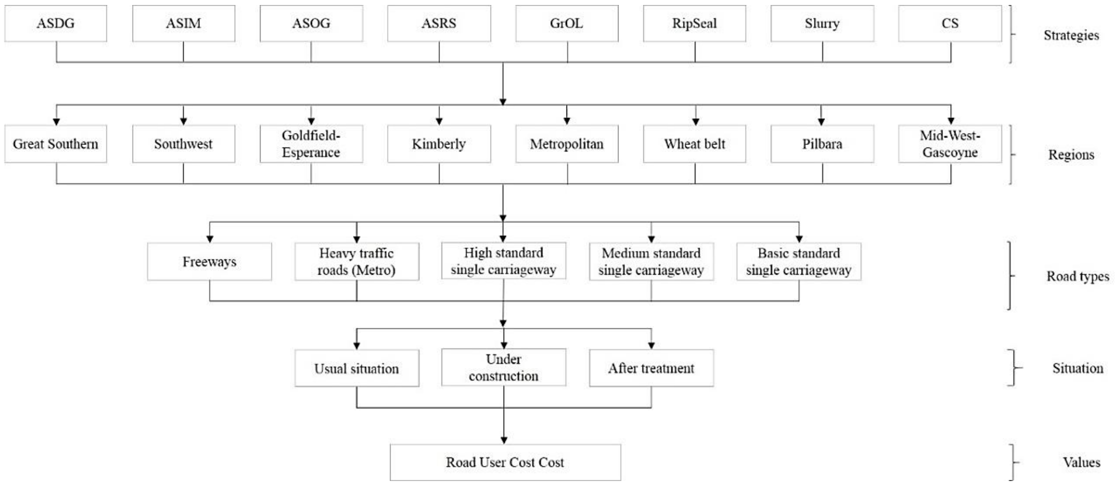


Figure 3.5: RUC Value Calculation Framework for the Case Study

Following the sophisticated classification, the results were calculated based on three different situations, as follows: (1) usual road situation, (2) during construction (speed limit of 40 km/h) and (3) after the treatment work is completed (roughness change). Therefore, this study held a few assumptions and limitations during the calculation process, based on typical roads in Australia. Vehicle classifications appropriate to Australia were reviewed, and the Austroads 12-vehicle classification was selected for calculation. A detailed percentage of AADT for the 12 classes was analysed; however, this was limited to calculating passengers on buses because of lack of information. The cost model structure and coefficients were adapted from the ATAP Guidelines and PV2 Road Parameter Values (Transport and Infrastructure Council 2016). As mentioned above, every case was categorised based on regions, road types and speed limits, assuming a rise and fall of 0% and curvature of 20º/km, which influenced the method of calculation. Figure 3.6 presents the generalised decision tree for calculating RUCs in variable situations.

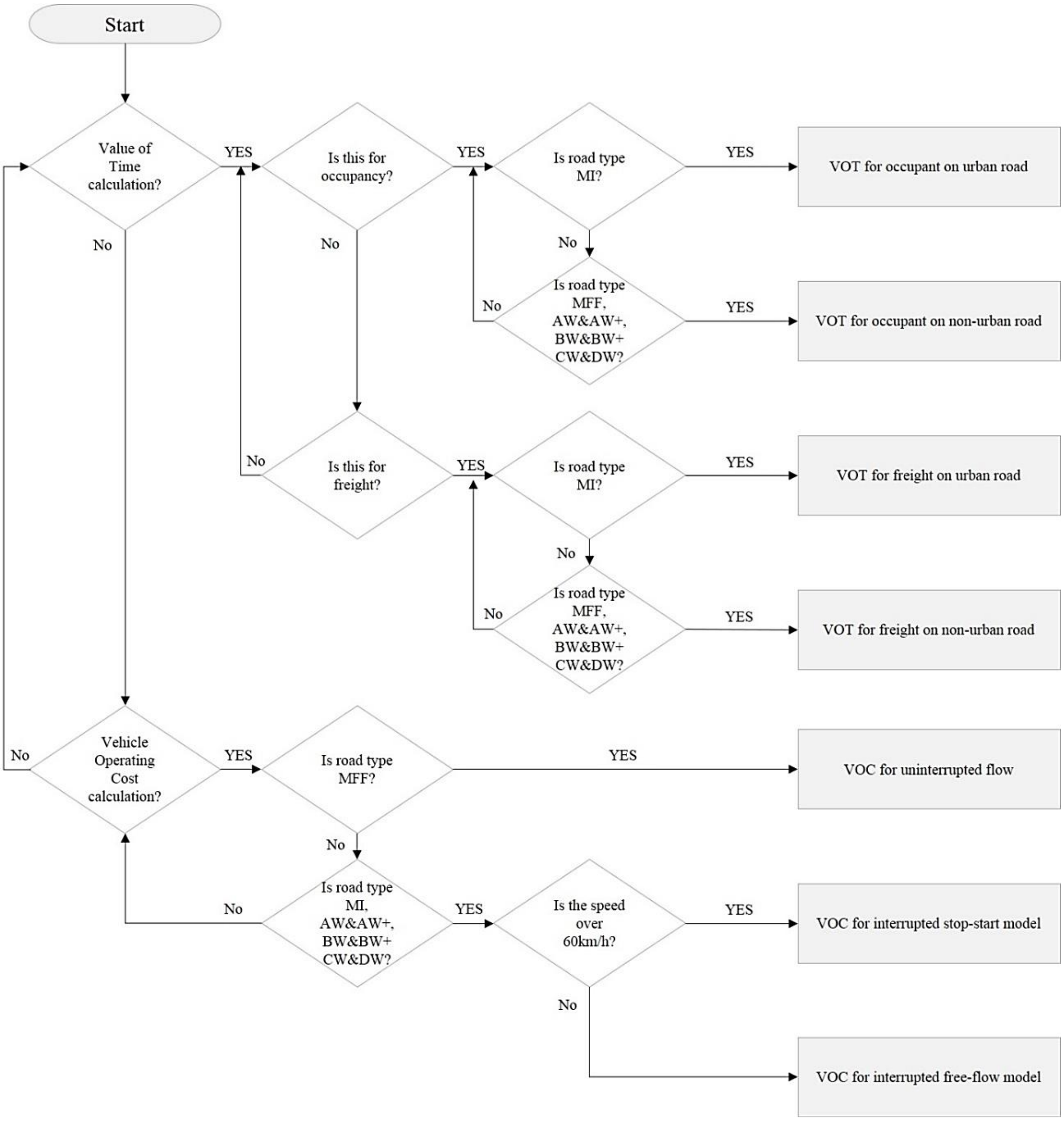


Figure 3.6: Decision Tree for Calculating RUC

The specific details of the equations employed in this study are discussed below.

3.5.1 Value of Time for Occupants of Urban Roads

The following equation was used to calculate the value of time for occupants of urban roads. Road type MI; heavy traffic roads, generally metro place come under this method:

$$\mathrm{VOT} = \sum_{class=1}^{12} \frac{X_1 \times X_2}{100} \times E_{1u} \times E_{2u} \times \frac{X_3}{X_4}$$

where:

- X_1 = AADT
- X_2 = traffic composition
- X_3 = length
- X_4 = speed
- E_{1u} = occupancy rate (urban)
- E_{2u} = value per occupancy (urban).

3.5.2 Value of Time for Occupants of Non-urban Roads

The following equation was used to calculate the value of time for occupants of non-urban roads. The road types MFF, AW and AW+, BW and BW+, CW and DW come under this method:

$$\mathrm{VOT} = \sum_{class=1}^{12} \frac{X_1 \times X_2}{100} \times E_1 \times E_2 \times \frac{X_3}{X_4}$$

where:

- X_1 = AADT
- X_2 = traffic composition
- X_3 = length
- X_4 = speed
- E_1 = occupancy rate (non-urban)
- E_2 = value per occupancy (non-urban).

3.5.3 Value of Time for Freight Travel Time on Urban Road

The following equation was used to calculate freight travel time value per vehicle hour on urban roads. Road type MI; heavy traffic roads, generally metro place come under this method:

$$\mathrm{VOT} = \sum_{class=1}^{12} \frac{X_1 \times X_2}{100} \times E_{1fu} \times E_{2fu} \times \frac{X_3}{X_4}$$

where:

- X_1 = AADT
- X_2 = traffic composition
- X_3 = length
- X_4 = speed
- E_{1fu} = occupancy rate (urban)
- E_{2fu} = freight travel time values per vehicle hour (urban).

3.5.4 Value of Time for Freight Travel Time on Non-urban Road

The following equation was used to calculate the value of freight travel time on non-urban roads. The road types MFF, AW and AW+, BW and BW+, CW and DW come under this method:

$$\mathrm{VOT} = \sum_{class=1}^{12} \frac{X_1 \times X_2}{100} \times E_{1f} \times E_{2f} \times \frac{X_3}{X_4}$$

where:

- X_1 = AADT
- X_2 = traffic composition
- X_3 = length
- X_4 = speed
- E_{1f} = occupancy rate (non-urban)
- E_{2f} = freight travel time values per vehicle hour (non-urban).

3.5.5 Vehicle Operating Cost for Uninterrupted Flow

The following equation was used to calculate the VOC for uninterrupted freeways (road type MFF):

$$\mathrm{VOC} = \sum_{class=1}^{12} E_3 \times (K_1 + \frac{K_2}{X_4} + K_3 \times {X_4}^2 + K_4 \times X_5 + K_5 \times {X_5}^2 + K_6 \times E_4) \times \frac{X_1 \times X_2}{100} \times X_3$$

where:

- E_3 = base VOC
- K_1, K_2, K_3, K_4, K_5 and K_6 = coefficients related to RUC
- X_1 = AADT
- X_2 = traffic composition
- X_3 = length
- X_4 = speed
- X_5 = IRI
- E_4 = GVM.

3.5.6 Vehicle Operating Cost for Interrupted Stop–Start Model

The following equation was used to calculate VOC for interrupted roads, such as MI, AW and AW+, BW and BW+, CW and DW, where the speed limit is under 60 km/h:

$$\mathrm{VOC} = \sum_{class=1}^{12} (A + \frac{B}{X_4}) \times \frac{X_1 \times X_2}{100} \times X_3$$

where:

- A and B = coefficients
- X_1 = AADT
- X_2 = traffic composition
- X_3 = length
- X_4 = speed.

3.5.7 Vehicle Operating Cost for Interrupted Free-flow Model

The following equation was used to calculate VOC for interrupted roads, such as MI, AW and AW+, BW and BW+, CW and DW, where the speed limit is over 60 km/h:

$$\mathrm{VOC} = \sum_{class=1}^{12} (C_0 + C_1 \times X_4 + C_2 \times {X_4}^2) \times \frac{X_1 \times X_2}{100} \times X_3$$

where:

- C_0, C_1 and C_2 = coefficients
- X_1 = AADT
- X_2 = traffic composition
- X_3 = length
- X_4 = speed.

In summary, this research categorised 6,174 cases based on strategy type, region area, road type and speed limit, and then calculated each specific situation by using seven different modified methods.

3.6 Integration of Road Maintenance Impact Factors

The aim of the case study was to examine how the environmental and social impacts can be applied to road maintenance decision making with direct costs. The environmental cost and RUC, including VOC and VOT, were used as an indicator of road maintenance activities. This research established seven scenario options using data provided by MRWA on road segments. The case was analysed with the lifecycle cost of different maintenance programs over a 20-year lifecycle.

Maintenance budget allocation is critical to ensuring that various asset types are adequately maintained (Fwa and Farhan 2012). Maintenance budget allocation at the state network level is based on several factors, including the direct cost of maintenance and pavement performance improvement. Using LCC approach, this research developed an integrated approach to evaluating budget allocation, considering the effects of roadworks on road users. Figure 3.7 presents the framework for validating the integration of factors.

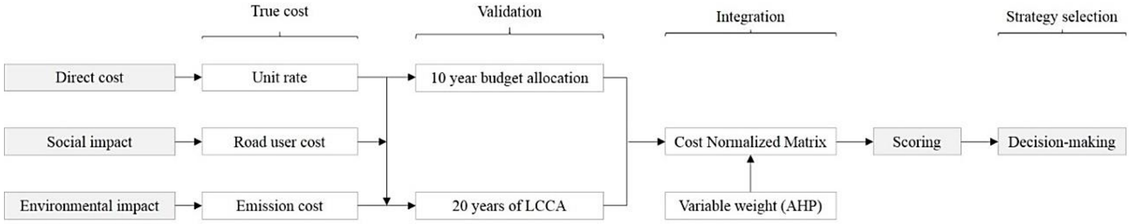


Figure 3.7: Validation and Implementation Framework

To weight the impact factors, this research adopted the decision-making method of analytic hierarchy process (AHP) proposed by Saaty (1980) through McGraw-Hill. This method classifies problems that include multiple objectives, multiple evaluation criteria and multiple decision-making subjects, and classifies the elements in the upper class by pair comparison to determine the importance or weight of each element. The overall ranking is calculated by determining the total score. The first step of rating and normalisation is to model the AHP structure with five evaluation criteria: unit rate, environmental cost and three types of RUC. The eight evaluation targets' overall hierarchical structure indicates the treatment strategies. Figure 3.8 details the evaluation criteria hierarchy. Each pair of evaluation elements constituting a hierarchy is paired with each other to evaluate their relative importance from the viewpoint of the superior type.

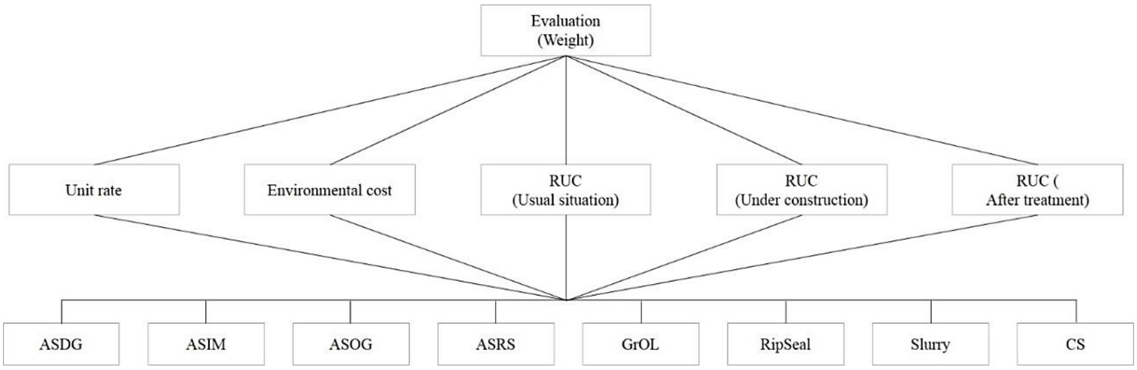


Figure 3.8: Evaluation Criteria Hierarchy

The next step is to normalise the five variables—unit rate, environmental cost and three types of RUC—in all eight strategies, based on the calculation result. By dividing the sum of the columns to adjust the importance of each pair of evaluation values, row averaging provides the weights for the evaluation criteria. The result of the normalised matrix is calculated with the factors' weight of importance to determine the maintenance decision making. Further details and examples of the normalisation process are presented in Chapter 7.

3.7 Summary

This chapter has discussed the methodology adopted in this research, including the desk research, interviews and questionnaire. The comprehensive literature review identified the important factors for road maintenance. Based on this, this research investigated the current status of social impact application in road maintenance decision making, and the reasons leading to the limited consideration of social impacts (Objective 1).

The literature review also indicated the appropriate methods to calculate carbon emissions, VOC and VOT for road maintenance strategies. Australia-specific values and methods were adopted to determine accurate results based on Australia-specific details (Objectives 2 and 3). In the following chapters, the results will be normalised into matrix form to determine the importance of weights, based on the calculated results, to finally integrate social impacts into the decision making for road maintenance (Objective 4). The case study will indicate the relevant application of this approach and demonstrate its practical benefits.

Chapter 4: Influencing Impact Factors

4.1 Introduction

In Western Australia, roads are categorised as national highways (federal government funded), state roads (state government funded) and local roads (local government funded), which are managed by MRWA. Satisfactory maintenance of roads requires constant vigilance in detecting potential failures, prompt action in preventing or correcting defects that may develop, and adequate supervision and trained personnel to ensure the use of sound techniques and appropriate planning of operations to enable the most effective use of the available resources.

4.2 Respondents' Background

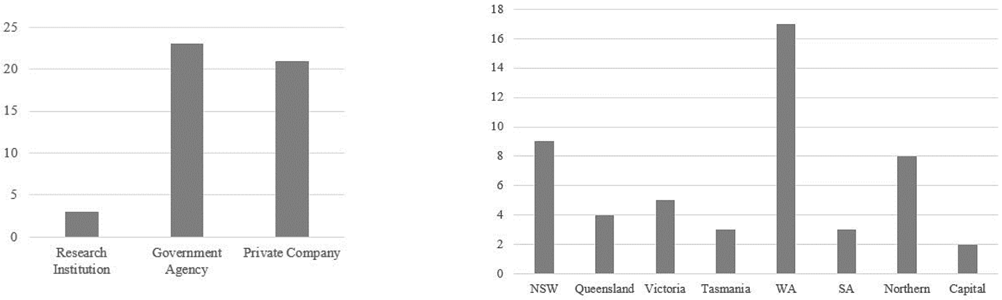
To achieve this study's objectives, an online questionnaire survey was conducted. In the questionnaire, the respondents were asked to provide their background information and rate the significance of the factors influencing decision making in road maintenance. A nine-point scale (1 = not important at all, 5 = moderately important, 9 = extremely important) was used to measure the factors' importance to enable the responses to align with Miller's (1956) principle. During the research period, 216 respondents were initially contacted to determine their suitability for the survey. A total of 68 questionnaires were sent out, and 51 responses were collected (75%). Finally, 47 meaningful responses were identified for further analysis. Table 4.1 displays the profile of these final respondents.

Table 4.1: Respondents' Profile

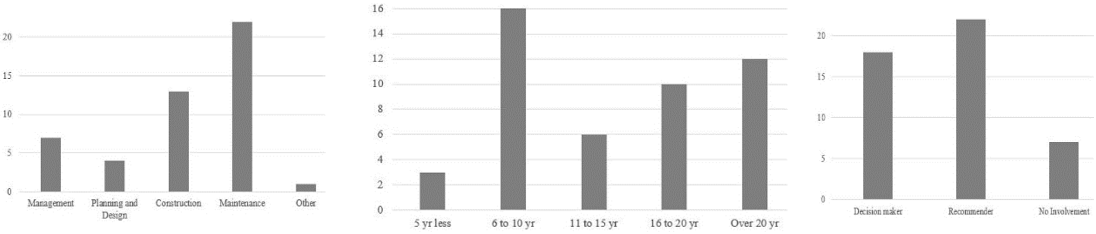
Characteristics	Parameters	N	%
Organisation	Research institution	3	6.38
	Government agency	23	48.94
	Private company (engineering consultant)	21	44.68
Region	New South Wales	9	17.65
	Queensland	4	7.84
	Victoria	5	9.80
	Tasmania	3	5.88
	Western Australia	17	33.33
	South Australia	3	5.88
	Northern Territory	8	15.69
	Australian Capital Territory	2	3.92
Field of work	Management	7	14.89
	Planning and design	4	8.51
	Construction	13	27.66
	Maintenance	22	46.81
	Other	1	2.13
Work experience	Less than 5 years	3	6.38
	6 to 10 years	16	34.04
	11 to 15 years	6	12.77
	16 to 20 years	10	21.28
	More than 20 years	12	25.53
Role in decision making	Decision maker	18	38.30
	Recommender/influencer	22	46.81
	No involvement	7	14.89

The respondents were from research institutions (excluding university academics) (6.4%); private companies, such as engineering consultants and contractors (48.9%); and government agencies (44.7%). Given that government agencies have the most influence on making decisions, this research received a high response rate from all government agencies in Australia that had a department for managing road maintenance. There were 17 respondents from Western Australia (33.3%), followed by nine respondents from New South Wales (17.7%). In terms of field of work, 46.8% of the respondents' were from maintenance, followed by construction (27.7%) and management (14.9%). The respondents' years of work experience encompassed six to 10 years (34%), while 22 respondents (46.8%) had more than 16 years of experience in their field. Finally, 38.3%

of respondents were decision makers, 46.8% were recommenders who could influence decision making, and 14.9% had no involvement in decision making. Figure 4.1 presents graphs displaying the profile of the respondents.



(a) Organisation (b) Region



(c) Work area (d) Work experience (e) Role in decision making

Figure 4.1: Respondents' Profiles

4.3 Assessing the Effects of Maintenance Activities

4.3.1 Reliability

The literature review identified a total of 19 factors (variables) influencing decision making in road maintenance, which were categorised into five groupings, as displayed in Table 4.2. In the survey's Section 1, the five highest classification-level groups (M) were economic, organisational, social and environmental factors, and willingness to improve maintenance practice. The economic factors were construction material cost (M_{c1}), transportation cost (M_{c2}), onsite construction cost (M_{c3}) and end-of-life cost (M_{c4}). The organisational factors were budget limitations (M_{o1}), selection of contractors and sub-contractors (M_{o2}), availability of human resources (M_{o3}), guidelines/regulations/policies (M_{o44}) and road conditions (M_{o5}). The social factors consisted of VOCs (M_{s1}), such as fuel, tyres, maintenance and depreciation; VOT (M_{s2}), which encompassed user delay time; and ACs (M_{s3}), such as fatalities, property damage and local business effects (M_{s4}). The environmental factors were emission costs (M_{e1}), such as air pollution, GHGs, waste (M_{e2}) and energy (M_{e3}). Finally, willingness to improve maintenance practice included top management commitment (M_{w1}), availability of relevant resources (M_{w2}) and appropriate training (M_{w3}).

Table 4.2: Impact Factors on Road Maintenance

Grouping	Code	Factor
Economic (cost)	M_{c1}	Construction material cost
	M_{c2}	Transportation cost
	M_{c3}	Onsite construction cost
	M_{c4}	End-of-life cost
Organisational	M_{o1}	Budget limitation
	M_{o2}	Selection of contractors/sub-contractors
	M_{o3}	Availability of human resources
	M_{o4}	Guidelines, regulations, policies
	M_{o5}	Road conditions
Social	M_{s1}	VOC
	M_{s2}	VOT
	M_{s3}	AC
	M_{s4}	Local business effects
Environmental	M_{e1}	Emissions cost
	M_{e2}	Waste
	M_{e3}	Energy
Willingness to improve maintenance practice	M_{w1}	Top management commitment
	M_{w2}	Availability of relevant resources
	M_{w3}	Appropriate training

The communalities of all factors were higher than 0.4; therefore, the variance could be explained by the factors of each variable's variance. Although the significance values of Bartlett's test of sphericity is 0 to satisfy; however, the result of the KMO measure of sampling adequacy value was 0.6 at the suggested minimum. This was because the budget limit factor (M_{o1}) result was much higher than the other factors. The varimax factor analysis was conducted to confirm the commonality of variables and the relationship between factors. The Cronbach's alpha coefficient of most factors was over 0.6, which indicated high data reliability (Nunnally 1978). Table 4.3 presents the results of the statistical reliability analysis. As with the KMO test, the Cronbach's alpha for the organisational group was 0.562, which was less the limit of 0.6 but similar to the minimum requirement. However, the reason is that most of the respondent-rated budget limitations (M_{o1}) were more important than the other factors, and caused gaps between the other factors' scores. Although it is slightly lower than the minimum requirement but budget is not excluded because it is most important factor as respondent rated which affected the result.

Table 4.3: Statistical Reliability of Road Maintenance Factors

Code	Communalities	Rotated components	Cronbach's alpha
M_{c1}	0.808	0.886	0.642
M_{c2}	0.815	0.778	
M_{c3}	0.567	0.646	
M_{c4}	0.669	0.709	
M_{o1}	0.524	0.647	0.562
M_{o2}	0.584	0.619	
M_{o3}	0.672	0.558	
M_{o4}	0.730	0.779	
M_{o5}	0.721	0.723	
M_{s1}	0.739	0.822	0.757
M_{s2}	0.606	0.578	
M_{s3}	0.818	0.811	
M_{s4}	0.784	0.584	
M_{e1}	0.695	0.815	0.896
M_{e2}	0.727	0.836	
M_{e3}	0.904	0.940	
M_{w1}	0.725	0.553	0.672
M_{w2}	0.615	0.687	
M_{w3}	0.751	0.745	

4.3.2 Ranking in Order

This section of the survey aimed to determine the importance of impact factors on road maintenance decision making. The results of the respondents' ranking scores, in order of importance, indicated the current situation of road maintenance decision making by considering the impact factors. Table 4.4 presents the ranking in order of factor analysis for road maintenance decision making. The results indicated that budget limitation was the primary consideration in road maintenance. The following high-ranking factors were onsite construction cost, AC and road conditions. Factors affecting the direct cost of road maintenance—such as budgets and site conditions—seemed to be considered important. While ACs are not a direct component of construction costs, they were the only social factor included in the top group because of their strong influence on society. The results also indicated that environmental and social factors were included in lower ranking groups. This demonstrates that direct cost components are currently given greater significance than other factors, such as environmental and social impacts.

Table 4.4: Factor Analysis in Order

Order	Code	Mean	Standard deviation (SD)	Factor
1	M_{o1}	7.49	1.019	Budget limitation
2	M_{c3}	7.09	1.442	Onsite construction cost
3	M_{s3}	6.98	1.581	AC
4	M_{o5}	6.91	1.365	Road conditions
5	M_{w2}	6.79	1.473	Availability of relevant resources
6	M_{w1}	6.49	1.730	Top management commitment
7	M_{o4}	6.32	1.431	Guidelines, regulations, policies
8	M_{s4}	6.30	1.614	Local business effects
	M_{w3}	6.30	1.397	Appropriate training
10	M_{c4}	6.26	1.635	End-of-life cost
11	M_{c1}	6.17	1.833	Construction material cost
12	M_{s2}	6.04	1.668	VOT
13	M_{c2}	5.87	2.242	Transportation cost
14	M_{o2}	5.64	1.634	Selection of contractors/sub-contractors
15	M_{e2}	5.60	1.664	Waste
16	M_{o3}	5.57	1.514	Availability of human resources
17	M_{e1}	5.09	1.840	Emissions cost
	M_{s1}	5.09	1.943	VOC
19	M_{e3}	4.96	1.841	Energy

4.3.3 Perceptions of Stakeholders

This study conducted further analysis of the stakeholders’ perceptions. Although government agencies, private companies and research institutes were the main respondents, the research institutes group was excluded because of the low response rate and disturbing answers to reliability. Table 4.5 presents the order of importance for the government agencies and private companies. The results indicated that both groups highlighted the most significant impact factor as budget limitation, with similar means of 7.77 and 7.76. Although the important factors were slightly different, the results indicated a similar pattern, except for construction material cost. It seems that private companies devote more attention to material costs than do government agencies. Meanwhile, similar views were identified for factors considered less important. Both groups indicated VOC, emissions cost and energy as less important considerations for road maintenance. This again indicates that environmental and social impacts were considered relatively less important and not reflected in the decision-making process. In addition, the mean value of the high factors—such as budget limitation, construction cost and road conditions—were similar in both groups, yet the private companies' mean value of rest impact factors were relatively lower than that of the government agencies.

Table 4.5: Comparison of Respondent Groups

Order	**Government agency**		**Private company**	
	Factor	**Mean**	**Factor**	**Mean**
1	Budget limitation	7.77	Budget limitation	7.76
2	AC	7.59	Onsite construction cost	7.29
3	Road conditions	7.32	Road conditions	6.71
4	Availability of relevant resources	7.18	AC	6.53
5	Onsite construction cost	6.82	Construction material cost	6.47
6	Top management commitment	6.77	Availability of relevant resources	6.24
7	Guidelines, regulations, policies	6.64	Top management commitment	6.12
8	Appropriate training	6.59	Local business impact	6.06
9	Local business impact	6.55	Transportation cost	5.76
10	End-of-life cost	6.52	Selection of contractors/sub-contractors	5.71
11	VOT	6.36	VOT	5.65
12	Transportation cost	6.32	Waste	
13	Construction material cost	6.18	Appropriate training	
14	Availability of human resources	5.91	Guidelines, regulations, policies	5.59
15	Selection of contractors/sub-contractors	5.86	End-of-life cost	5.24
16	Waste	5.55	Availability of human resources	5.06
17	VOC	5.50	Emissions cost	
18	Emissions cost	5.05	VOC	4.88
19	Energy	4.95	Energy	4.82

4.4 Factors Leading to Low Adoption of Road User Cost

4.4.1 Reliability

Section 2 of the survey presented for rating the barriers that prevent consideration of social issues in road maintenance. A total of 11 factors were identified and categorised into three groupings, as displayed in Table 4.6.

Table 4.6: Factors Affecting RUC

Grouping	Code	Factor
Organisational	R_{O1}	Cost of investment
	R_{O2}	Learning curves to obtain new knowledge
	R_{O3}	Lack of expertise
	R_{O4}	Difficulty measuring benefits
Knowledge	R_{k1}	Unfamiliar with the assessment methodology
	R_{k2}	Unavailability of a ready-to-use platform
	R_{k3}	Translation of RUC to maintenance decision making
Legal	R_{l1}	Lack of industry standards
	R_{l2}	Limited successful implementation
	R_{l3}	Lack of incentive
	R_{l4}	Lack of promotion from the government

The organisational factors included the cost of investment (R_{O1}), learning curves to obtain new knowledge (R_{O2}), lack of expertise (R_{O3}) and difficulty measuring benefits (R_{O4}). Knowledge factors included lack of familiarity with the assessment methodology (R_{k1}), unavailability of a ready-to-use platform (R_{k2}) and translation to maintenance decision making (R_{k3}). Finally, the legal factors included lack of industry standard (R_{l1}), limited successful implementation (R_{l2}), lack of incentive (R_{l3}) and lack of promotion from the government (R_{l4}).

The communalities of all factors were higher than 0.47; therefore, the variance could be explained by the factors of each variable’s variance. The significance values of Bartlett’s test of sphericity were 0 to satisfy, and the KMO measure of sampling adequacy was 0.766. The Cronbach’s alpha coefficient of knowledge and legal factors was over 0.7, which indicated high data reliability (Nunnally 1978), while the organisational coefficient was 0.574, which was close to the minimum requirement. The reason is that the cost of investment ($F_{r}1$) attained a much higher score than did the others. In particular, most respondents rated the cost of investment (R_{O1}) as a more important factor than the other factors, which created gaps between the other factors' scores. Table 4.7 presents the summarised results for the statistical reliability analysis.

Table 4.7: Statistic Reliability Analysis of RUC Factors

Code	Communalities	Rotated components	Cronbach's alpha
R_{O1}	0.896	0.934	0.674
R_{O2}	0.657	0.726	
R_{O3}	0.606	0.593	
R_{O4}	0.750	0.855	
R_{k1}	0.804	0.866	0.862
R_{k2}	0.786	0.851	
R_{k3}	0.729	0.686	
R_{l1}	0.764	0.854	0.718
R_{l2}	0.928	0.943	
R_{l3}	0.474	0.628	
R_{l4}	0.754	0.848	

4.4.2 Ranking in Order

This section of the survey aimed to determine the factors leading to the low adoption of RUC. The results of the respondents' ranking score, in order of importance, indicated the current barriers to adopting RUC. Table 4.8 presents the ranking in order of factor analysis on RUC adoption barrier reasons. The results indicated that the cost of investment was the primary consideration in RUC, followed by lack of expertise and difficulty in measuring benefits. It turned out that high ranking of three factors is organisational impacts. Overall, the cost-related factors—such as lack of incentive and promotion from the government—were higher than in term of theory or methodology. This indicated that the participants considered the problem of substantial compensation more important than the lack of methodology or regulation. The processes of measuring benefits and translating RUC to maintenance decision making appeared to be the major obstacles, rather than standards or methodology. In other words, there were more difficulties in measuring and applying RUC practically than in measuring it theoretically.

Table 4.8: RUC Factor Analysis in Order

Order	Code	Mean	SD	Factor
1	R_{O1}	6.96	1.299	Cost of investment
2	R_{O3}	6.46	1.747	Lack of expertise
3	R_{O4}	6.30	1.762	Difficulty measuring benefits
4	R_{I3}	6.28	1.772	Lack of incentive
5	R_{k3}	6.24	1.900	Translation of RUC to maintenance decision making
6	R_{I4}	6.04	2.160	Lack of promotion from government
7	R_{I2}	5.93	1.831	Limited successful implementation
8	R_{k1}	5.89	1.841	Unfamiliar with the assessment methodology
9	R_{O2}	5.78	1.800	Learning curves to obtain new knowledge
10	R_{k2}	5.67	1.886	Unavailability of a ready-to-use platform
11	R_{I1}	5.61	1.666	Lack of industry standards

4.4.3 Perceptions of Stakeholders

Further analysis of the stakeholders’ perceptions was conducted for the government agencies and private companies. Table 4.9 displays the order of importance in the government agencies and private companies. Although the cost of investment was the strongest factor in both groups, the results indicated a distinct difference. It seems that the private companies focused more on cost, benefits, incentives and promotion, while the government agencies focused more on expertise, standards and methodology. The results indicated a gap between government agencies and private companies.

Table 4.9: Comparison of RUC between Government Agency and Private Company in Order of Importance

Order	Government agency		Private company	
	Factor	**Mean**	**Factor**	**Mean**
1	Cost of investment	6.95	Cost of investment	7.29
2	Lack of expertise	6.52	Difficulty measuring benefits	6.82
3	Lack of industry standards	6.05	Lack of incentive	6.71
4	Difficulty measuring benefits	5.95	Translation of RUC to maintenance decision making	6.41
5	Translation of RUC to maintenance decision making		Lack of promotion from the government	
6	Unfamiliar with the assessment methodology	5.91	Lack of expertise	6.06
7	Limited successful implementation	5.86	Unfamiliar with the assessment methodology	5.65
8	Lack of incentive	5.73	Unavailability of a ready-to-use platform	5.53
9	Unavailability of a ready-to-use platform	5.55	Limited successful implementation	5.41
10	Learning curves to obtain new knowledge	5.45	Learning curves to obtain new knowledge	5.35
11	Lack of promotion from the government		Lack of industry standards	4.82

4.5 Factors Leading to Low Adoption of Environmental Consideration

4.5.1 Reliability

Section 3 of the survey presented for rating the barriers that prevent consideration of environmental impacts during road maintenance. A total of 11 factors were identified and categorised into three groupings, as displayed in Table 4.10. The organisational factors included the cost of investment (E_{O1}), learning curves to obtain new knowledge (E_{O2}), lack of expertise (E_{O3}) and difficulty measuring benefits (E_{O4}). The knowledge factors included lack of familiarity with the assessment methodology (E_{k1}), unavailability of a ready-to-use platform (E_{k2}) and translation to maintenance decision making (E_{k3}). Finally, the legal factors included lack of industry standard (E_{l1}), limited successful implementation (E_{l2}), lack of incentive (E_{l3}) and lack of promotion from the government (E_{l4}).

Table 4.10: Factors Affecting Environmental Assessment

Grouping	Code	Factor
Organisational	E_{O1}	Cost of investment
	E_{O2}	Learning curves to obtain new knowledge
	E_{O3}	Lack of expertise
	E_{O4}	Difficulty measuring benefits
Knowledge	E_{k1}	Unfamiliar with the assessment methodology
	E_{k2}	Unavailability of a ready-to-use platform
	E_{k3}	Translation of environmental assessment to maintenance decision making
Legal	E_{l1}	Lack of industry standards
	E_{l2}	Limited successful implementation
	E_{l3}	Lack of incentive
	E_{l4}	Lack of promotion from the government

This section of the survey investigated the factors leading to the limited consideration of environmental concerns. The communalities of all factors were higher than 0.74; therefore, the variance could be explained by the factors of each variable's variance. The significance values of Bartlett's test of sphericity were 0 to satisfy, and the KMO measure of sampling adequacy was 0.817. The Cronbach's alpha coefficient of knowledge and legal factors were over 0.7, which indicated high data reliability (Nunnally 1978). Table 4.11 presents the results of the statistical reliability analysis. Most respondents rated the cost of investment (E_{O1}) as more important than the other factors, which caused gaps between the other factors' scores.

Table 4.11: Statistical Reliability Analysis of Environmental Factors

Code	Communalities	Rotated components	Cronbach's alpha
E_{O1}	0.796	0.880	0.780
E_{O2}	0.925	0.951	
E_{O3}	0.807	0.553	
E_{O4}	0.745	0.686	
E_{k1}	0.746	0.690	0.862
E_{k2}	0.790	0.663	
E_{k3}	0.826	0.672	
E_{l1}	0.807	0.887	0.921
E_{l2}	0.905	0.824	
E_{l3}	0.818	0.886	
E_{l4}	0.801	0.739	

4.5.2 Ranking in Order

This section of the survey aimed to determine the factors leading to the low adoption of environmental impacts. The results of the respondents' ranking score, in order of importance, indicated the current barriers to adopting environmental considerations. Table 4.12 presents the ranking in order of factor analysis on environmental impact factor adoption barrier reasons. The results indicated that the cost of investment was the primary consideration, followed by difficulty measuring benefits and learning curves to obtain new knowledge. It turned out that high ranking of three factors is organisational impacts. Unlike RUC, the overall results indicated that measurement of benefits, knowledge, translation of environmental assessment to maintenance decision making, and methodology held greater importance than economic factors, such as incentives and promotion. Thus, it appears that more theory and knowledge is needed for environmental considerations during road maintenance.

Table 4.12: Environmental Factor Analysis in Order

Order	Code	Mean	SD	Factor
1	E_{O1}	6.47	1.898	Cost of investment
2	E_{O4}	6.04	1.781	Difficulty measuring benefits
3	E_{O2}	5.87	1.541	Learning curves to obtain new knowledge
4	E_{k3}	5.85	1.933	Translation of environmental assessment to maintenance decision making
	E_{l3}		1.876	Lack of incentive
6	E_{k1}	5.81	1.513	Unfamiliar with the assessment methodology
7	E_{O3}	5.77	1.856	Lack of expertise
	E_{l4}		2.286	Lack of promotion from government
9	E_{k2}	5.66	1.809	Unavailability of a ready-to-use platform
10	E_{l2}	5.53	1.977	Limited successful implementation
11	E_{l1}	5.34	1.736	Lack of industry standards

4.5.3 Perceptions of Stakeholders

This research conducted further analysis of the stakeholders' perceptions for the government agencies and private companies. Table 4.13 displays the order of importance for the government agencies and private companies. Although the cost of investment was the highest factor for both groups, the results indicated a distinct difference. Similarly to RUC, the results indicated that private companies focus more on costs, benefits and incentives, while government agencies focus more on methodology, measurement and translation. However, in contrast to RUC, both stakeholder groups require further theoretical support focusing on methodology, measurement and expertise.

Table 4.13: Order of Importance of Environmental Considerations between Government Agency and Private Company

Order	Government agency		Private company	
	Factor	Mean	Factor	Mean
1	Cost of investment	6.00	Cost of investment	7.24
2	Unfamiliar with the assessment methodology	5.86	Difficulty measuring benefits	6.29
3	Difficulty measuring benefits	5.82	Lack of incentive	6.06
4	Translation of environmental assessment to maintenance decision making		Lack of expertise	6.00
5	Learning curves to obtain new knowledge	5.68	Translation of environmental assessment to maintenance decision making	5.94
6	Lack of incentive		Limited successful implementation	
7	Lack of expertise	5.67	Lack of promotion from the government	5.76
8	Lack of promotion from the government	5.55	Learning curves to obtain new knowledge	5.71
9	Unavailability of a ready-to-use platform	5.45	Unfamiliar with the assessment methodology	5.59
10	Limited successful implementation	5.27	Lack of industry standards	5.47
11	Lack of industry standards	5.23	Unavailability of a ready-to-use platform	5.18

4.6 Summary

This chapter has analysed the current status of road maintenance considerations in Australia. From a comprehensive literature review, this chapter identified a total of 19 factors influencing road maintenance decision making, and 11 factors each for RUC and environmental assessment. This research implemented a questionnaire survey with professionals working in the Australian road maintenance sector. Budget limitations, onsite construction costs and ACs were the three most significant factors considered during road maintenance. The three strongest factors leading to the limited consideration of RUC were the cost of investment, lack of expertise and difficulty measuring benefits. Likewise, the top three factors leading to the limited consideration of environmental issues were the cost of investment, difficulty measuring benefits and learning curves required to obtain new knowledge.

The results indicated a number of issues influencing economic and organisational factors, with the greatest importance attached to budget and costs. However, social issues—such as user costs and environmental factors—have significantly fewer impacts. Although social impacts are considered an essential factor in the road lifecycle, the results indicated that direct cost items tend to have more issues with road maintenance. This emphasises the need for innovative decision making in road maintenance by integrating social impacts.

Through employing a questionnaire survey, this chapter has described the ways in which decision makers consider factor weights (importance). Budget limitation held the greatest importance, thereby suggesting that cost should be carefully managed during this phase. Onsite construction cost and AC were ranked second and third, respectively. Generally, direct costs and site conditions tended to rank higher than other social impacts.

RUC factors and environmental factors tended to display a similar trend in road maintenance management. The results for both factors indicated that budget limitation is the most significant consideration. Although the results indicated a similar trend, the only difference was that RUC requires more expertise, and the learning curves required to obtain new knowledge of environmental assessment should be considered. Therefore, the primary factors causing difficulty in incorporating social impacts into road maintenance are budgets, measuring benefits and lack of expertise. Notably, the results indicated that social impacts receive limited consideration in Australia, which reiterated that this research is useful to emphasise the importance of integrating social impacts into road management, and to propose an innovative method to achieve this.

Chapter 5: Environmental Impacts of Road Maintenance

5.1 Introduction

Road pavement construction and maintenance processes consume energy as a result of pavement material production, pavement construction processes, and transportation of materials. To quantify the environmental cost of these processes, this chapter estimates the total emissions of eight pavement strategies that are adopted by MRWA. The emissions values are calculated using the LCA approach, which is widely adopted to evaluate environmental impacts. The emissions values are then converted to emissions cost using the carbon tax value to enable decision makers to make relevant decisions.

5.2 Assumptions

The eight strategies of the road treatment process were extracted from system boundary and adopted. Details of the back data and assumptions regarding raw materials, transportation and equipment are described below.

5.2.1 Raw Materials

The IVL Report from the Swedish Environmental Research Institute calculated per tonne produced bitumen from crude oil extraction to delivery from the local depot. They calculated the steps of bitumen production, including crude oil extraction, storage in the local depot, filling of the tanker lorry and delivery to the customer. The current study used Australia-specific emission factors in the database, such as SimaPro, the Australian LCA Dataset (2010) and the Greenhouse Gas Assessment Workbook for Road Projects (February 2013). Table 5.1 displays the emissions factors for mix asphalts, reclaimed asphalt pavement (RAP) and bitumen.

Table 5.1: Asphalt and Bitumen Emissions Factors for Australia

Asphalt and bitumen	Emissions factors for Australia	Unit	Boundary
Hot mix asphalt (400 MJ/t)	0.058	t Co_2-e/t	Mine to end of production
Hot mix asphalt (400 MJ/t) 10% RAP	0.057		
Hot mix asphalt (400 MJ/t) 20% RAP	0.056		
Hot mix asphalt (400 MJ/t) 30% RAP	0.055		
Hot mix asphalt (400 MJ/t) 40% RAP	0.054		
Hot mix asphalt (400 MJ/t) 50% RAP	0.053		
Warm mix asphalt (372 MJ/t)	0.054		
Warm mix asphalt (372 MJ/t) 10% RAP	0.053		
Warm mix asphalt (372 MJ/t) 20% RAP	0.052		
Warm mix asphalt (372 MJ/t) 30% RAP	0.051		
Warm mix asphalt (372 MJ/t) 40% RAP	0.050		
Warm mix asphalt (372 MJ/t) 50% RAP	0.049		
Bitumen	0.630		

Source: The Greenhouse Gas Assessment Workbook for Road Projects (2013).

The LCI of crushed aggregates is based on the production of crushed aggregates from rock mass. The rock is blasted, and the blasted rock is transported by diesel driven maintenance vehicles to a stone breaker. The blasted rock is then crushed and sieved to become the final product. This research referred to the Australia-specific emissions factors in *Sustainable Aggregates—CO_2 Emission Factor Study* and *Greenhouse Gas Assessment Workbook for Road Projects*. The emissions factors are shown in Table 5.2.

Table 5.2: Aggregate Emissions Factors for Australia

Asphalt and bitumen	Emissions factors for Australia	Unit	Boundary
Aggregate (e.g., crushed rock)	0.005	t Co_2-e/t	Mine to end of Production
Sand	0.003		
Crushed brick/glass/concrete	0.004		
RAP	0.009		

Source: The Greenhouse Gas Assessment Workbook for Road Projects (2013).

In this study's analysis, the extraction of natural gravel and sand was assumed to occur from a pit where the gravel (sand) is dug out of the pit using a wheel loader, and is thereafter loaded onto lorry loaders for further transportation. The inventory analysis data for cement included data from the working to the final product at the factory gate. The

Australia-specific emissions factors for cement were adopted from *Greenhouse Gas Assessment Workbook for Road Projects*, as displayed in Table 5.3.

Table 5.3: Emissions Factors for Cement and Concrete for Australia

Cement and concrete	Emissions factor for Australia	Unit	Boundary
Concrete 40 MPa (1:1:5:3)	0.155	t Co_2-e/t	Mine to end of production
Concrete 30 MPa (1:2:4)	0.127		
Concrete 20 MPa (1:3:6)	0.096		
Portland cement	0.82		
Fly ash	0.161		
Lime (calcined)	1.09		
Lime (re-carbonated)	0.42		

Source: The Greenhouse Gas Assessment Workbook for Road Projects (2013).

This research applied practical data related to pavement maintenance strategies from MRWA to calculate accurate results. Table 5.4 presents the detailed consumption of the four main raw materials used in the eight strategies examined in this research.

Table 5.4: Raw Material Consumption and Assumptions

Treatment	Bitumen (litre/m^2)	Crushed aggregate (m^3/m^2)	Gravel (m^3/m^2)	Cement (kg/m^2)	Details
ASDG	3.6	0.03	0	0	Density of asphalt = 2.4 tonne/m^3 Density of bitumen = 1 tonne/m^3 Binder content of 5%
ASIM	4.8	0.04	0	0	
ASOG	3.6	0.03	0	0	
ASRS	12	0.1	0	0	100 mm asphalt
CS	1.8	0.001429	0	0	Binder application rate = 1.8 L/m^2 Aggregate spread rate = 700 m^2/m^3
Slurry	1.92	0.02	0	0.064	Residual bitumen 6% Density 1.6 tonne/m3 Mineral filler (cement) 0.2 %
RipSeal	1.8	0.001429	0.05	0	Sprayed seal + 50 mm new gravel base + 150 mm cement stabilisation subbase with 1.5% cement
GrOL	1.8	0.001429	0.15	4.95	Sprayed seal + 150 mm new gravel base + 150 mm cement stabilisation subbase with 1.5% cement

5.2.2 Mixing Plant

A hot mixed asphalt plant mixes bitumen and stone kind according to the high-temperature method. Warm bitumen is mixed with stones that are heated using an oil burner. In the production of cold mixed asphalt, bitumen is emulsified in emulsifiers to become 65% bituminous and 35% water emulsion. Asphalt is generally manufactured in asphalt plants for cold mixing in geographical locations other than tanks (IVL 2001). Table 5.5 displays the capacity and consumption of hot and cold mixing plants for asphalts.

Table 5.5: Consumption and Capacity of Mixing Plants

Type	Consumption	Capacity	Source
Hot mixing plant	10,480 KWh	50 m^3/h	IVL Report
Cold mixing plant	3,168 KWh		

Additionally, Table 5.6 displays the indirect emissions factors for the consumption of purchased electricity.

Table 5.6: Indirect Emissions Factors for Consumption of Purchased Electricity

State or territory	Emissions factor (kg CO_2-e/kWh)
New South Wales and Australian Capital Territory	0.84
Victoria	1.13
Queensland	0.79
South Australia	0.56
South West Interconnected System in Western Australia	0.76
North Western Interconnected System in the Northern Territory	0.66
Darwin Katherine Interconnected System in the Northern Territory	0.57
Tasmania	0.12
Northern Territory	0.67

Sources: National Greenhouse and Energy Reporting (Measurement) Determination (2008) and Department of the Environment.

5.2.3 Transportation

This study considered four scenarios of fuel and energy consumption in transportation: (1) fuel consumption at maximum load, (2) fuel consumption without load, (3) fuel consumption at maximum load and empty on return and (4) energy consumption at maximum load and empty on return. For the first scenario, this research assumed that the delivery truck would have a full load for delivery without considering empty returns. Figure 5.1 displays the location and region distribution of Western Australia. Through the eight regions studied, a total of 17,610 actual cases were analysed. Table 5.7 presents the average transport distance and treated area information, and indicates the areas in Western Australia and regional centres where the delivery starts are listed.

Figure 5.1: Location and Region Distribution of Western Australia

Table 5.7: Transport Distance

Region no.	Name	Regional centre	Case count	Treated area (m^2)
1	Great Southern	Albany (452 km)	325	12,202,356
2	Southwest	Bunbury (165 km)	1,070	16,640,903
5	Goldfield-Esperance	Kalgoorlie (597 km)	1,407	19,438,381
6	Kimberley	Kununurra (3,208 km) Derby (2,512 km)	1,796	12,896,096
7	Metropolitan	Perth City (25 km)	5,242	13,971,201
8	Wheat Belt	Northam (99.7 km) Narrogin (180 km)	1,080	23,849,336
11	Pilbara	Port Headland (1,663 km)	2,692	21,834,968
14	Mid-West-Gascoyne	Carnarvon (907 km) Geraldton (431 km)	3,998	30,345,685

Source: MRWA, Deighton's Total Infrastructure Management System.

Figure 5.2 presents a simplified diagram showing the sequence of transport activity. Three significant groups of transport activity include materials transport from port and quarry to mixing plan (5c, 5d, 5e and 5f), transport from port and quarry to site directly (5g, 5h, 5i and 5j), and transport from mixing plant to the site (5k).

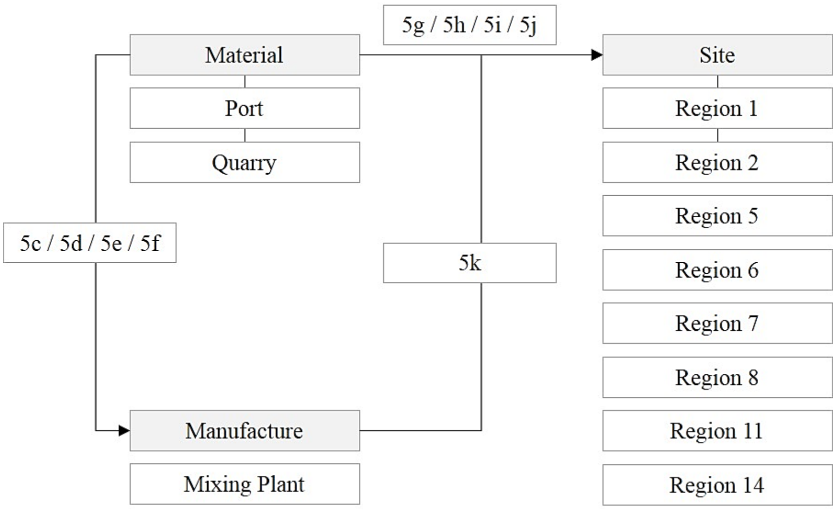


Figure 5.2: Transport Activity Diagram

Finally, Table 5.8 presents the transport emissions factors from *The Greenhouse Gas Assessment Workbook for Road Projects*, calculated with SimaPro 2010. This research only considered heavy goods vehicles.

Table 5.8: Transport Emissions Factors for Australia

Vehicle	Emissions factor	Unit	Boundary
Car	4.19E-04	t CO_2-e/km	Indirect
Light commercial vehicles	6.88E-04		
Medium goods vehicles	1.16E-04		
Heavy goods vehicles	2.14E-04		

Source: The Greenhouse Gas Assessment Workbook for Road Projects (2013).

5.2.4 Equipment

Excavation is one of the basic activities of construction. Excavators are a type of heavy construction equipment, consisting of a boom, dipper, bucket and cab on a rotating platform (TWMM 1916). The volume is used to measure the amount of material during production calculations for excavation in roadworks. Wheel loader activity can be distinguished depending on usage minus vehicle loading and carrying. To calculate the production of the wheel loader, information is required about the loader (e.g., bucket and cycle time), material (e.g., density, workability and bearing capacity) and site (e.g., condition and worker ability).

Dumpers are a compact construction vehicle with a front- or rear-mounted skip used to transport construction materials around a site. If equipped with a towing eye, a dumper can also be used as a tractor to tow a trailer (Machinery Zone 2018). When calculating loading volumes, one must distinguish between the fixed volume in the ground and the loose volume that the material fills when it has been dug up and loaded onto the dumper. The relationship between the loose volume and fixed volume is called the ‘swelling factor’. The fuel consumption in production using dumpers is heavily dependent on the driving conditions that exist at the work site. Variations can occur because of the slope and characteristics of the ground. If the dumpsite is situated higher than the point of loading, fuel consumption is increased. The nature of the ground can also vary between pure asphalt road and very uneven and slippery conditions (IVL report 2001). By considering both Australia-specific descriptions and references and international references, Table 5.9 presents the results of the emissions factor calculations for earthwork equipment.

Table 5.9: Earthwork Equipment Capacity, Consumption and Emissions Factor

Equipment		Capacity	Consumption	Emissions factor (kg CO_2 eq/h)
Bulldozer		500 m^3/h	25 litres/h	73.50
Soil compactor		1,006 m^2/h	18 litre/h	52.92
Dumper	flat	140 m^3/h km	20 litre/h	58.80
	broken	140 m^3/h km	28 litre/h	80.85
	hilly	140 m^3/h km	35 litre/h	102.90
Excavator	< 5% stones	450 m^3/h	34 litre/h	99.96
	< 25% stones	430 m^3/h		
	< 50% stones	360 m^3/h		
	< 50% stones	300 m^3/h		
Motor grader		15,385 m^2/h	42 litre/h	123.48
Hydraulic hammer		40 m^3/hr	18 litre/h	52.92
Wheeled loader	< 5% stones	520 m^3/hr	23 litre/h	67.62
	< 25% stones	470 m^3/hr		
	< 50% stones	410 m^3/hr	35 litre/h	102.90
	< 50% stones	370 m^3/hr		
Pulvimixer		9,173 m^2/h	46 litre/h	135.24
Water sprayer		40,000 m^2/h	27 litre/h	79.38

Source: IVL Report (2001), The World Bank (2010), Shanghai Zenith Company, Caterpillar.

Likewise, Table 5.10 presents the results of the emissions factor calculation for pavement equipment. For the road rollers and asphalt pavers, this study only considered the direct fuel consumption and production of the corresponding amount of fuel.

Table 5.10: Pavement Equipment Capacity, Consumption and Emissions Factor

Equipment		Capacity	Consumption	Emissions factor (kg CO_2 eq/h)
Asphalt paver		1,300 m^2/h	22 litre/h	64.68
Backhoe loader		520 m^3/h	16 litre/h	47.04
Bitumen sprayer		22,800 m^2/h	3 litre/h	8.82
Soil compactor		1,006 m^2/h	18 litre/h	52.92
Asphalt compactor		791 m^2/h	18 litre/h	52.92
Dumper	flat	140 m^3/h km	20 litre/h	58.80
	broken	140 m^3/h km	28 litre/h	80.85
	hilly	140 m^3/h km	35 litre/h	102.90
Excavator (hydraulic)		360 m^3/h	45 litre/h	132.30
Motor grader		15,385 m^2/h	42 litre/h	123.48
Aggregate spreader		19,125 m^2/hr	20 litre/h	58.80
Water sprayer		40,000 m^2/h	27 litre/h	79.38

Source: IVL Report (2001), The World Bank (2010), Shanghai Zenith Company, Caterpillar.

5.3 Results

The following four steps were taken to calculate CO_2 emission from the fuels:

1. collect data on the quantity of fuel combusted on a volume, mass or energy basis
2. collect data on the fuel's density and calorific heating value, and convert the fuel data to a common volume, mass or energy content basis
3. estimate the carbon content of each of the fuels combusted
4. collect data to determine oxidation fraction.

Based on the investigation and calculation of data, the emissions of the eight treatment strategies are discussed in the below sections.

5.3.1 ASDG

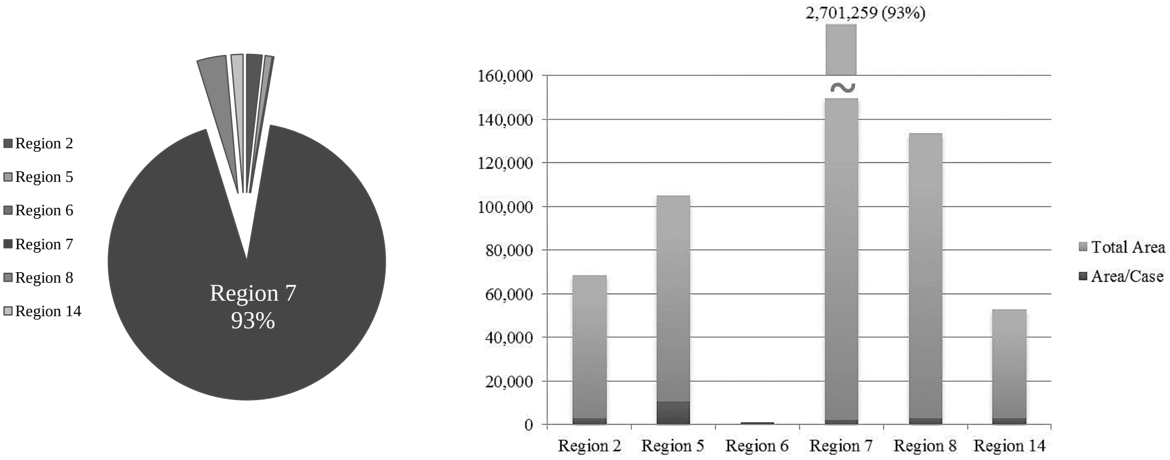
ASDG is asphalt replacement that requires an asphalt mixing plant, asphalt paver and compactor/roller. The depth of ASDG is 30 mm, which consumes bitumen (3.6 litres/m^2) and crushed aggregate (0.03 m^3/m^2). ASDG involves plant mix work, in which the asphalt mixing plant manufacturing generates the most CO_2 emissions. The formula for converting raw material units was calculated, such as converting bitumen volume to weight (litre to tonne). Density is mass per volume ($\rho = m/V$), which means $V = m/\rho$ and has units (kilograms)/(kilograms per cubic metre) = cubic metre. Therefore, 3.6 litres/m^2 consumption of ASDG can convert 3.6 litres to 0.0029988 tonnes for substance with a density of 833 kg/m^3. Likewise, tonnage for crushed aggregate can be derived from the volume. Volume is calculated in length, width and depth as a cubic metre. For example, 1 m^3 is 1.5 tonne to 2.2 tonne of crushed stone, depending on the grading and degree of compaction, which indicates that 1 m^3 is 2.1 tonnes of crushed aggregates.

For the manufacture of asphalt mixing plant, capacity was 50 m^3/h and consumption was 10,480 KW (IVL Report). The indirect emissions factors of the South West Interconnected System in Western Australia (0.76 kg$CO_{2\text{-}e}$/kWh) were used for consumption of electricity (National Greenhouse and Energy Reporting Determination 2008 and Department of the Environment).

The specific equipment used in ASDG encompasses preparation for mowing and clearing, an asphalt paver and a compactor/roller. The capacity and consumption was adopted from the IVL Report and the calculated emissions factor for preparation was 0.05904 kg$CO_{2\text{-}e}$/m^2, for the asphalt paver was 0.044676923 kg$CO_{2\text{-}e}$/m^2 and for the compactor/roller was 0.060075853 kg$CO_{2\text{-}e}$/m^2.

For transport, the critical activity is to delivery raw materials from the port to the asphalt mixing plant (5c and 5d) and from the mixing plant to the site (5k). The distance data were calculated based on Table 5.5, and the transport emissions factors were adopted from *The Greenhouse Gas Assessment Workbook for Road Projects*, as described in Table 5.6.

A total of 1,214 ASDG cases were analysed from six regions. Based on the number of cases counted, the Metro Region 7 had the highest number, with 1,123 (92.5%) cases. Calculating ratio between treated area and cases count indicated that the Metro Region 7 had an average of 2,334.71 m^2/case, while Regions 2, 8 and 14 (which surrounded the Metro area) had 3,113.136 m^2/case to 3,187.405 m^2/case. The faraway Region 5 had an average of 10,533.1 m^2/case, which indicated that the treated area per case was three to five times greater in distant regions than in regions near to providers. Figure 5.3 displays the percentage of treated case frequencies and total treated areas, with the average treated area for each case.



(a) Percentage of case counted

(b) Total treated area and average case per treated area

Figure 5.3: Case Count and Area Information for ASDG

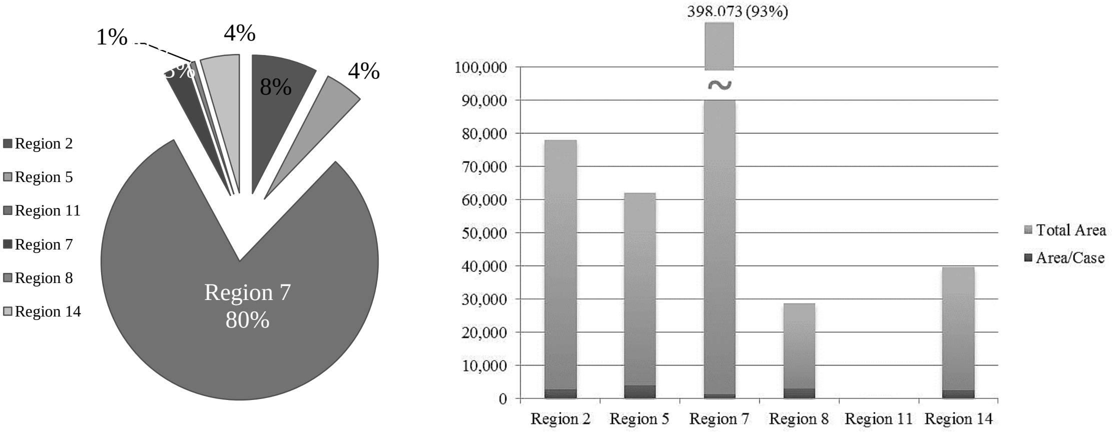
Based on the information discussed above, the average CO_2 emissions factor of ASDG was calculated, as displayed in Table 5.11. The results indicated that the average of six regions was 13.14 $kgCO_2e/m^2$. The result can be the group of three different types according to distance. Regions 2, 7 and 8 had an average of 5.94 $kgCO_2e/m^2$, and Regions 5 and 14 had results similar to the average of 11.98 $kgCO_2e/m^2$. Region 6 was much higher than other regions, with 37.08 $kgCO_2e/m^2$, because of the distance of transportation required.

Table 5.11: Results of ASDG Emissions Factors

		Region 2 (22 cases)	**Region 5 (10 cases)**	**Region 6 (one case)**	**Region 7 (1,123 cases)**	**Region 8 (41 cases)**	**Region 14 (17 cases)**
Material	Bitumen	9,531.7397	32,250.2696	3,588.4302	7,106.5192	9,890.8086	9,562.9975
	Crushed aggregate	748.0819	2,531.1057	281.6316	557.7427	776.2628	750.5351
Manufacture	Asphalt mixing plant	2,509.0036	7,770.8190	942.8095	1,910.8298	2,624.9440	2,912.2839
Placement	Preparation	111.7733	378.1807	42.0795	83.3341	115.9839	1,121.1399
	Asphalt paver	139.0845	470.5868	52.3614	103.6963	144.3239	139.5406
	Compactor/roller	187.0231	632.7854	70.4089	139.4377	194.0684	187.6364
Transport	Transport 5c	171.6016	580.6072	64.6031	127.9399	178.0660	172.1643
	Transport 5d	1,216.6803	4,116.5902	458.0457	907.1127	1,262.5137	1,220.6702
	Transport 5k	5,817.1855	71,213.8465	37,960.0982	657.1337	5,121.7293	23,698.7607
Total	kgCO$_2$e	20,432.1735	119,944.7891	43,460.4682	11,593.7462	20,308.7007	38,756.7285
	kgCO$_2$e/m^2	**6.4944**	**11.5892**	**37.0823**	**5.0070**	**6.3080**	**12.3719**

5.3.2 ASIM

ASIM is an asphalt replacement that requires an asphalt mixing plant, asphalt paver and compactor/roller. The process and depth of ASIM is 30 mm, as with ASDG. However, a difference from ASDG is the amount of material used. For ASIM, 4.8 litres/m^2 of bitumen is used and 0.004 m^3/m^2 of crushed aggregate is used. Therefore, the same methods for manufacture, placement equipment and transport were calculated. Calculation of raw materials also adapted the same methods, except for the consumed amount of bitumen and crushed aggregate. A total of 329 ASIM cases were analysed from six regions. Based on the number of cases, the Metro Region 7 was the highest, with 281 (80%) cases. Calculating the ratio between the treated area and cases indicated that the faraway Region 5 had an average of 4,144.6 m^2/case, which indicated that the treated area per case was two to three times greater in distant regions than in Metro Region 7. Figure 5.4 displays the percentage of treated case frequency and total treated area, with the average of the treated area for each case.



(a) Percentage of case counted

(b) Total treated area and average case per treated area

Figure 5.4: Case Count and Area Information for ASIM

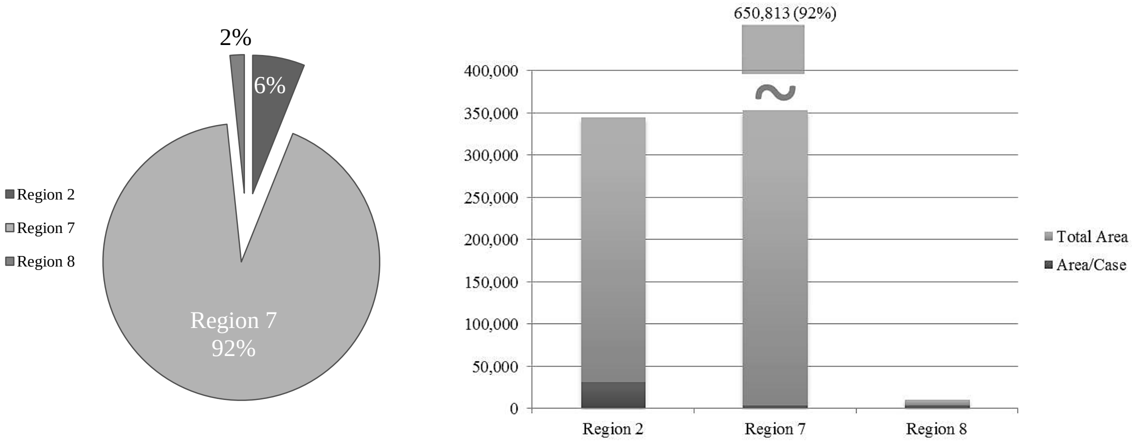
The results of the average CO_2 emissions factor of ASIM were calculated, as displayed in Table 5.12. The total emissions were 168,012.1774 kgCO$_2$e, which indicated an average of 14.1975 kgCO$_2$e/m^2. Regions 2, 7 and 8 had an average of 7.67 kgCO$_2$e/m^2; Regions 5 and 14 had an average of 15.48 kgCO$_2$e/m^2; and the farthest Region 11 had 31.21 kgCO$_2$e/m^2.

Table 5.12: Results of ASIM Emissions Factors

		Region 2 (25 cases)	**Region 5 (15 cases)**	**Region 7 (263 cases)**	**Region 8 (nine cases)**	**Region 11 (two cases)**	**Region 14 (15 cases)**
Material	Bitumen	12,076.3270	16,919.8848	5,865.1401	13,051.5757	429.8767	10,863.3250
	Crushed aggregate	947.7893	1,327.9275	460.3152	1,024.3300	33.7381	852.5890
Manufacture	Asphalt mixing plant	3,322.4381	2,761.0853	1,151.8957	2,814.0254	100.1307	1,748.4024
Placement	Preparation	106.2092	148.8075	51.5829	114.7863	3.7807	95.5411
	Asphalt paver	132.1608	185.1676	64.1869	142.8337	4.7045	118.8859
	Compactor/roller	177.7130	248.9899	86.3103	192.0646	6.3260	159.8627
Transport	Transport 5c	217.4122	304.6116	105.5911	234.9698	7.7391	195.5743
	Transport 5d	1,541.4846	2,159.7412	748.6567	1,665.9703	54.8717	1,386.6507
	Transport 5k	7,370.1376	37,361.8630	542.3444	6,758.4604	2,644.1919	26,921.1970
Total	kgCO_2e	25,891.6719	61,418.0784	9,076.0233	25,999.0162	3,285.3594	42,342.0282
	kgCO_2e/m^2	**8.6050**	**15.0335**	**6.2796**	**8.1314**	**31.2108**	**15.9252**

5.3.3 ASOG

ASOG is an asphalt replacement that requires an asphalt mixing plant, asphalt paver and compactor/roller, as with ASDG and ASIM. The process and methods are the same, and even the raw material consumption is the same as ASDG, with bitumen of 3.6 litres/m^2 and crushed aggregate of 0.03 m^3/m^2. However, the important difference is that the depth is 40 mm, which is 10 mm thicker. The only three regions—Regions 2, 7 and 8—had a total of 181 cases. The Metro Region 7 most adopted this strategy, with 167 cases (92%). Figure 5.5 displays the cases counted and treated area.



(a) Percentage of case counted

(b) Total treated area and case per treated area

Figure 5.5: Case Count and Area Information for ASOG

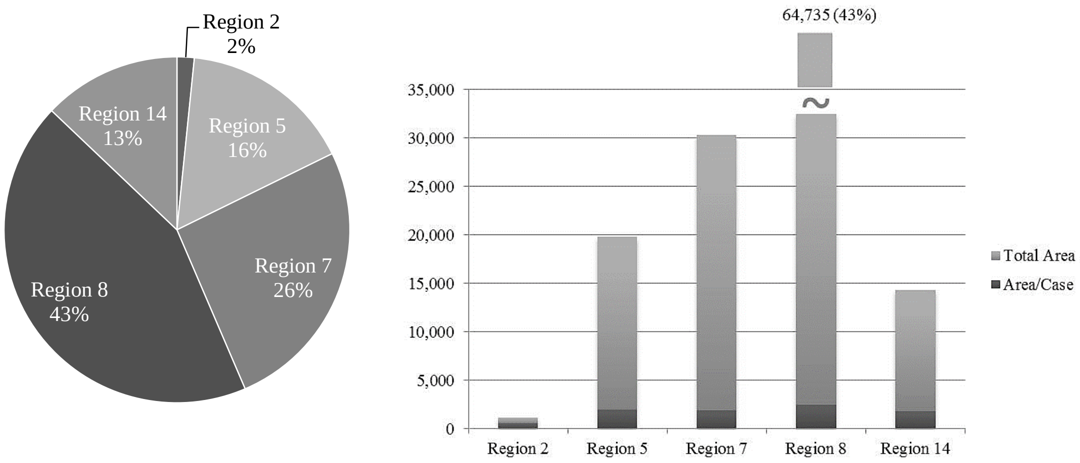
Table 5.13 presents the results of the ASOG average emissions factor of 5.9662 kgCO$_2$e/m^2. ASOG cases were placed in Regions 2, 7 and 8, which were all close to Metro Region 7, where the material transport began. Therefore, the average emissions were similar to the average of 5.9662 kgCO$_2$e/m^2.

Table 5.13: Emissions Factor of ASOG

		Region 2 (11 cases)	Region 7 (167 cases)	Region 8 (three cases)
Material	Bitumen	95,989.0221	11,932.0997	10,710.1764
	Crushed aggregate	7,533.5300	936.4699	840.5694
Manufacture	Asphalt mixing plant	20,476.5523	2,155.3196	5,485.4756
Placement	Preparation	1,125.6091	139.9210	125.5922
	Asphalt paver	1,400.6448	174.1098	156.2799
	Compactor/roller	1,883.4092	234.1208	210.1453
Transport	Transport 5c	1,728.1071	214.8157	192.8172
	Transport 5d	12,252.5331	1,523.0746	1,367.1021
	Transport 5k	58,581.7447	1,103.3509	5,546.0202
Total	kgCO$_2$e	200,971.1523	18,413.2820	24,634.1783
	kgCO$_2$e/m^2	**6.5283**	**4.7703**	**6.6002**

5.3.4 ASRS

ASRS aims to increase the structural capacity of the pavement, as well as providing surfacing with adequate properties. It requires an asphalt mixing plant for manufacture and a profiler, asphalt paver and compactor/roller for placement. Therefore, transport has two critical activities: transport from the port to the manufacturing plant (5c and 5d) and from the plant to each site (5k). For the profiler, a specification from Wirtgen was adopted for 52 litres/h consumption with 375 m^3/h capacity. This was calculated to be 0.36608 kgCO^{2}e/m^3. ASRS has full-depth asphalt, which involves major rehabilitation, with the top 150 mm replaced once every 50 years, and 5% of the road replaced to full depth every 50 years for patching and repair. Among the total of 62 cases, Region 8 (Wheat Belt) mostly used ASRS treatment, with 27 cases, while Region 7 was the second highest, with 16 cases. Figure 5.6 displays the detailed percentage of case frequency and treated area.



(a) Percentage of case counted (b) Total treated area and case per treated area

Figure 5.6: Case Count and Area Information for ASRS

Table 5.14 presents the results of the emissions factor of ASRS. Despite having a similar process and method as the other plant mix works, it has a higher emissions factor because of the four to five times depth and the earthwork of the profiler. In particular, the profiler is affected by the cubic metres of the site and, for that reason, the greater depth causes much higher emissions factors than in the other plant mix works. Consequently, the average emissions factor of ASRS was 25.0002 kgCO$_2$e/m^2 through the Western Australia regions. Regions 2, 7 and 8 had an average of 17.0995 kgCO$_2$e/m^2, and Regions 5 and 14 had an average of 36.8513 kgCO$_2$e/m^2.

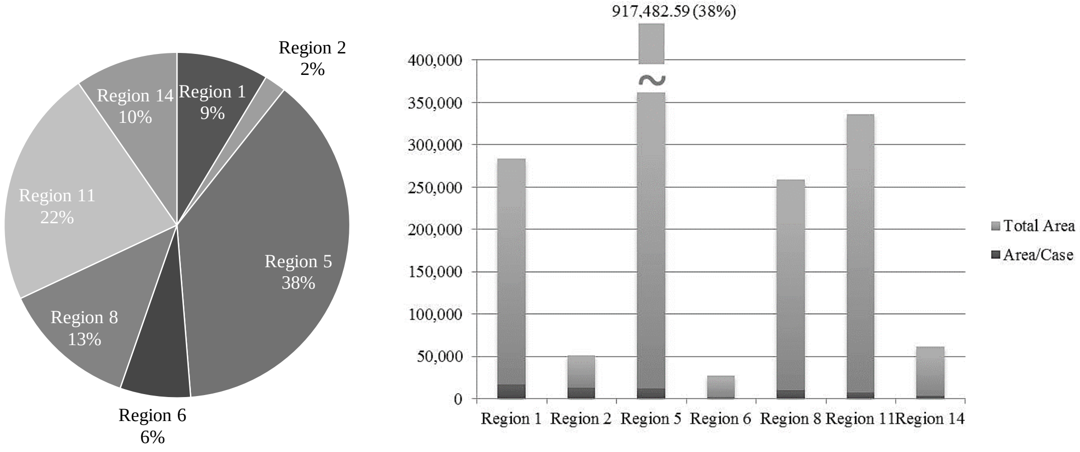
Table 5.14: Results of ASRS Calculation

		Region 2 (one case)	**Region 5 (10 cases)**	**Region 7 (16 cases)**	**Region 8 (27 cases)**	**Region 14 (eight cases)**
Material	Bitumen	6,123.6000	20,215.0242	19,337.8181	25,411.0458	18,309.5569
	Crushed aggregate	480.6000	1,586.5407	1,517.6947	1,994.3413	1,436.9934
Manufacture	Asphalt mixing plant	123.6946	433.7449	462.5245	657.3697	727.5455
Placement	Preparation	47.3801	45.3834	53.4900	48.2969	49.2764
	Profiler	21.5424	71.1151	68.0291	89.3943	64.4118
	Asphalt paver	26.8062	88.4916	84.6516	111.2372	80.1504
	Compactor/roller	36.0455	118.9922	113.8287	149.5777	107.7760
Transport	Transport 5c	110.2442	363.9346	348.1421	457.4795	329.6301
	Transport 5d	781.6498	2,580.3498	2,468.3787	3,243.5968	2,337.1261
	Transport 5k	3,737.2104	44,638.0677	1,788.1513	13,158.5297	45,374.2465
Total	$kgCO_2e$	11,488.7712	70,141.6442	26,242.7090	45,320.8690	68,816.7131
	$kgCO_2e/m^2$	**19.1480**	**35.4339**	**13.9070**	**18.2436**	**38.2687**

5.3.5 GrOL

GrOL is a spray work treatment strategy with granular, spray and seal. It requires four raw materials: bitumen (1.8 litre/m^2), crushed aggregate (0.001429 m^3/m^2), gravel/sand (0.15 m^3/m^2) and cement (4.95 kg/m^2). For the bitumen and crushed aggregates, the same methods as above were used to convert from volume to tonnes. Additionally, 0.15 m^3 of gravel/sand (dry) was converted into 0.2475 tonnes for a substance with a density of 1,650 kg/m^3. Moreover, 4.95 m^3 of cement (clinker) was converted into 7.00425 tonnes for a substance with a density of 1,415 kg/m^3. Pavement stabilisation and seal are included with two respray and major rehabilitation within 50 years of 150 mm replaced arrogate.

After preparation for the placement, the following earthwork equipment is needed: bulldozer, motor grader, soil compactor, Pulvimixer and water sprayer. For the pavement, a dumper, bitumen sprayer, compactor/roller and aggregate spreader are needed. The bulldozer and motor grader specification were adapted from Caterpillar as 0.05 litre/m^3 and 0.00273 litre/m^2, which was calculated to 0.132 kgCO$_2$e/m^3 and 0.00720702 kgCO$_2$e/m^2. The soil compactor (0.017893 litre/m^2), Pulvimixer (0.005015 litre/m^2), water sprayer (0.000675 litre/m^2), dumper (0.2 litre/m^3), bitumen sprayer (0.000132 litre/m^2) and aggregate sprayer (0.001046 litre/m^2) specifications were adopted from the IVL Report. Each equipment emissions factor was calculated as follows: soil compactor = 0.047236581 kgCO$_2$e/m^2, Pulvimixer = 0.013238853 kgCO$_2$e/m^2, water sprayer = 0.001782 kgCO$_2$e/m^2, dumper = 0.528 kgCO$_2$e/m^3, bitumen sprayer = 0.000347368 kgCO$_2$e/m^2 and aggregate sprayer = 0.002760784 kgCO$_2$e/m^2. As a result of requiring four raw materials, four different methods of transport are needed to deliver the materials to seven site regions. However, GrOL is spray work, which does not need a mixing plant. Therefore, the materials are sent to each site directly (5g, 5h, 5i and 5j). A total of 197 cases were investigated, with 195,040 m^2 of treated area. Region 5 (Goldfield-Esperance) adopted 75 cases with 929,881 m^2, while Region 11 (Pilbara) was the second highest, with 44 cases and 336,221 m^2. Figure 5.7 displays the case frequency and treated area information.



(a) Percentage of case counted

(b) Total treated area and case per treated area

Figure 5.7: Case Count and Area Information for GrOL

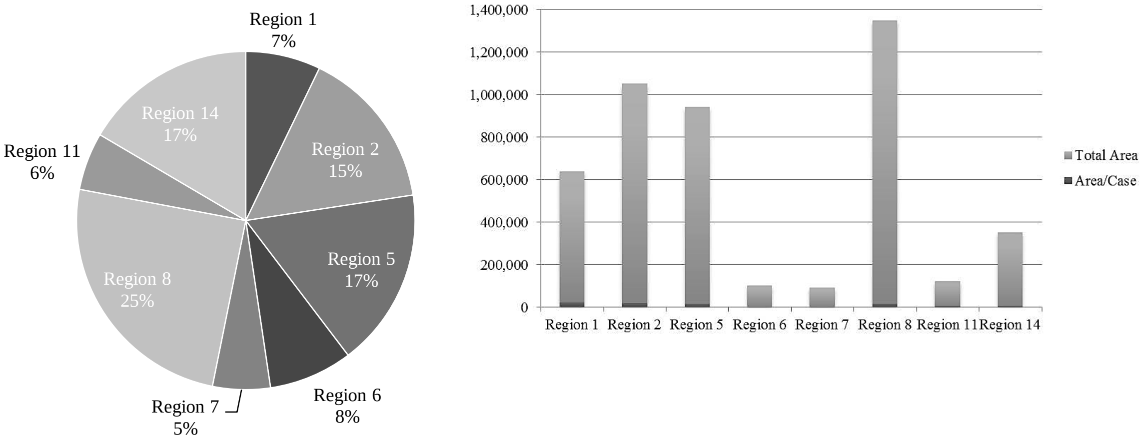
The average result for the emissions factor for GrOL was 8.5273 $kgCO_2e/m^2$. The result for each region indicated that the greater the distance from the supplier (metro region), the higher the average emissions factor. This meant that the GrOL factor was more affected by transport than the other strategies. Table 5.15 presents the detailed calculation results. Although the distance of transport was the criteria used to group the result, the distances between different regions of GrOL treatment did not seem to be higher than that of other plant mixing works. Further analysis will be conducted in the discussion section.

Table 5.15: Results of GrOL Emissions Factor

		Region 1 (17 cases)	**Region 2 (four cases)**	**Region 5 (75 cases)**	**Region 6 (13 cases)**	**Region 8 (25 cases)**	**Region 11 (44 cases)**	**Region 14 (19 cases)**
Material	Bitumen	25,531.5473	19,763.5450	18,980.7311	3,296.3804	15,852.5348	11,698.1855	5,017.9678
	Crushed aggregate	190.8380	147.7245	141.8733	24.6391	118.4913	87.4392	37.5073
	Gravel/sand	13,433.7065	10,398.8082	9,986.9220	1,734.4271	8,340.9869	6,155.1299	2,640.2594
	Cement	67,693.8732	52,400.6985	50,325.1600	8,739.9623	42,031.1182	31,016.3530	13,304.5472
Placement	Preparation	598.7881	463.5119	445.1526	77.3096	371.7875	274.3560	117.6858
	Bulldozer	18.9460	19.2946	20.5431	2.5657	12.0813	6.5107	4.3698
	Motor grader	120.1949	93.0409	89.3556	15.5184	74.6290	55.0716	23.6231
	Soil compactor	787.7869	609.8127	585.6587	101.7112	489.1368	360.9526	154.8316
	Pulvimixer	220.7906	170.9104	164.1408	28.5063	137.0889	101.1631	43.3942
	Water sprayer	29.7193	23.0052	22.0940	3.8371	18.4527	13.6169	5.8410
	Dumper	35.1794	43.5639	50.4887	31.8840	33.5543	27.5791	30.2396
	Bitumen sprayer	5.7932	4.4844	4.3068	0.7480	3.5970	2.6544	1.1386
	Aggregate spreader	46.0429	35.6410	34.2293	5.9446	28.5880	21.0962	9.0493
	Compactor/roller	1,001.9136	775.5646	744.8453	129.3572	622.0880	459.0623	196.9160
Transport	Transport 5g	3,920.0246	1,107.6996	3,849.1115	3,202.4074	753.8761	6,608.2121	1,142.0257
	Transport 5h	3,691.8750	1,043.2304	3,625.0891	3,016.0239	709.9997	6,223.6072	1,075.5586
	Transport 5i	433,138.5222	122,393.9729	425,303.0603	353,846.2540	83,298.6555	730,166.6477	126,186.7956
	Transport 5j	3,985.2353	2,256.4252	7,840.7827	6,523.4226	1,535.6735	13,461.1728	2,326.3487
Total	kgCO$_2$e	125,312.2549	89,356.9610	96,910.4845	26,934.6448	71,133.6840	76,572.1625	26,131.3035
	kgCO$_2$e/m^2	**7.5155**	**6.9261**	**7.8226**	**12.5332**	**6.8711**	**10.0387**	**7.9843**

5.3.6 RipSeal

RipSeal is spray work that has the same process as GrOL; however, RipSeal includes a 150 mm cement stabilisation, placement of 50 mm gravel and a seal of 10 mm. Therefore, it requires bitumen of 1.8 litre/m^2, crushed aggregate of 0.001429 m^3/m^2, gravel/sand of 0.05 m^3/m^2 and cement of 4.95 kg/m^2. A total of 363 cases was investigated over an area of 4,659,613 m^2. Region 8 was the highest area adopted, while Region 1 (Great Southern), Region 2 (South West) and Region 5 were similar. Figure 5.8 presents detailed information of the case frequency and treated area.



(a) Percentage of case counted

(b) Total treated area and case per treated area

Figure 5.8: Case Count and Area Information for RipSeal

The average result of the emissions factor for RipSeal was 11.5992 kgCO$_2$e/m^2. As with GrOL, the results for each region indicated that the greater the distance from the supplier (metro region), the higher the average emissions factor. Table 5.16 presents detailed calculation results.

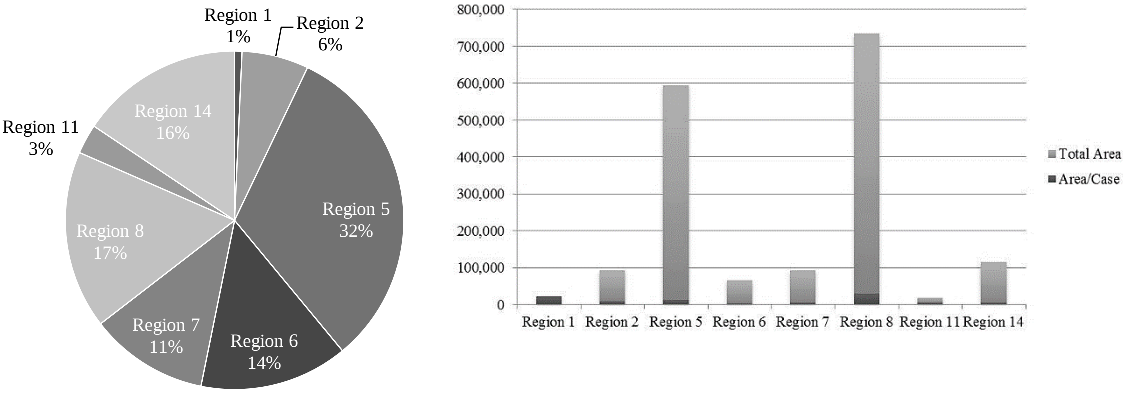
Table 5.16: Results of RipSeal Emissions Factor

		Region 1 (26 cases)	**Region 2 (56 case)**	**Region 5 (62 cases)**	**Region 6 (29 cases)**	**Region 7 (20 cases)**	**Region 8 (90 cases)**	**Region 11 (20 cases)**	**Region 14 (60 cases)**
Material	Bitumen	37,670.4093	28,828.8151	23,283.8363	5,454.0977	7,199.3751	22,957.5220	9,410.7110	8,990.1966
	Crushed aggregate	281.5710	215.4837	174.0372	40.7672	53.8124	171.5982	70.3413	67.1981
	Gravel/sand	6,606.9011	5,056.2002	4,083.6828	956.5780	1,262.6770	4,026.4515	1,650.5166	1,576.7639
	Cement	99,878.6278	76,436.1882	61,734.3339	14,460.8938	19,088.2902	60,869.1500	24,951.3854	23,836.4414
Placement	Preparation	883.4792	676.1185	546.0728	127.9142	168.8460	538.4198	220.7082	210.8459
	Bulldozer	25.5247	19.6951	19.6018	2.9662	5.3763	16.9410	7.3546	5.8043
	Motor grader	177.3410	135.7175	109.6133	25.6763	33.8925	108.0772	44.3028	42.3232
	Soil compactor	1,162.3368	889.5255	718.4328	168.2885	222.1398	708.3643	290.3716	277.3964
	Pulvimixer	325.7646	249.3046	201.3530	47.1657	62.2585	198.5311	81.3816	77.7450
	Water sprayer	43.8492	33.5574	27.1029	6.3487	8.3802	26.7230	10.9543	10.4648
	Dumper	29.8102	35.0894	43.4739	26.7387	52.6724	35.3196	33.9630	33.4434
	Bitumen sprayer	8.5476	6.5414	5.2832	1.2376	1.6336	5.2092	2.1353	2.0399
	Aggregate spreader	67.9338	51.9891	41.9894	9.8358	12.9832	41.4010	16.9710	16.2127
	Compactor/roller	1,478.2690	1,131.3055	913.7085	214.0307	282.5192	900.9032	369.2968	352.7949
Transport	Transport 5g	57,837.8309	16,157.8645	47,217.4026	52,986.1258	611.3755	10,917.5771	53,160.3596	20,460.5459
	Transport 5h	5,447.1608	1,521.7460	4,446.9300	4,990.2277	57.5793	1,028.2163	5,006.6370	1,926.9720
	Transport 5i	213,024.1099	59,511.4761	173,907.7173	195,154.6610	2,251.7740	40,210.8293	195,796.3861	75,358.8007
	Transport 5j	11,781.7804	3,291.4168	9,618.3598	10,793.4701	124.5395	2,223.9509	10,828.9621	4,167.8890
Total	$kgCO_2e$	223,707.1374	134,736.5585	153,185.2143	90,312.3626	29,248.3506	104,774.3552	106,156.3523	62,055.0773
	$kgCO_2e/m^2$	**9.0929**	**7.1659**	**10.0797**	**25.3811**	**6.2295**	**6.9890**	**17.2777**	**10.5782**

5.3.7 Slurry

Slurry is spray work that refers to slurry/micro-surfacing. It is a cold mix surface treatment that consists of applying a 3~20 mm layer of aggregate, poly-modified bitumen emulsion, adhesion agents, water and cement or lime. Therefore, it requires bitumen of 1.92 litre/m^2, crushed aggregate of 0.02 m^3/m^2 and cement of 0.064 kg/m^2. Placement requires preparation, a dumper, a slurry mixer and paver, a compactor/roller and a rotary broom. A Bergkamp slurry mixer and paver was adopted with 0.000867 litre/m^2, and calculated as 0.002288 $kgCO_2e/m^2$. For rotary broom specifications, a Bobcat was used, with 0.022756 litre/m^2, calculated into 0.060075853 $kgCO_2e/m^2$.

Three critical transport activities (5g, 5h and 5j) were calculated for the delivery of three materials. A total of 141 cases were investigated over 1,741,711 m^2 of treated area. Region 5 adopted the highest number, with 75 cases; however, the treated area of Region 8 was higher. This means that the treated area for each case was higher than the cases from Region 5. Figure 5.9 displays the case number and area information. The average result of the emission factor for slurry is 8.1194 $kgCO_2e/m^2$. Table 5.17 presents the detailed calculation results.



(a) Percentage of case counted

(b) Total treated area and case per treated area

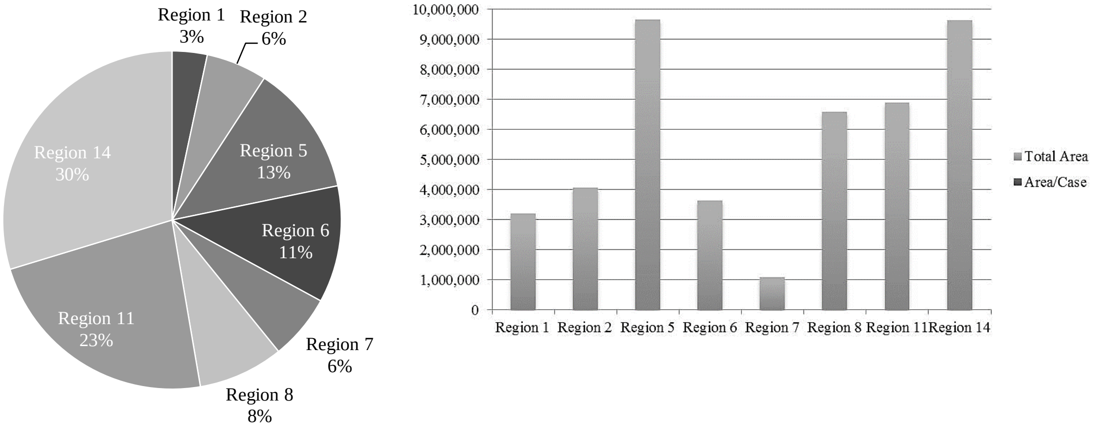
Figure 5.9: Case Count and Area Information for Slurry

Table 5.17: Results of Slurry Emissions Factor

		Region 1 (one case)	**Region 2 (nine cases)**	**Region 5 (45 cases)**	**Region 6 (20 cases)**	**Region 7 (16 cases)**	**Region 8 (24 cases)**	**Region 11 (four cases)**	**Region 14 (22 cases)**
Material	Bitumen	38,376.1930	16,899.5001	21,542.7000	5,383.3762	9,610.6841	50,046.7510	7,698.4312	8,677.1040
	Crushed aggregate	3,764.8602	1,657.9095	2,113.4263	528.1310	942.8471	4,909.7893	755.2473	851.2591
	Cement	1,233.3235	543.1154	692.3384	173.0107	308.8678	1,608.4004	247.4119	278.8644
Placement	Preparation	843.7799	371.5704	473.6608	118.3646	211.3107	1,100.3812	169.2659	190.7841
	Dumper	45.7354	48.3834	48.6732	38.2942	63.0300	46.6819	62.4481	44.4722
	Slurry mixer and paver	53.7703	23.6785	30.1843	7.5428	13.4659	70.1223	10.7866	12.1578
	Rotary broom	1,411.8426	621.7249	792.5461	198.0520	353.5727	1,841.1971	283.2218	319.2267
	Compactor/roller	1,411.8426	621.7249	792.5461	198.0520	353.5727	1,841.1971	283.2218	319.2267
Transport	Transport 5g	5,892.1467	947.1767	4,368.6544	5,229.9072	81.6145	2,380.0010	4,348.7827	1,974.7987
	Transport 5h	72,833.4795	11,708.1570	54,001.4223	64,647.4641	1,008.8464	29,149.4574	53,755.7858	24,410.7059
	Transport 5j	145.4851	23.3871	107.8680	129.1335	2.0152	58.7655	107.3773	48.7605
Total	kgCO$_2$e	126,012.4677	33,466.3281	84,964.0198	76,651.3283	12,949.8270	93,322.7444	67,721.9803	37,127.3600
	kgCO$_2$e/m^2	**5.3620**	**3.2397**	**6.4496**	**23.2767**	**2.2079**	**3.0488**	**14.3760**	**6.9946**

5.3.8 Chip Seal

CS is spray work that refers to surface dressing. For example, bitumen is sprayed onto a road surface, followed by the spreading of aggregate layers. CS requires 1.8 litres/m^2 of bitumen and 0.001429 m^3/m^2 of crushed aggregates. Therefore, this study calculated data for transport (5g and 5h), preparation, a dumper, an aggregate spreader, a compactor/roller, a water sprayer, a bitumen sprayer and a rotary broom. A total of 3,817 cases of 42,170,017 m^2 were investigated, which was the highest number of cases among the eight strategies, as displayed in Figure 5.10.



(a) Percentage of case counted

(b) Total treated area and case per treated area

Figure 5.10: Case Count and Area Information for CS

The average result of the emissions factor for CS was 2.4059 kgCO$_2$e/m^2. Table 5.18 presents the detailed calculation results.

Table 5.18: Results of CS Emissions Factor

		Region 1 (128 cases)	**Region 2 (222 cases)**	**Region 5 (480 cases)**	**Region 6 (427 cases)**	**Region 7 (238 cases)**	**Region 8 (311 cases)**	**Region 11 (877 cases)**	**Region 14 (1,134 cases)**
Material	Bitumen	38,564.6887	27,418.2422	21,915.1471	12,928.2980	6,899.8990	32,398.6804	11,901.0296	11,069.3248
	Crushed aggregate	288.2554	204.9403	163.8068	96.6388	51.5739	242.1670	88.9554	82.7387
Placement	Preparation	904.4527	643.0365	513.9731	303.2057	161.8224	759.8421	279.1133	259.6074
	Dumper	27.8197	26.3235	29.8648	26.2142	29.7049	28.5266	24.1718	25.3079
	Aggregate spreader	69.5465	49.4453	39.5212	23.3145	12.4431	58.4269	21.4620	19.9621
	Water sprayer	44.8901	31.9154	25.5097	15.0488	8.0316	37.7127	13.8531	12.8849
	Bitumen sprayer	8.7505	6.2213	4.9726	2.9335	1.5656	7.3514	2.7004	2.5117
	Rotary broom	1,513.3624	1,075.9516	859.9981	507.3346	270.7671	1,271.3948	467.0223	434.3844
	Compactor/roller	1,513.3624	1,075.9516	859.9981	507.3346	270.7671	1,271.3948	467.0223	434.3844
Transport	Transport 5g	5,921.0876	1,536.7272	4,444.1831	12,559.7389	58.5944	1,540.7372	6,722.7971	2,519.2378
	Transport 5h	5,576.4741	1,447.2880	4,185.5270	2,479.9611	55.1841	1,451.0647	6,331.5232	2,372.6155
Total	kgCO$_2$e	54,432.6902	33,516.0429	33,042.5018	29,450.0178	7,820.3533	39,067.2988	26,319.6505	17,232.9597
	kgCO$_2$e/m^2	**2.1631**	**1.8816**	**2.3157**	**3.5074**	**1.7419**	**1.8480**	**3.4008**	**2.3891**

5.4 Discussion

The input factors contributing to the carbon emissions of road maintenance treatment strategies are as follows: (1) manufacturing of the raw material, (2) manufacturing process at the mixing plant, (3) placement process at the site and (4) transportation of the materials. The following sections describe the environmental cost of each treatment, and analysis of those factors affection.

5.4.1 Environmental Costs of Treatment Strategies

In Australia, a carbon tax was introduced by the Labor Government in 2011. Although the carbon tax was revoked from July 2014, it provided a useful guide on the value of environmental impacts, especially for global climate change. According to the Labor Government, the carbon price from 2012 to 2013 and 2013 to 2014 was AUD$23.00 and AUD$24.15, respectively. An average value of AUD$23.58 was adopted for this research. Table 5.19 displays the environmental cost of the eight examined strategies.

Table 5.19: Environmental Cost of Eight Strategies

Treatment strategies	Total emissions (kg CO_{2-e}/m^2)	Carbon price ($/ tonne CO_{2-e})	Environmental cost ($/$m^2$)
ASDG	14.0330	23.58	0.3309
ASIM	18.3479		0.4326
ASOG	14.0239		0.3307
ASRS	43.9552		1.0364
GrOL	8.2918		0.1955
RipSeal	11.5992		0.2735
Slurry	8.1194		0.1915
CS	2.4056		0.0567

5.4.2 Source of Emission Values

The following sections discuss the sources of the emissions values of the eight maintenance treatment strategies, including detailed analysis.

5.4.2.1 ASDG

Table 5.20 displays the sources of emissions factors for the plant mixing work of ASDG. The results indicated the kgCO_{2e}/m^2 emissions values and percentage of sources in each region. Since the process of manufacturing plant is same, emissions of Regions 1 and 11 were estimated based on the average of another region because of the lack of actual cases.

Table 5.20: Emissions Value of ASDG in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
RA 1	3.3021	0.8409*	0.1407	5.5648	9.0076
RA 2	3.3021	0.7371	0.1407	2.3146	6.4944
RA 5	3.3021	0.9395	0.1407	7.2069	11.5892
RA 6	3.3021	0.8044	0.1407	32.8351	37.0823
RA 7	3.3021	0.8352	0.1407	0.7291	5.0070
RA 8	3.3021	0.8338	0.1407	2.0314	6.3080
RA 11	3.3021	0.8409*	0.1407	19.2792	22.7220
RA 14	3.3021	0.8956	0.1407	8.0336	12.3719
Average	**3.3021**	**0.8409**	**0.1407**	**9.7493**	**14.0330**
Percentage	**23.53 %**	**5.99 %**	**1.00 %**	**69.47 %**	**100 (%)**

Transportation was the largest source of emissions in the ASDG treatment, accounting for 69.47% of the carbon emissions in ASDG treatment. Although Australia has a very large land mass, unlike Singapore or South Korea, it transports materials by heavy vehicle trucks. Therefore, it is important to ensure effective management of materials transport. The followed source is the manufacture of raw materials at 23.53%. Although bitumen contributes significantly more than crushed aggregates, both materials need to be carefully managed through the design. Of total emissions, the hot mixing plant comprised 5.99%, while the placement of the site comprised only 1.00%. The environmental cost can be transferred as Table 5.21 referred to the carbon tax.

Table 5.21: Environmental Cost of ASDG ($\$/m^2$)

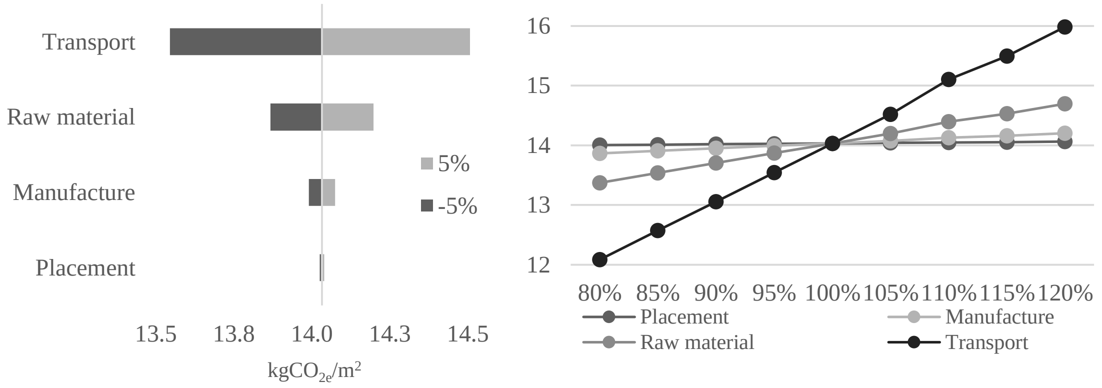
	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
Environmental cost	0.0779	0.0198	0.0033	0.2299	0.3309

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for four sources. Table 5.22 displays the results of the sensitivity analysis.

Table 5.22: Sensitivity Analysis Results of ASDG

	Materials	**Manufacture**	**Placement**	**Transport**
± 5%	± 0.1651 (1.18%)	± 0.0420 (0.30%)	± 0.0070 (0.05%)	± 0.4875 (3.47%)
± 10%	± 0.3302 (2.35%)	± 0.0841 (0.60%)	± 0.0141 (0.10%)	± 0.9749 (6.95%)
± 15%	± 0.4953 (3.53%)	± 0.1261 (0.90%)	± 0.0211 (0.15%)	± 1.4624 (10.42%)
± 20%	± 0.6604 (4.71%)	± 0.1682 (1.20%)	± 0.0281 (0.20%)	± 1.9499 (13.89%)

According to the sensitivity analysis results, transportation has the highest effect on the total emissions of the four sources. Figure 5.11 presents a tornado plot with the different percentages.



(a) ± 5% of tornado plot (b) Fluctuation of each percentage

Figure 5.11: Tornado Plot for ASDG

A 5% change in transport emissions would create a 3.74% change in total emissions. This means that a 5% reduction of transport emissions could save \$0.0115/m^2, and a 5% reduction of raw material emissions could save a total of \$0.0039/m^2. In summary, a 1% fluctuation in each source affected the total emissions as follows: material = 0.235%, manufacture = 0.060%, placement = 0.010% and transport = 0.695%.

5.4.2.2 ASIM

Table 5.23 displays the sources of emission factors for plant mixing work of ASIM. The results indicate the kgCO$_{2e}$/m^2 emission values and percentage of emissions sources in each region.

Table 5.23: Emissions Value of ASIM in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
RA 1	4.4028	0.8553	0.1407	7.4197	12.8185
RA 2	4.4028	0.9754	0.1407	3.0861	8.6050
RA 5	4.4028	0.8809	0.1407	9.6092	15.0336
RA 6	4.4028	0.8553	0.1407	43.3801	48.7789
RA 7	4.4028	0.7641	0.1407	0.9721	6.2797
RA 8	4.4028	0.8793	0.1407	2.7086	8.1314
RA 11	4.4028	0.9617	0.1407	25.7056	31.2108
RA 14	4.4028	0.6703	0.1407	10.7115	15.9253
Average	**4.4028**	**0.8553**	**0.1407**	**12.9491**	**18.3479**
Percentage	**24.00 %**	**4.66%**	**0.77 %**	**70.58 %**	**100 (%)**

Like other strategies, transportation was the largest source of emissions for ASIM treatment at 12.9491 $kgCO_2/m^2$, which comprised 70.58% of the total emissions. The second-highest source was the manufacture of raw materials at 24.00%. The hot mixing plant comprised 5.66%, while the placement of the site accounted for only 0.77% of the total emissions. The difference between ASDG and ASIM lay in the quantity of raw materials, which affected the other sources as well. The environmental cost can be transferred as Table 5.24 referred to the carbon tax.

Table 5.24: Environmental Cost of ASIM ($\$/m^2$)

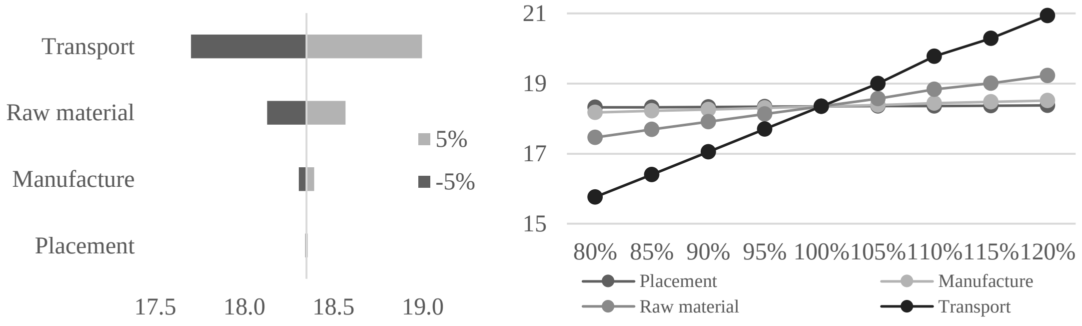
	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
Environmental cost	0.1038	0.0202	0.0033	0.3053	0.4326

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for four sources. Table 5.25 displays the results of the sensitivity analysis.

Table 5.25: Sensitivity Analysis Results of ASIM

	Materials	Manufacture	Placement	Transport
± 5%	± 0.2201 (1.20%)	± 0.0428 (0.23%)	± 0.0070 (0.04%)	± 0.6475 (3.53%)
± 10%	± 0.4403 (2.40%)	± 0.0855 (0.47%)	± 0.0141 (0.08%)	± 1.2949 (7.06%)
± 15%	± 0.6604 (3.60%)	± 0.1283 (0.70%)	± 0.0211 (0.12%)	± 1.9424 (10.59%)
± 20%	± 0.8806 (4.80%)	± 0.1711 (1.93%)	± 0.0281 (0.15%)	± 2.5898 (14.12%)

According to the sensitivity analysis results, transportation had the highest effect on the total emissions of the four sources. Figure 5.12 presents a tornado plot of the different percentages.



(a) ± 5% of tornado plot

(b) Fluctuation of each percentage

Figure 5.12: Tornado Plot for ASIM

A 5% change in transport emissions created a 3.53% change in the total emissions. In summary, a 1% fluctuation in each source affected the total emissions as follows: material = 0.240%, manufacture = 0.080%, placement = 0.047% and transport = 0.706%.

5.4.2.3 ASOG

Table 5.26 displays the sources of emissions factors for plant mixing work for ASOG. The results indicated the $kgCO_{2e}/m^2$ emissions values and percentage of sources in each region. The manufacturing plant emissions for Regions 1, 5, 6, 11 and 14 were based on the average of other regions because of a lack of actual data (The manufacture of raw material process is same). Unlike the transportation sector, which is greatly influenced by regional distance, it is reasonable to use the average of another region for the mixing plant because mixing plants are mostly influenced by materials, which are same and small part as the surface depth.

Table 5.26: Emissions Value of ASOG in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
RA 1	3.3021	0.8318*	0.1407	5.5648	9.8394
RA 2	3.3021	0.7710	0.1407	2.3146	6.5284
RA 5	3.3021	0.8318*	0.1407	7.2069	11.4815
RA 6	3.3021	0.8318*	0.1407	32.8351	37.1097
RA 7	3.3021	0.5985	0.1407	0.7291	4.7704
RA 8	3.3021	1.1260	0.1407	2.0314	6.6002
RA 11	3.3021	0.8318*	0.1407	19.2792	23.5538
RA 14	3.3021	0.8318*	0.1407	8.0336	12.3082
Average	**3.3021**	**0.8318**	**0.1407**	**9.7493**	**14.0239**
Percentage	**23.55 %**	**5.93 %**	**1.00 %**	**69.52 %**	**100 (%)**

Transportation was the largest source of emissions in the ASOG treatment at 9.7493 $kgCO_2/m^2$, which was 69.52% of the total emissions. The second-highest source was the manufacture of raw materials at 23.55%. The hot mixing plant comprised 5.93%, while placement of the site accounted for only 1.00% of the total emissions. The environmental cost can be transferred as Table 5.27 referred to the carbon tax.

Table 5.27: Environmental Cost of ASOG ($\$/m^2$)

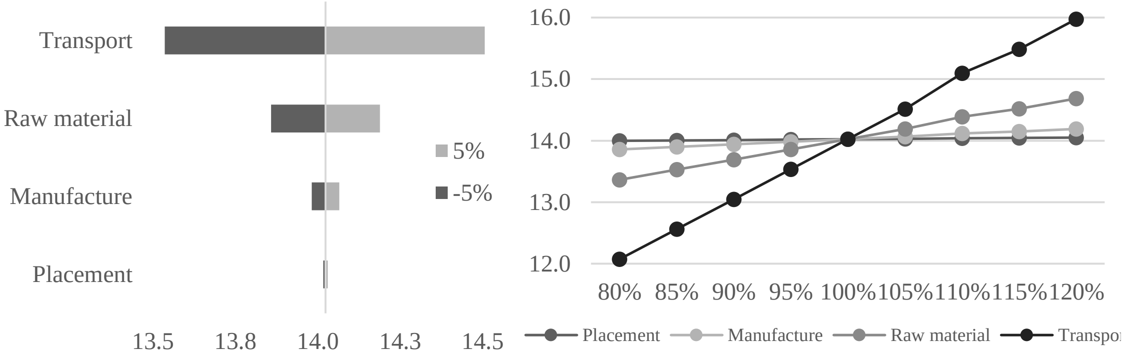
	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
Environmental cost	0.0779	0.0196	0.0033	0.2299	0.3307

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for four sources. Table 5.28 displays the results of the sensitivity analysis.

Table 5.28: Sensitivity Analysis Results of ASOG

	Materials	**Manufacture**	**Placement**	**Transport**
± 5%	± 0.1651 (1.18%)	± 0.0416 (0.30%)	± 0.0070 (0.05%)	± 0.4875 (3.48%)
± 10%	± 0.3302 (2.35%)	± 0.0832 (0.59%)	± 0.0141 (0.10%)	± 0.9749 (6.95%)
± 15%	± 0.4953 (3.53%)	± 0.1248 (0.89%)	± 0.0211 (0.15%)	± 1.4624 (10.43%)
± 20%	± 0.6604 (4.71%)	± 0.1664 (1.19%)	± 0.0281 (0.20%)	± 1.9499 (13.90%)

According to the sensitivity analysis result, transportation had the highest effect on the total emissions of the four sources. Figure 5.13 presents a tornado plot of the different percentages.



(a) ± 5% of tornado plot

(b) Fluctuation of each percentage

Figure 5.13: Tornado Plot ASOG

In summary, a 1% fluctuation in each source affected the total emissions as follows: material = 0.235%, manufacture = 0.059%, placement = 0.01% and transport = 0.695%.

5.4.2.4 ASRS

Table 5.29 displays the sources of emissions factors for plant mixing work of ASRS. The results indicate the $kgCO_{2e}/m^2$ emission values and percentage of sources in each region. Although they all involve plant mixing work, the values differ for ASDG, ASIM and ASOG because of the methods of the plants, which influence the material amount and placement method. Like as, an average of value has been adopted in lack data.

Table 5.29: Emissions Value of ASRS in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
RA 1	11.0070	0.2575*	0.1929*	18.5493	29.5563
RA 2	11.0070	0.2062	0.2196	7.7152	19.1480
RA 5	11.0070	0.2190	0.1848	24.0230	35.4338
RA 6	11.0070	0.2575*	0.1929*	109.4503	120.9077
RA 7	11.0070	0.2850	0.1893	2.4302	13.9115
RA 8	11.0070	0.2764	0.1888	6.7714	18.2436
RA 11	11.0070	0.2575*	0.1929*	64.2641	75.7215
RA 14	11.0070	0.3010	0.1820	26.7787	38.2687
Average	**11.0070**	**0.2575**	**0.1929**	**32.4978**	**43.9552**
Percentage	**25.04 %**	**0.59 %**	**0.44 %**	**73.93 %**	**100 (%)**

Transportation was the largest source of emissions for the ASRS treatment at 32.4978 $kgCO_2/m^2$, which was 73.93% of the total emissions. The second-highest source was the manufacture of raw materials at 25.04%. The mixing plant comprised 0.59%, while the placement of the site accounted for only 0.44% of the total emissions. The environmental cost can be transferred as Table 5.30 referred to the carbon tax.

Table 5.30: Environmental Cost of ASRS ($\$/m^2$)

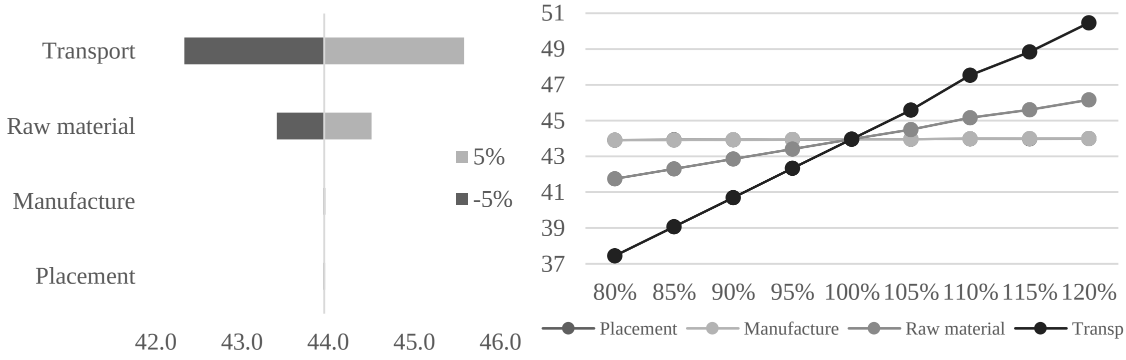
	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
Environmental cost	0.0779	0.0196	0.0033	0.2299	0.3307

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for four sources. Table 5.31 displays the results of the sensitivity analysis.

Table 5.31: Sensitivity Analysis Results of ASRS

	Materials	Manufacture	Placement	Transport
± 5%	± 0.5504 (1.25%)	± 0.0129 (0.03%)	± 0.0096 (0.02%)	± 1.6249 (3.70%)
± 10%	± 1.1007 (2.50%)	± 0.0258 (0.06%)	± 0.0193 (0.04%)	± 3.2498 (7.39%)
± 15%	± 1.6511 (3.76%)	± 0.0386 (0.09%)	± 0.0289 (0.07%)	± 4.8747 (11.09%)
± 20%	± 2.2014 (5.01%)	± 0.0515 (0.12%)	± 0.0386 (0.09%)	± 6.4996 (14.79%)

According to the sensitivity analysis results, transportation had the highest effect on the total emissions of the four sources. Figure 5.14 presents a tornado plot of the different percentages.



(a) ± 5% of tornado plot (b) Fluctuation of each percentage

Figure 5.14: Tornado Plot for ASRS

Unlike with the hot mixing plant works, ASRS was less affected by manufacturing at the mixing plant. The placement and manufacture were very similar, with little effect on the total emissions. In summary, 1% fluctuation in each source affected the total emissions as follows: material = 0.250%, manufacture = 0.060%, placement = 0.04% and transport = 0.739%.

5.4.2.5 GrOL

Table 5.32 displays the sources of emissions factors for GrOL. The results indicated the $kgCO_{2e}/m^2$ emissions values and percentage of sources in each region. GrOL is a spray work, which does not require manufacturing at a mixing plant. The results indicated that, unlike with the plant mixing works, raw material was the factor that generated the most emissions.

Table 5.32: Emissions Value of GrOL in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
RA 1	6.4068	0	0.1734	0.9352	7.5154
RA 2	6.4068	0	0.1778	0.3414	6.9260
RA 5	6.4068	0	0.1806	1.2352	7.8226
RA 6	6.4068	0	0.2088	5.9176	12.5332
RA 7	6.4068	0	0.1853*	0.0517	6.6438
RA 8	6.4068	0	0.1745	0.2892	6.8705
RA 11	6.4068	0	0.1910	3.4409	10.0387
RA 14	6.4068	0	0.1912	1.3863	7.9843
Average	**6.4068**	**0**	**0.1853**	**1.6997**	**8.2918**
Percentage	**77.27 %**	**0 %**	**2.23 %**	**20.50 %**	**100 (%)**

GrOL is a treatment that uses bitumen, crushed aggregate, gravel and cement. Therefore, raw materials were the largest source of emissions in the GrOL treatment at 6.4068 $kgCO_2/m^2$, which comprised 77.27% of the total emissions. The second-highest source was transportation at 20.50%. Placement at the site accounted for 2.23% of the total emissions. The environmental cost can be transferred as Table 5.33 referred to the carbon tax.

Table 5.33: Environmental Cost of GrOL ($\$/m^2$)

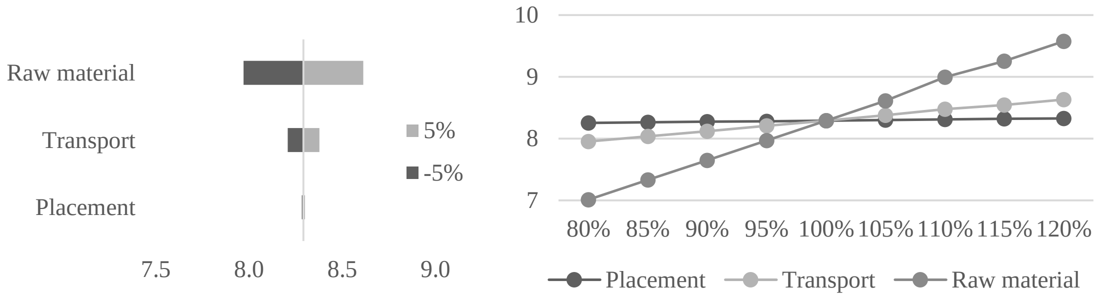
	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
Environmental cost	0.1511	0	0.0044	0.0401	0.1955

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for four sources. Table 5.34 displays the results of the sensitivity analysis.

Table 5.34: Sensitivity Analysis Result of GrOL

	Materials	**Placement**	**Transport**
± 5%	± 0.3203 (3.86%)	± 0.0093 (0.11%)	± 0.0850 (1.02%)
± 10%	± 0.6407 (7.73%)	± 0.0185 (0.22%)	± 0.1700 (2.05%)
± 15%	± 0.9610 (11.59%)	± 0.0278 (0.34%)	± 0.2250 (3.07%)
± 20%	± 1.2814 (15.45%)	± 0.0371 (0.45%)	± 0.3399 (4.10%)

According to the sensitivity analysis results, raw materials had the strongest effect on the total emissions of the three sources. Figure 5.15 presents a tornado plot of the different percentages.



(a) ± 5% of tornado plot

(b) Fluctuation of each percentage

Figure 5.15: Tornado Plot for GrOL

In summary, a 1% fluctuation in each source affected the total emissions as follows: material = 0.773%, placement = 0.022% and transport = 0.205%.

5.4.2.6 RipSeal

Table 5.35 displays the sources of emissions factors for RipSeal. The results indicated the $kgCO_{2e}/m^2$ emissions values and percentage of sources in each region. RipSeal is spray work, which does not require manufacturing at a mixing plant. The raw material accounted for 50.61% of emissions, followed by transportation at 47.80%.

Table 5.35: Emissions Value of RipSeal in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
RA 1	5.8698	0	0.1724	3.0507	9.0929
RA 2	5.8698	0	0.1824	1.1136	7.1658
RA 5	5.8698	0	0.1805	4.0293	10.0796
RA 6	5.8698	0	0.2084	19.3029	25.3811
RA 7	5.8698	0	0.1909	0.1687	6.2294
RA 8	5.8698	0	0.1742	0.9449	6.9889
RA 11	5.8698	0	0.1839	11.2240	17.2777
RA 14	5.8698	0	0.1863	4.5220	10.5781
Average	**5.8698**	**0**	**0.1849**	**5.5445**	**11.5992**
Percentage	**50.61 %**	**0 %**	**1.59 %**	**47.80 %**	**100 (%)**

RipSeal is a treatment that uses bitumen, crushed aggregate, gravel and cement. The emissions value of raw materials was 5.8698 $kgCO_2/m^2$, which was 50.61% of the total emissions. The second-highest source was transportation at 47.80%, similar to raw materials. Placement at the site accounted for 1.59% of the total emissions. The environmental cost can be transferred as Table 5.36 referred to the carbon tax.

Table 5.36: Environmental Cost of RipSeal ($\$/m^2$)

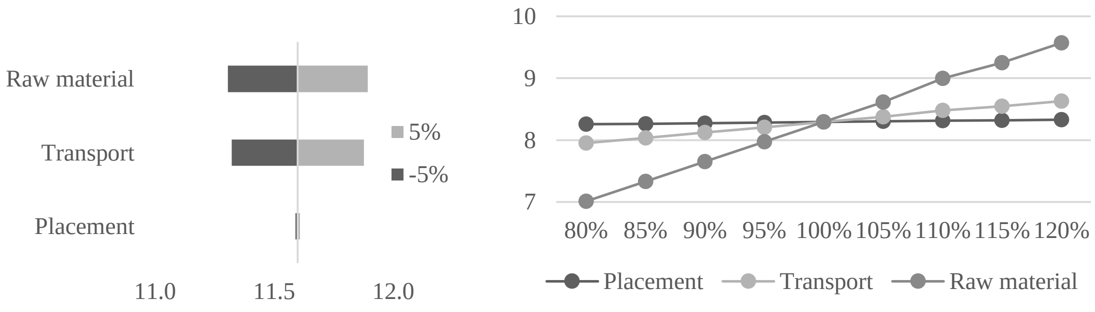
	Manufacture of raw materials	**Manufacture at mixing plant**	**Placement at site**	**Transportation**	**Total**
Environmental cost	0.1384	0	0.0044	0.1307	0.2735

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for four sources. Table 5.37 displays the results of the sensitivity analysis.

Table 5.37: Sensitivity Analysis Results of RipSeal

	Materials	**Placement**	**Transport**
± 5%	± 0.2935 (2.53%)	± 0.0092 (0.08%)	± 0.2772 (2.39%)
± 10%	± 0.5870 (5.06%)	± 0.0185 (0.16%)	± 0.8317 (4.78%)
± 15%	± 0.8805 (7.59%)	± 0.0277 (0.24%)	± 0.5544 (7.17%)
± 20%	± 1.1740 (10.12%)	± 0.0370 (0.32%)	± 0.2772 (9.56%)

According to the sensitivity analysis results, raw materials had the strongest effect on the total emissions of the three sources. Figure 5.16 presents a tornado plot of the different percentages.



(a) ± 5% of tornado plot

(b) Fluctuation of each percentage

Figure 5.16: Tornado Plot for RipSeal

In summary, a 1% fluctuation in each source affected the total emissions as follows: material = 0.506%, placement = 0.016% and transport = 0.478%.

5.4.2.7 Slurry

Table 5.38 displays the sources of emissions factors for slurry. The results indicated the $kgCO_{2e}/m^2$ emissions values and percentage of sources in each region.

Table 5.38: Emissions Value of Slurry in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
RA 1	1.8456	0	0.1603	3.3561	5.3620
RA 2	1.8456	0	0.1689	1.2251	3.2396
RA 5	1.8456	0	0.1713	4.4327	6.4496
RA 6	1.8456	0	0.1957	21.2353	23.2766
RA 7	1.8456	0	0.1766	0.1856	2.2078
RA 8	1.8456	0	0.1637	1.0395	3.0488
RA 11	1.8456	0	0.1827	12.3477	14.3760
RA 14	1.8456	0	0.1742	4.9747	6.9945
Average	**1.8456**	**0**	**0.1742**	**6.0996**	**8.1194**
Percentage	**22.73 %**	**0 %**	**2.15 %**	**75.12 %**	**100 (%)**

Slurry is a treatment that uses bitumen, crushed aggregate and cement. The emissions value of raw materials was 1.8456 $kgCO_2/m^2$, which comprised 22.73% of the total emissions. The highest source was transportation at 75.12%, which was 6.0996 $kgCO_2/m^2$. Placement at the site accounted for 2.15% of the total emissions. The environmental cost can be transferred as Table 5.39 by referring to the carbon tax.

Table 5.39: Environmental Cost of Slurry ($/m^2)

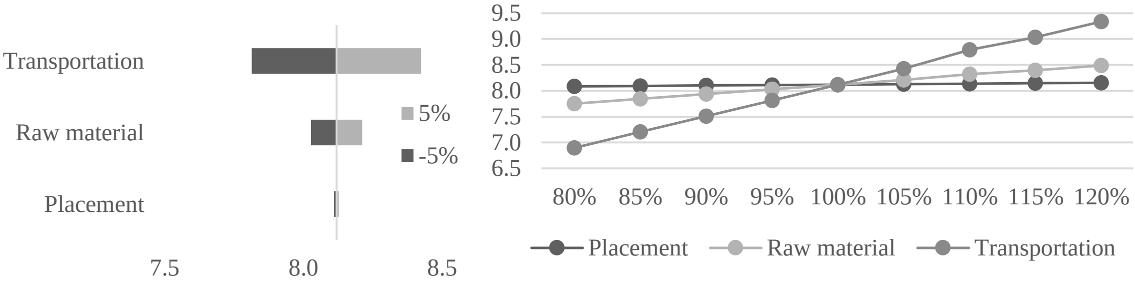
	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
Environmental cost	0.0435	0	0.0041	0.1438	0.1915

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for three sources. Table 5.40 displays the results of the sensitivity analysis.

Table 5.40: Sensitivity Analysis Results of Slurry

	Materials	**Placement**	**Transport**
± 5%	± 0.0923 (1.14%)	± 0.0087 (0.11%)	± 0.3050 (3.76%)
± 10%	± 0.1846 (2.27%)	± 0.0174 (0.21%)	± 0.6100 (7.51%)
± 15%	± 0.2768 (3.41%)	± 0.0261 (0.32%)	± 0.9149 (11.27%)
± 20%	± 0.3691 (4.55%)	± 0.0348 (0.43%)	± 1.2199 (15.02%)

According to the sensitivity analysis results, raw materials had the strongest effect on the total emissions of the three sources. Figure 5.17 presents a tornado plot of the different percentages.



(a) ± 5% of tornado plot

(b) Fluctuation of each percentage

Figure 5.17: Tornado Plot for Slurry

In summary, a 1% fluctuation in each source affected the total emissions as follows: material = 0.227%, placement = 0.021% and transport = 0.751%.

5.4.2.8 Chip Seal

Table 5.41 displays the sources of emissions factors for CS. The results indicated the $kgCO_{2e}/m^2$ emissions values and percentage of sources in each region.

Table 5.41: Emissions Value of CS in Each Region (kg CO_{2e}/m^2)

	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
RA 1	1.5423	0	0.1643	0.4564	2.1630
RA 2	1.5423	0	0.1727	0.1666	1.8816
RA 5	1.5423	0	0.1705	0.6028	2.3156
RA 6	1.5423	0	0.1829	1.7796	3.5048
RA 7	1.5423	0	0.1743	0.0252	1.7418
RA 8	1.5423	0	0.1643	0.1414	1.8480
RA 11	1.5423	0	0.1792	1.6793	3.4008
RA 14	1.5423	0	0.1702	0.6765	2.3890
Average	**1.5423**	**0**	**0.1723**	**0.6910**	**2.4056**
Percentage	**64.11 %**	**0 %**	**7.16 %**	**28.72 %**	**100 (%)**

CS is a treatment that uses bitumen and crushed aggregate. The emissions value of raw materials was 1.5423 kgCO_2/m^2, which comprised 64.11% of the total emissions. The second-highest source was transportation at 28.72%. Placement at the site accounted for 7.16% of the total emissions. The environmental cost can be transferred as Table 5.42 referred to the carbon tax.

Table 5.42: Environmental Cost of CS ($/$m^2$)

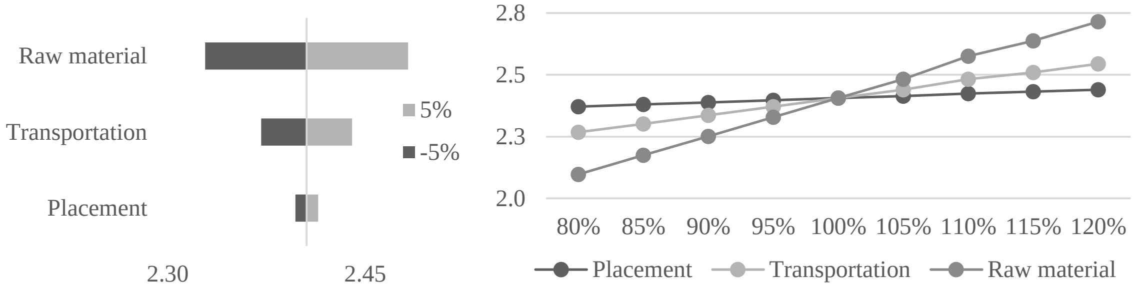
	Manufacture of raw materials	Manufacture at mixing plant	Placement at site	Transportation	Total
Environmental cost	0.0364	0	0.0041	0.0163	0.0567

Additionally, a sensitivity analysis of ± 5%, ± 10%, ± 15% and ± 20% was conducted for three sources. Table 5.43 displays the results of the sensitivity analysis.

Table 5.43: Sensitivity Analysis Results of CS

	Materials	Placement	Transport
± 5%	± 0.0345 (1.44%)	± 0.0086 (0.36%)	± 0.0771 (3.21%)
± 10%	± 0.0691 (2.87%)	± 0.0172 (0.72%)	± 0.1542 (6.41%)
± 15%	± 0.1037 (4.31%)	± 0.0258 (1.07%)	± 0.2313 (9.62%)
± 20%	± 0.1382 (5.74%)	± 0.0345 (1.43%)	± 0.3085 (12.82%)

According to the sensitivity analysis results, raw materials had the strongest effect on the total emissions of the three sources. Figure 5.18 presents a tornado plot of the different percentages.



(a) ± 5% of tornado plot

(b) Fluctuation of each percentage

Figure 5.18: Tornado Plot for CS

In summary, a 1% fluctuation in each source affected the total emissions as follows: material = 0.287%, placement = 0.072% and transport = 0.641%.

5.4.3 Emissions Referring to Regions

A sensitivity analysis of the eight strategies’ emissions indicated that transportation had the greatest effect on the total emission values. Among the eight strategies, GrOL, RipSeal and CS were mostly affected by raw materials, and the other five strategies were highly influenced by transportation. Additionally, even in the same types of strategies, the emissions value gap between regions was high for transportation. To make the best decisions based on accurate data, consideration of region is needed. Figure 5.19 displays the actual emissions value for the eight regions. The result of these values is proportional to distance. The Kimberly Region 6 (2,860 km) has the highest value, while the Metropolitan Region 7 has the lowest. Moreover, Figure 5.20 displays the value of regions in each strategy.

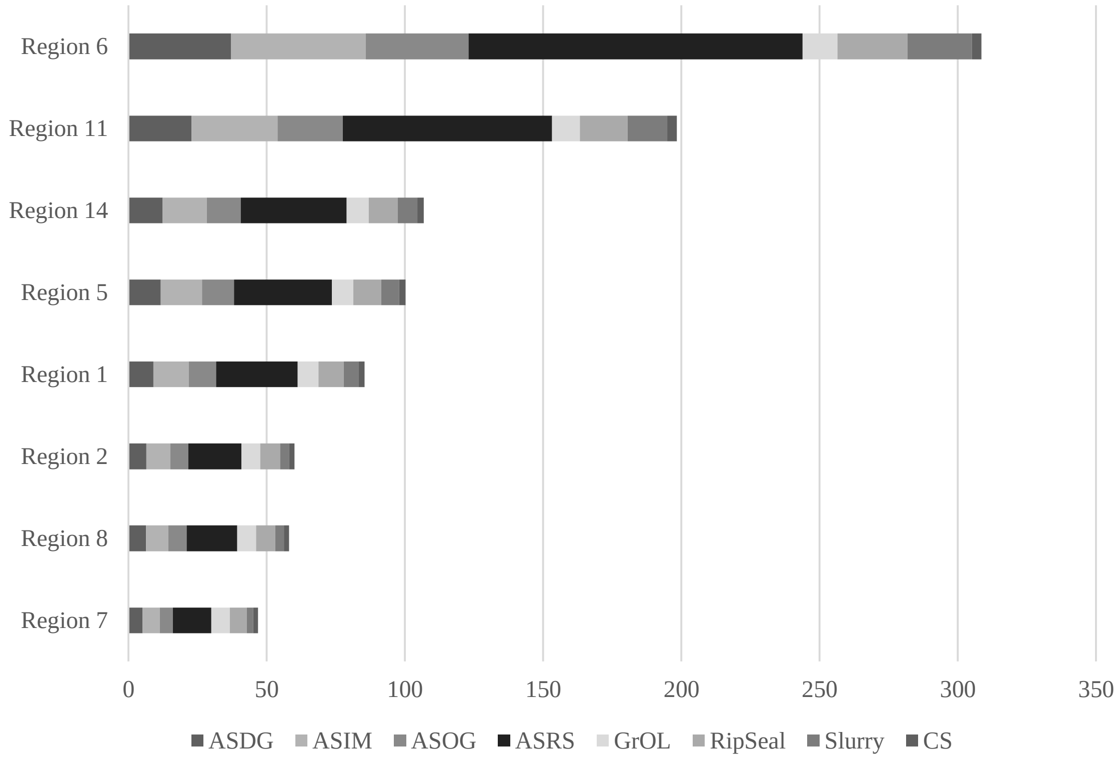


Figure 5.19: Percentage of Each Strategy in Each Region

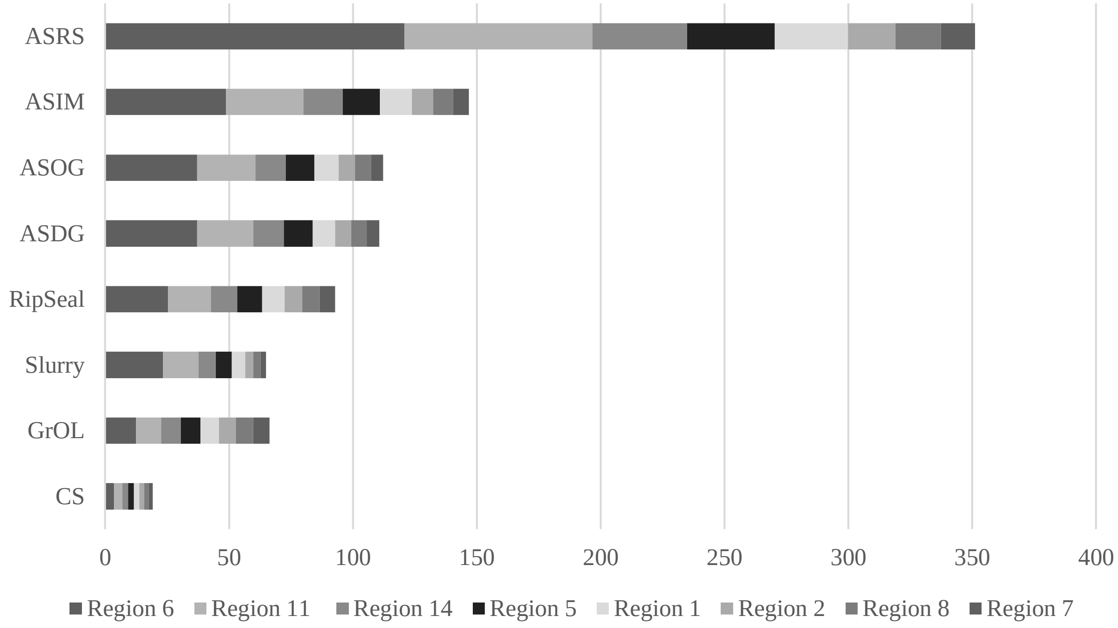


Figure 5.20: Regional Percentage in Each Strategy

The ASRS had the highest value, followed by the plant mix works of ASIM, ASOG and ASDG. To compare the percentage of strategy values in each region, Figure 5.21 displays the results.

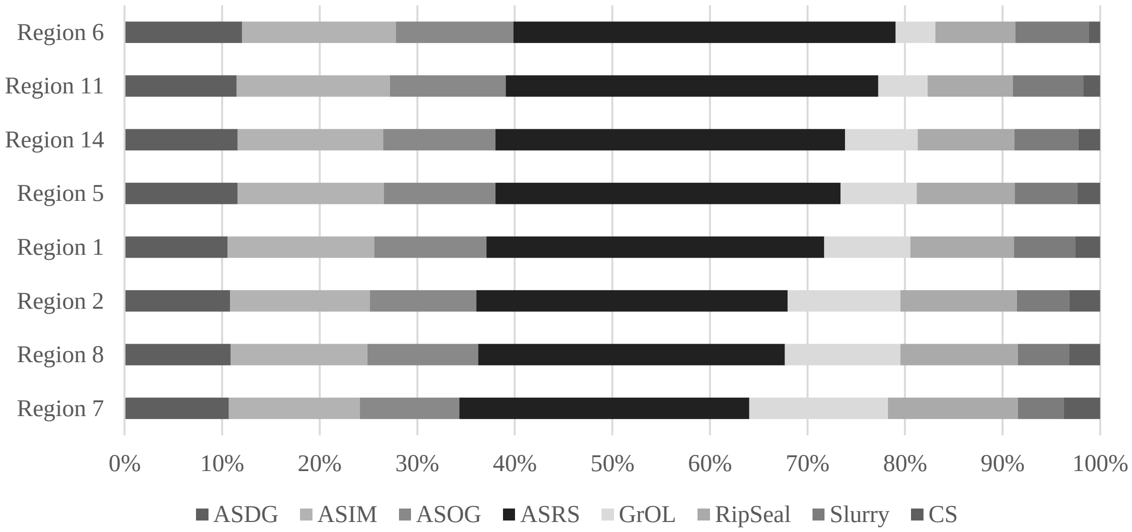


Figure 5.21: Ratio of Strategies in Each Region

In each region, ASRS comprised the largest part of the emissions value, followed by other plant mixing works. However, Figure 5.22 shows that RipSeal, GrOL and CS did not have much affection for regions like other strategies. Although Region 6 has far distance, the emissions value gap in the region was not much different to the other strategies.

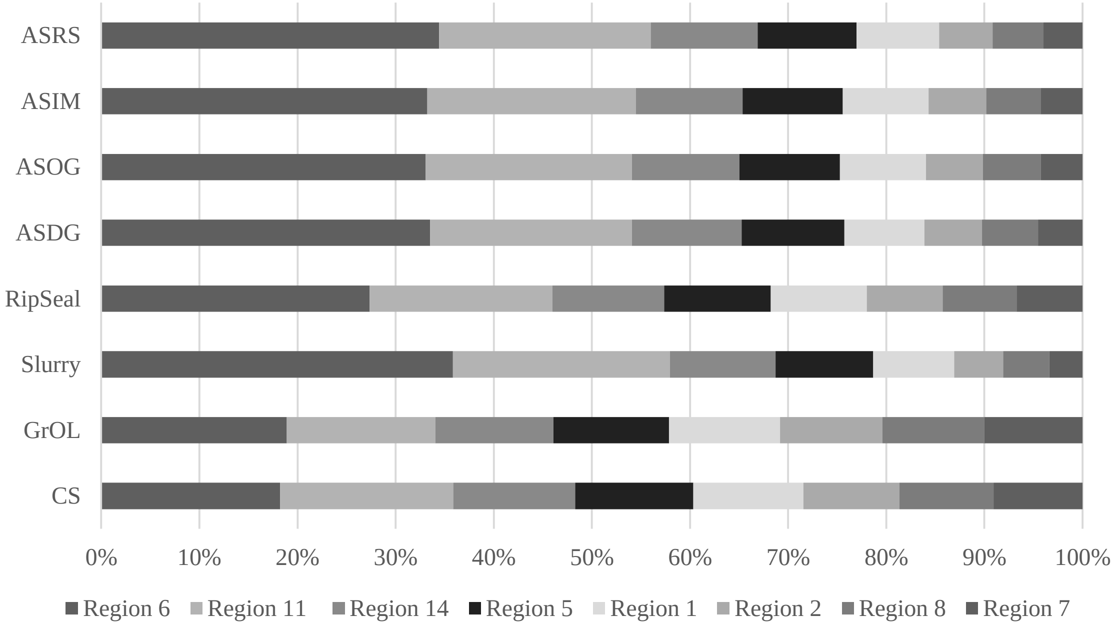


Figure 5.22: Percentage of Regions in Each Strategy

In other words, the variables for emissions values were raw materials, manufacturing, placement and transportation. Thus, the emissions values must be categorised based on the specific process of the strategies because they were affected by different variables. This research analysed the emissions values of the eight strategies in the eight regions. The results indicated that transportation was the most influential variable because of the large landmass of Australia. Therefore, the average emissions value and specific value for each region was necessary to enable detailed analysis during decision making for road maintenance. Table 5.44 displays the results of the emissions values of the eight strategies in the different regions.

Table 5.44: Emissions Values in Each Region for Each Strategy

RA	Strategy	Raw material	Manufacture	Placement	Transport	Total	RA	Strategy	Raw material	Manufacture	Placement	Transport	Total
1	ASDG	3.3021	0.8409	0.1407	5.5648	9.0076	7	ASDG	3.3021	0.8352	0.1407	0.7291	5.0070
	ASIM	4.4028	0.8553	0.1407	7.4197	12.8185		ASIM	4.4028	0.7641	0.1407	0.9721	6.2797
	ASOG	3.3021	0.8318	0.1407	5.5648	9.8394		ASOG	3.3021	0.5985	0.1407	0.7291	4.7704
	ASRS	11.0070	0.2575	0.1929	18.5493	29.5563		ASRS	11.0070	0.2850	0.1893	2.4302	13.9115
	GrOL	6.4068	0	0.1734	0.9352	7.5154		GrOL	6.4068	0	0.1853	0.0517	6.6438
	RipSeal	5.8698	0	0.1724	3.0507	9.0929		RipSeal	5.8698	0	0.1909	0.1687	6.2294
	Slurry	1.8456	0	0.1603	3.3561	5.3620		Slurry	1.8456	0	0.1766	0.1856	2.2078
	CS	1.5423	0	0.1643	0.4564	2.1630		CS	1.5423	0	0.1743	0.0252	1.7418
2	ASDG	3.3021	0.7371	0.1407	2.3146	6.4944	8	ASDG	3.3021	0.8338	0.1407	2.0314	6.3080
	ASIM	4.4028	0.9754	0.1407	3.0861	8.6050		ASIM	4.4028	0.8793	0.1407	2.7086	8.1314
	ASOG	3.3021	0.7710	0.1407	2.3146	6.5284		ASOG	3.3021	1.1260	0.1407	2.0314	6.6002
	ASRS	11.0070	0.2062	0.2196	7.7152	19.1480		ASRS	11.0070	0.2764	0.1888	6.7714	18.2436
	GrOL	6.4068	0	0.1778	0.3414	6.9260		GrOL	6.4068	0	0.1745	0.2892	6.8705
	RipSeal	5.8698	0	0.1824	1.1136	7.1658		RipSeal	5.8698	0	0.1742	0.9449	6.9889
	Slurry	1.8456	0	0.1689	1.2251	3.2396		Slurry	1.8456	0	0.1637	1.0395	3.0488
	CS	1.5423	0	0.1727	0.1666	1.8816		CS	1.5423	0	0.1643	0.1414	1.8480
5	ASDG	3.3021	0.9395	0.1407	7.2069	11.5892	11	ASDG	3.3021	0.8409	0.1407	19.2792	22.7220
	ASIM	4.4028	0.8809	0.1407	9.6092	15.0336		ASIM	4.4028	0.9617	0.1407	25.7056	31.2108
	ASOG	3.3021	0.8318	0.1407	7.2069	11.4815		ASOG	3.3021	0.8318	0.1407	19.2792	23.5538
	ASRS	11.0070	0.2190	0.1848	24.0230	35.4338		ASRS	11.0070	0.2575	0.1929	64.2641	75.7215
	GrOL	6.4068	0	0.1806	1.2352	7.8226		GrOL	6.4068	0	0.1839	11.2240	17.2777

	RipSeal	5.8698	0	0.1805	4.0293	10.0796		RipSeal	5.8698	0	0.1827	12.3477	14.3760
	Slurry	1.8456	0	0.1713	4.4327	6.4496		Slurry	1.8456	0	0.1827	12.3477	14.3760
	CS	1.5423	0	0.1705	0.6028	2.3156		CS	1.5423	0	0.1792	1.6793	3.4008
6	ASDG	3.3021	0.8044	0.1407	32.8351	37.0823	14	ASDG	3.3021	0.8956	0.1407	8.0336	12.3719
	ASIM	4.4028	0.8553	0.1407	43.3801	48.7789		ASIM	4.4028	0.6703	0.1407	10.7115	15.9253
	ASOG	3.3021	0.8318	0.1407	32.8351	37.1097		ASOG	3.3021	0.8318	0.1407	8.0336	12.3082
	ASRS	11.0070	0.2575	0.1929	109.4503	120.9077		ASRS	11.0070	0.3010	0.1820	26.7787	38.2687
	GrOL	6.4068	0	0.2088	5.9176	12.5332		GrOL	6.4068	0	0.1912	1.3863	7.9843
	RipSeal	5.8698	0	0.2084	19.3029	25.3811		RipSeal	5.8698	0	0.1863	4.5220	10.5781
	Slurry	1.8456	0	0.1957	21.3477	23.2766		Slurry	1.8456	0	0.1742	4.9747	6.9945
	CS	1.5423	0	0.1829	1.7796	3.5048		CS	1.5423	0	0.1702	0.6765	2.3890

5.5 Summary

Based on data from MRWA, this research analysed 6,304 cases of road maintenance treatments, encompassing a total treated area of 55,330,752 m^2. Among the eight strategies investigated, CS was the highest adopted treatment. Following this, 4,746 cases (75%) adopted spray work, while 1,558 (25%) cases involved plant mix work. However, the treated area indicated that spray work comprised 50,521,745 m^2 (92%) of road maintenance works. Table 5.45 displays the final results of the average carbon emissions factor for the eight strategies, as well as the transferred environmental cost.

Table 5.45: Final Results of Calculation

Treatment type	Total emissions ($kgCO_{2e}/m^2$)	Total cost ($\$/m^2$)
ASDG	14.0330	0.3309
ASIM	18.3479	0.4326
ASOG	14.0239	0.3307
ASRS	43.9552	1.0364
GrOL	8.2918	0.1955
RipSeal	11.5992	0.2735
Slurry	8.1194	0.1915
CS	2.4056	0.0567

According to the analysed results, transportation had the largest influence on emissions factors. In particular, plant mix works had a much higher effect than spray works. Based on these results, detailed analysis of each region was necessary. The carbon emissions value was estimated based on the LCA method. The data identified in this chapter will be integrated into the decision-making model presented in Chapter 7.

Chapter 6: Road User Cost Factor

6.1 Introduction

RUCs are usually excluded from the road maintenance stage, partly because of a lack of reliable information, and largely because they are essentially similar for each possible alternative, provided that minimum levels of serviceability are maintained. Nevertheless, RUCs can significantly affect the selection of the optimum design, where there is a difference in the level and frequency of maintenance activities, in the duration of user cost. As such, the exclusion of RUC needs to be carefully considered, particularly for projects carrying high traffic volumes, because traffic distribution costs caused by maintenance activities can incur significant RUC. If the duration of maintenance activities is different for each of the possible alternatives, RUC should be included. For alternatives involving frequent maintenance activities, the RUC associated with delays and diversions may be significant on roads with high traffic volumes. The purpose of this chapter is to calculate the RUC and link the RUC to maintenance strategies to enable evaluation of the social impact of maintenance activities. This analysis will aid decision makers to select road maintenance strategies with different options, including social impacts. Additionally, this chapter examines the research question of how RUC applies to road maintenance strategies and reflects the variables.

6.2 Calculation Method and Assumption

The cost model structure and coefficients were adapted from the ATAP Guidelines and PV2 Road Parameter Values (Transport and Infrastructure Council 2016). Table 6.1 summarises the calculation method.

Table 6.1: Summary of Calculation Methods

Value	Method	Equation
VOT	Estimated values of travel time − occupant and freight payload values	Occupancy rate × value per occupant
VOC	Uninterrupted	Base VOC × ($k_1 + k_2/V + k_3{*}V^2 + k_4{*}\text{IRI} + k_5{*}\text{IRI}^2 + k_6{*}\text{GVM}$)
	Stop–start model	$A + B/V$
	Free-flow model	$C_0 + C_1V + C_2V^2$

Source: ATAP.

In the equations in Table 6.1, *IRI* = roughness; *GVM* = gross vehicle mass; *k*, *A*, *B* and *C* = coefficients; *V* = speed; and *base VOC* = lowest VOC from HDM-4.

Following the sophisticated method due to classification, the results were calculated for three different situations: (1) usual road situation, (2) during construction (speed limit of 40 km/h) and (3) after treatment work is completed (roughness change). Therefore, a few assumptions and limitations were made during the calculation process for standard road situations in Australia. Vehicle classifications appropriate to Australia were reviewed, and the Austroads 12-vehicle classification was selected for calculation. The percentage of AADT for the 12 classes was analysed; however, it had the limitation of calculating only passengers on buses because of lack of information. Every case was categorised based on regions, road types and speed limits, assuming a rise and fall of 0% and curvature of 20°/km, which influenced the equation method.

This research developed the method to be used easily in suitable situations, especially for Western Australia users. In other words, the method was developed in accordance with the type of road, considering the traffic flow, regional location and AADT. Moreover, the calculation method was improved according to the usual road situation (without maintenance work), the construction stage during maintenance work, and the improved road situation after construction. Thus, based on different methods of calculation and equations for different conditions and situations, the data were categorised into eight treatment strategies, eight different regions and five different road types, as shown in Figure 6.1.

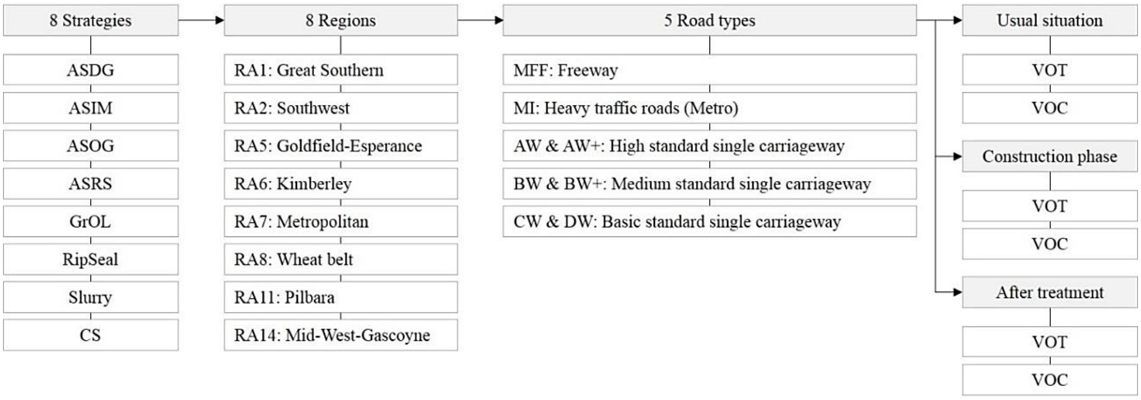


Figure 6.1: Data Categorisation Process for Calculation

6.3 Case Project Background

This research calculated a total of 6,174 actual cases of VOT and VOC, which encompassed a total of 6,599.88 km and 54,201,382 m^2 in Western Australia. For the eight maintenance strategies, CS was the most common treatment, at 61% among the cases. Table 6.2 presents the case frequency treated, treated distance and treated area.

Table 6.2: Project Description of Strategies

Strategies	**Actual cases**		**Total treated distance**		**Total treated area**	
	Count	**%**	**km**	**%**	**m^2**	**%**
ASDG	1,136	18.39	282.09	4.27	2,933,204	5.41
ASIM	335	5.42	52.78	0.79	564,497	1.04
ASOG	175	2.83	107.13	1.62	1,316,443	2.42
ASRS	59	0.95	14	0.21	131,625	0.24
GrOL	189	3.06	243.21	3.68	2,665,798	4.91
RipSeal	362	5.86	603.22	9.13	4,692,850	8.65
Slurry	141	2.28	216.07	3.27	1,741,711	3.21
CS	3,777	61.17	5,081.39	76.99	40,155,254	74.08
Total	**6,174**	**100.00**	**6,599.88**	**100.00**	**54,201,382**	**100.00**

The data analysed by region indicated that the Metropolitan (Region 7) and Mid-West-Gascoyne (Region 14) areas were the most repaired areas in Western Australia. Table 6.3 displays the case frequency, treated distance and area of each region. The frequency of cases indicates that Regions 7 and 14 had the highest numbers; however, the distance and treated area showed that Regions 5, 8 and 14 had the highest rankings, close to 17%. These results indicate that, while Region 7 has been treated a larger number of times, the project scale was smaller than in the other regions.

Table 6.3: Project Descriptions of Regions

Region area	Actual cases		Total treated distance		Total treated area	
	Count	%	km	%	m^2	%
Region 1	172	2.78	561.17	8.50	4,962,132	9.15
Region 2	334	5.40	684.75	10.37	5,605,473	10.34
Region 5	686	11.11	1,149.40	17.41	9,471,476	17.47
Region 6	474	7.67	481.75	7.29	3,800,430	7.01
Region 7	1,781	28.84	492.36	7.46	5,249,764	9.68
Region 8	521	8.43	1,165.84	17.66	9,047,000	16.69
Region 11	946	15.32	927.91	14.05	7,267,152	13.40
Region 14	1,260	20.40	1,136.68	17.22	8,797,955	16.23
Total	**6,174**	**100**	**6,599.88**	**100**	**54,201,382**	**100**

Table 6.4 displays the case frequency, treated distance and treated area analysed based on the type of road. It shows that the medium standard single carriageway (BW and BW+) had the highest value of frequency, treated distance and treated area. The freeway (MFF) and heavy traffic roads (MI and Metro) values indicated that the scale was small, yet relatively large numbers of jobs were needed for this type of road.

Table 6.4: Project Description for Road Types

Strategies	Actual cases		Total treated distance		Total treated area	
	Count	%	km	%	m^2	%
MFF	636	10.30	300.47	4.55	3,343,158	6.16
MI	1,212	19.63	315.78	4.78	3,262,742	6.01
AW and AW+	913	14.78	1,327.86	20.11	11,206,944	20.67
BW and BW+	2,226	36.05	3,042.82	46.10	24,447,567	45.10
CW and DW	1,187	19.22	1,612.94	24.43	11,940,971	22.03
Total	**6,174**	**100**	**6,599.88**	**100**	**54,201,382**	**100**

In contrast, AADT was the most important factor in calculating the VOT and VOC of RUC. AADT values differ because of the region and road type. Tables 6.5 and 6.6 present an analysis of AADT for each region and road type. Region 7 had a total of 88%, while the other regions had less than 5%. As an extension of the result, road type MI was highest at 54%, while MFF was second at 36%.

Table 6.5: AADT of Each Region and Road Type

Category	AADT (cars)	%
Region 1	147,981	0.4
Region 2	1,766,674	4.75
Region 5	419,143	1.13
Region 6	203,713	0.55
Region 7	32,599,453	87.63
Region 8	534,685	1.44
Region 11	508,227	1.37
Region 14	1,020,913	2.74
Total	**37,200,789**	**100**

Table 6.6: AADT of Road Type

Category	AADT (cars)	%
MFF	13,241,824	35.60
MI	20,267,583	54.48
AW and AW+	2,029,129	5.45
BW and BW+	1,425,244	3.83
CW and DW	237,009	0.64
Total	**37,200,789**	**100**

6.4 Results

The results were derived from the analysed values of RUC consisting of VOT and VOC in three road situations: usual condition, under construction and after treatment.

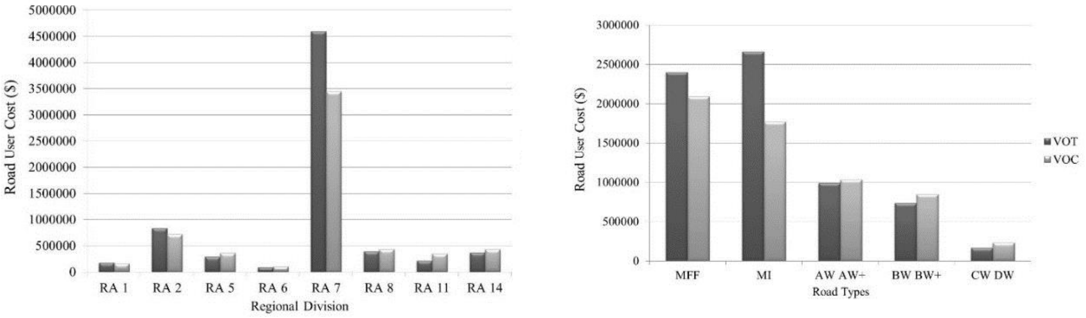
6.4.1 Actual Road User Cost of Cases

The actual cost of VOT for occupancy, VOT for freight and VOC was calculated through the 6,174 cases. Table 6.7 presents the actual calculated results of the raw data, which were analysed based on the unit. The results indicated that the RUC of ASDG was the highest, followed by CS treatment. Meanwhile, Region 7 (Metro) occupied a much larger portion than the other regions because it had the largest population and movement of vehicles, as supported by AADT. The RUC categorised by road type indicated that MFF was the highest, followed by MI.

Table 6.7: Calculation Results of actual RUC

		VOT ($)			VOC ($)^{b}	Total ($) $^{a+b}$
		VOT (occupancy)	**VOT (freight)**	**VOT (total)^{a}**		
Strategies	ASDG	2,687,652.34	65,082.4	2,752,735	1,917,228	4,669,962
	ASIM	349,707.79	15,805.6	365,513	244,926	610,440
	ASOG	1,010,755.85	17,057.7	1,027,814	913,916	1,941,729
	ASRS	36,915.39	1,480.82	383,96.2	29,477	67,873.2
	GrOL	58,407.37	11,184.2	69,591.6	80,947	150,539
	RipSeal	333,451.74	38,788.9	372,241	361,807	734,048
	Slurry	77,967.06	9,195.03	87,162.1	93,563.3	180,725
	CS	2,002,273.74	227,599	2,229,873	2,325,545	4,555,418
	Total	**6,557,131.28**	**386,193.75**	**6,943,325.03**	**5,967,409.39**	**12,910,734.42**
Region	Region 1	161,204.88	11,184.4	172,389	154,176	326,565
	Region 2	806,822.72	26,248.9	833,072	717,184	1,550,255
	Region 5	233,763.52	51,991	285,755	356,256	642,011
	Region 6	72,423.69	10,850.9	83,274.6	99,395.3	182,670
	Region 7	4,476,138.93	117,186	4,593,325	3,444,770	8,038,095
	Region 8	339,993.34	51,457.8	391,451	425,705	817,156
	Region 11	152,783.12	62,188.5	214,972	344,104	559,076
	Region 14	314,001.08	55,086.2	369,087	425,819	794,906
	Total	**6,657,131.28**	**386,193.75**	**6,943,325.03**	**5,967,409.39**	**12,910,734.42**
Road type	MFF	2,352,791.53	44,551.8	2,397,343	2,092,351	4,489,694
	MI	2,570,212.62	89,969.9	2,660,183	1,767,365	4,427,548
	AW and AW+	871,677.39	116,338	988,015	1,030,238	2,018,254
	BW and BW+	635,508.35	98,394	733,902	846,900	1,580,803
	CW and DW	126,941.39	36,930.4	163,872	230,554	394,426
	Total	**6,557,131.28**	**386,183.96**	**6,943,315.24**	**5,967,409.39**	**12,910,724.63**

The graphs in Figure 6.2 display the actual RUC analysed by region and road type. The results indicated that the Metro Region 7 occupied a much larger part than the other regions, and MFF and MI comprised the largest part of RUC. The results emphasised that AADT and roughness were the most significant variables for calculating RUC.



(a) Actual RUC of regions

(b) Actual RUC of road types

Figure 6.2: Actual RUC of Regions and Road Types

Based on the actual values calculated, Table 6.8 summarises the overall results of the average unit rate and RUC average values for the eight strategies.

Table 6.8: Unit Rate and RUC Results of Eight Strategies

Strategy	**Unit rate (\$/m^2)**		**RUC (\$/m^2)**	
		Usual condition	**Under construction**	**After improvement**
ASDG	45.45	0.20	0.32	0.14
ASIM	58.87	0.14	0.21	0.14
ASOG	49.25	0.18	0.33	0.17
ASRS	130.12	0.06	0.11	0.06
GrOL	71.87	0.01	0.01	0.01
RipSeal	49.5	0.02	0.04	0.02
Slurry	13.59	0.01	0.02	0.01
CS	6.31	0.01	0.03	0.01
Total	**53.12**	**0.08**	**0.13**	**0.07**

Although the treatment strategies were not the parameter variables of the RUC calculation, this research found significant results through the case analysis. As noted in previous sections, traffic flow including AADT and special situation and conditions are important variables to consider. Although a cost value for maintenance strategies is difficult to quantify, the method to calculate the RUC suitably reflects the significance of the parameter values. For instance, as high traffic freeways rate and metro roads rate a high traffic disruption than the rural single carriageway. Therefore, the value result categorised by strategy already debate and reflect the road type, location, traffic flow, and conditions with specific information such as treated distance and area, and frequency of numbers choose as a maintenance strategy.

The results indicated that RUC has an average of 0.15% of the unit rate of usual conditions. In addition, during the construction phase—which reduces the speed limit to 40 km/h and causes delays—RUC increases to 62.5% over the usual condition. However, after treatment of rehabilitation improves the roughness of the road and RUC, especially the VOC has an effect on reduces 14.29% than usual conditions. According to the World Bank (2016), Ohio Department of Transport (2013) and Texas Transportation Institute (1999), RUC is assumed to be average of US$11.38 per hour for cars and US$27.23 per hour for trucks. Lee et al. (2018) calculated LCA, including RUC, based on current systems and assumed RUC to be US$10.46 per hour for cars and US$27.83 per hour for trucks. Thus, considering the average road construction work capability and allowed work per day, the current study's results are reasonable compared with other studies' results. Further, other studies made calculations based on virtual situations, while the current research analysed real cases in Western Australia.

6.4.2 Road User Cost of Treatment Strategies

6.4.2.1 ASDG

Table 6.9 presents the ASDG treatment strategy average values of three different situations—VOT, VOC and RUC. The speed limit changes to 40 km/h during construction work, which causes a change to RUC because most speed limits of roads are over 40 km/h. Therefore, the change of speed affects the occupancy and freight time for VOT and VOC. In particular, VOT is the parameter that seriously considers the concept of time. Each region displayed a significant difference in RUC values because of AADT. The Metro Region 7 had the highest value among all regions. In the usual road situation, the average total RUC was $0.1990/m^2. During the construction phase, the speed limit changed to 40 km/h and the average total RUC increased 66.66% to $0.3166/m^2. However, after rehabilitation treatment, as a result of the road improvement in roughness, the RUC changed to $0.1362/m^2, which was a 46.11% reduction in RUC.

Table 6.9: Results of ASDG

	Usual situation ($/m^2)			Under construction ($/m^2)			After improvement ($/m^2)		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0275	0.0191	0.0466	0.0563	0.0258	0.0821	0.0302	0.0048	0.0350
Region 2	0.1155	0.0805	0.1960	0.2282	0.1044	0.3326	0.1367	0.0218	0.1587
Region 5	0.0283	0.0197	0.0480	0.0561	0.0256	0.0817	0.0283	0.0045	0.0329
Region 6	0.0201	0.0140	0.0341	0.0407	0.0186	0.0593	0.0210	0.0033	0.0243
Region 7	0.6395	0.4454	1.0849	1.1440	0.5232	1.6672	0.6074	0.0971	0.7055
Region 8	0.0377	0.0263	0.0640	0.0774	0.0354	0.1128	0.0417	0.0067	0.0484
Region 11	0.0321	0.0224	0.0545	0.0588	0.0269	0.0857	0.0362	0.0058	0.0420
Region 14	0.0377	0.0263	0.0640	0.0762	0.0349	0.1111	0.0371	0.0059	0.0431
Total	**0.1173**	**0.0817**	**0.1990**	**0.2172**	**0.0994**	**0.3166**	**0.1173**	**0.0187**	**0.1362**

6.4.2.2 ASIM

Table 6.10 displays the ASIM treatment strategy of RUC values. Region 7 had the highest value among all regions because of the high value of AADT at $0.7369/m^2. In the usual road situation, the average of total RUC was $0.1352/m^2. During the construction phase, the speed limit changed to 40 km/h and the average total RUC increased to $0.2086/m^2, which was 54.29% higher. However, the improvement in roughness reduced the RUC to $0.1243/m^2—an 8.77% reduction in RUC. ASIM has a lower rate of decrease effect than ASDG, yet is effective in improving RUC savings.

Table 6.10: Results of ASIM

	Usual situation ($/m^2)			Under construction ($/m^2)			After improvement ($/m^2)		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0190	0.0127	0.0317	0.0362	0.0179	0.0541	0.0208	0.0151	0.0320
Region 2	0.0797	0.0534	0.1331	0.1466	0.0726	0.2192	0.0943	0.0684	0.1448
Region 5	0.0195	0.0131	0.0326	0.0360	0.0178	0.0539	0.0195	0.0142	0.0300
Region 6	0.0139	0.0093	0.0231	0.0261	0.0129	0.0391	0.0145	0.0104	0.0222
Region 7	0.4412	0.2957	0.7369	0.7350	0.3638	1.0988	0.4191	0.3042	0.6437
Region 8	0.0260	0.0174	0.0435	0.0497	0.0246	0.0743	0.0288	0.0208	0.0442
Region 11	0.0222	0.0149	0.0370	0.0378	0.0187	0.0565	0.0249	0.0182	0.0383
Region 14	0.0260	0.0174	0.0435	0.0490	0.0242	0.0732	0.0256	0.0186	0.0393
Total	**0.0809**	**0.0542**	**0.1352**	**0.1396**	**0.0691**	**0.2086**	**0.0809**	**0.0587**	**0.1243**

6.4.2.3 ASOG

Table 6.11 displays the ASOG treatment strategy average values of three different situations—VOT, VOC and RUC. The average total RUC in the usual road situation was \$0.1844/m^2. During the construction phase, the speed limit changed to 40 km/h and the average total RUC increased to \$0.3284/m^2, which was a 78.09% increase. However, after rehabilitation treatment, as a result of the road improvement in roughness, RUC changed to \$0.1670/m^2, which was a 10.42% reduction effect in cost.

Table 6.11: Results of ASOG

	Usual situation (\$/m^2)			**Under construction (\$/m^2)**			**After improvement (\$/m^2)**		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0229	0.0203	0.0432	0.0627	0.0225	0.0852	0.0251	0.0178	0.0429
Region 2	0.0961	0.0854	0.1815	0.2540	0.0910	0.3450	0.1137	0.0809	0.1946
Region 5	0.0236	0.0209	0.0445	0.0624	0.0224	0.0848	0.0236	0.0167	0.0403
Region 6	0.0167	0.0149	0.0316	0.0453	0.0162	0.0615	0.0174	0.0124	0.0298
Region 7	0.5320	0.4731	1.0051	1.2734	0.4561	1.7295	0.5053	0.3595	0.8648
Region 8	0.0314	0.0279	0.0593	0.0861	0.0308	0.1170	0.0347	0.0246	0.0593
Region 11	0.0267	0.0238	0.0505	0.0654	0.0234	0.0889	0.0301	0.0214	0.0515
Region 14	0.0314	0.0279	0.0593	0.0849	0.0304	0.1152	0.0309	0.0219	0.0528
Total	**0.0976**	**0.0868**	**0.1844**	**0.2418**	**0.0866**	**0.3284**	**0.0976**	**0.0694**	**0.1670**

6.4.2.4 ASRS

Table 6.12 displays the ASRS treatment strategy of RUC values. In the usual road situation, the average total RUC was \$0.0645/m^2. During the construction phase, the speed limit changed to 40 km/h and the average total RUC increased to \$0.1084/m^2—a 68.06% increase. However, the improvement in roughness reduced the RUC to \$0.0639/m^2—a 0.94% reduction in RUC. ASRS seems to be less effective in lowering RUC after roughness improvement than the other plant mix works.

Table 6.12: Results of ASRS

	Usual situation ($/m²)			Under construction ($/m²)			After improvement ($/m²)		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0085	0.0066	0.0151	0.0192	0.0089	0.0281	0.0094	0.0071	0.0164
Region 2	0.0359	0.0276	0.0635	0.0777	0.0361	0.1138	0.0425	0.0320	0.0745
Region 5	0.0088	0.0068	0.0156	0.0191	0.0089	0.0280	0.0088	0.0066	0.0154
Region 6	0.0062	0.0048	0.0110	0.0139	0.0064	0.0203	0.0065	0.0049	0.0114
Region 7	0.1988	0.1526	0.3514	0.3897	0.1810	0.5707	0.1888	0.1424	0.3312
Region 8	0.0117	0.0090	0.0207	0.0264	0.0122	0.0386	0.0130	0.0098	0.0227
Region 11	0.0100	0.0077	0.0177	0.0200	0.0093	0.0293	0.0112	0.0085	0.0197
Region 14	0.0117	0.0090	0.0207	0.0260	0.0121	0.0380	0.0115	0.0087	0.0202
Total	**0.0365**	**0.0280**	**0.0645**	**0.0740**	**0.0344**	**0.1084**	**0.0365**	**0.0275**	**0.0639**

6.4.2.5 GrOL

Table 6.13 displays the GrOL treatment strategy of RUC values. In the usual road situation, the average total RUC was $0.0071/m^2. During the construction phase, the total RUC increased to $0.0130/m^2—an 83.09% increase. However, the improvement in roughness reduced the RUC to $0.0063/m^2—a 12.69% reduction in RUC.

Table 6.13: Results of GrOL

	Usual situation ($/m²)			Under construction ($/m²)			After improvement ($/m²)		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0008	0.0009	0.0017	0.0021	0.0013	0.0034	0.0008	0.0008	0.0016
Region 2	0.0032	0.0037	0.0070	0.0085	0.0052	0.0137	0.0038	0.0035	0.0073
Region 5	0.0008	0.0009	0.0017	0.0021	0.0013	0.0034	0.0008	0.0007	0.0015
Region 6	0.0006	0.0006	0.0012	0.0015	0.0009	0.0024	0.0006	0.0005	0.0011
Region 7	0.0178	0.0207	0.0385	0.0425	0.0261	0.0686	0.0169	0.0157	0.0326
Region 8	0.0010	0.0012	0.0023	0.0029	0.0018	0.0046	0.0012	0.001.	0.0022
Region 11	0.0009	0.0010	0.0019	0.0022	0.0013	0.0035	0.0010	0.0009	0.0019
Region 14	0.0010	0.0012	0.0023	0.0028	0.0017	0.0046	0.0010	0.0010	0.0020
Total	**0.0033**	**0.0038**	**0.0071**	**0.0081**	**0.0050**	**0.0130**	**0.0033**	**0.0033**	**0.0063**

6.4.2.6 RipSeal

Table 6.14 displays the RipSeal treatment strategy of RUC values. In the usual road situation, the average total RUC was $0.0196/m^2. During the construction phase, the total

RUC increased to \$0.0358/m^2—an 82.65% increase. However, the improvement in roughness reduced the RUC to \$0.0176/m^2—an 11.36% reduction in RUC.

Table 6.14: Results of RipSeal

	Usual situation (\$/m^2)			Under construction (\$/m^2)			After improvement (\$/m^2)		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0023	0.0023	0.0046	0.0059	0.0034	0.0093	0.0025	0.0020	0.0045
Region 2	0.0098	0.0095	0.0193	0.0238	0.0138	0.0376	0.0116	0.0089	0.0205
Region 5	0.0024	0.0023	0.0047	0.0058	0.0034	0.0092	0.0024	0.0019	0.0043
Region 6	0.0017	0.0016	0.0033	0.0042	0.0025	0.0067	0.0018	0.0013	0.0031
Region 7	0.0541	0.0525	0.1066	0.1193	0.0690	0.1883	0.0513	0.0400	0.0913
Region 8	0.0032	0.0031	0.0063	0.0081	0.0047	0.0127	0.0035	0.0028	0.0063
Region 11	0.0027	0.0026	0.0054	0.0061	0.0035	0.0097	0.0031	0.0023	0.0054
Region 14	0.0032	0.0031	0.0063	0.0080	0.0046	0.0126	0.0031	0.0025	0.0056
Total	**0.0099**	**0.0096**	**0.0196**	**0.0227**	**0.0131**	**0.0358**	**0.0099**	**0.0077**	**0.0176**

6.4.2.7 Slurry

Table 6.15 displays the slurry treatment strategy RUC values. In the usual road situation, the average total RUC was \$0.0130/m^2. During the construction phase, the total RUC increased to \$0.0249/m^2—a 91.54% increase. However, the improvement in roughness reduced the RUC to \$0.01116/m^2—a 12.07% reduction in RUC.

Table 6.15: Results of Slurry

	Usual situation (\$/m^2)			Under construction (\$/m^2)			After improvement (\$/m^2)		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0015	0.0016	0.0031	0.0042	0.0022	0.0064	0.0016	0.0014	0.0030
Region 2	0.0062	0.0066	0.0128	0.0171	0.0090	0.0261	0.0073	0.0062	0.0135
Region 5	0.0015	0.0016	0.0031	0.0042	0.0022	0.0064	0.0015	0.0013	0.0028
Region 6	0.0011	0.0011	0.0022	0.0030	0.0016	0.0047	0.0011	0.0010	0.0021
Region 7	0.0341	0.0366	0.0707	0.0856	0.0453	0.1309	0.0324	0.0278	0.0602
Region 8	0.0020	0.0022	0.0042	0.0058	0.0031	0.0089	0.0022	0.0019	0.0041
Region 11	0.0017	0.0018	0.0036	0.0044	0.0023	0.0067	0.0019	0.0017	0.0036
Region 14	0.0020	0.0022	0.0042	0.0057	0.0030	0.0087	0.0020	0.0017	0.0037
Total	**0.0063**	**0.0067**	**0.0130**	**0.0163**	**0.0086**	**0.0249**	**0.0063**	**0.0054**	**0.0116**

6.4.2.8 Chip Seal

Table 6.16 displays the RUC values of CS treatment strategy. In the usual road situation, the average of total RUC was $\$0.0142/\text{m}^2$. During the construction phase, the total RUC increased to $\$0.0261/\text{m}^2$—an 83.80% increase. However, the improvement in roughness reduced the RUC to $\$0.0125/\text{m}^2$—a 13.6% reduction in RUC.

Table 6.16: Results of CS

	Usual situation ($\$/\text{m}^2$)			**Under construction ($\$/\text{m}^2$)**			**After improvement ($\$/\text{m}^2$)**		
	VOT	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**	**VOT**	**VOC**	**RUC**
Region 1	0.0016	0.0017	0.0033	0.0044	0.0024	0.0068	0.0018	0.0014	0.0032
Region 2	0.0068	0.0071	0.0140	0.0179	0.0096	0.0274	0.0081	0.0065	0.0146
Region 5	0.0017	0.0017	0.0034	0.0044	0.0024	0.0067	0.0017	0.0013	0.0030
Region 6	0.0012	0.0012	0.0024	0.0032	0.0017	0.0049	0.0012	0.0010	0.0022
Region 7	0.0378	0.0395	0.0773	0.0895	0.0480	0.1375	0.0359	0.0288	0.0647
Region 8	0.0022	0.0023	0.0046	0.0061	0.0032	0.0093	0.0025	0.0020	0.0044
Region 11	0.0019	0.0020	0.0039	0.0046	0.0025	0.0071	0.0021	0.0017	0.0039
Region 14	0.0022	0.0023	0.0046	0.0060	0.0032	0.0092	0.0022	0.0018	0.0040
Total	**0.0069**	**0.0072**	**0.0142**	**0.0170**	**0.0091**	**0.0261**	**0.0069**	**0.0056**	**0.0125**

6.5 Discussions

This section discusses the VOT components analysis between occupancy and freight and the delay time considering the fluctuation of the different situations in the eight strategies.

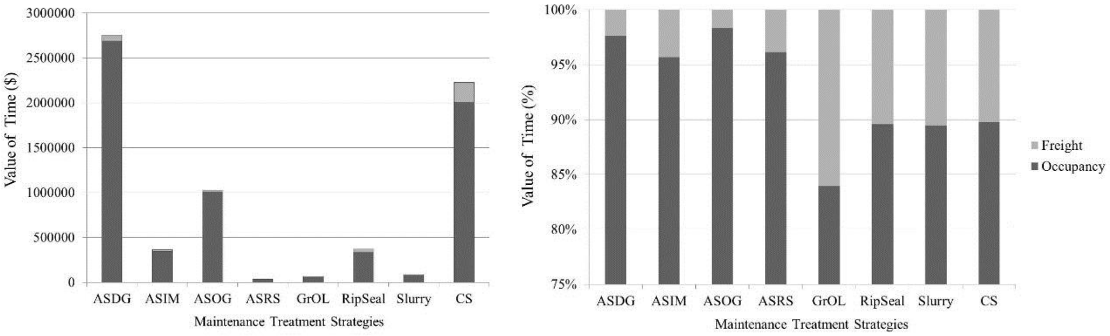
6.5.1 Value of Time Component

In terms of VOT percentage among occupancy and freight, the results indicated that GrOL had the most significant effects for freight, comprising 19% of total VOT. Additionally, spray work (such as RipSeal and CS) and slurry were close to 11%, while plant mix work (such as ASDG, ASIM, ASOG and ASRS) was between 2 and 4%. These results indicated that spray work takes more significant roles in freight, rather than plant mix work treatments. Table 6.17 presents the detailed VOT costs and percentages for occupancy and freight in the eight strategies.

Table 6.17: VOT Results for Strategies

Strategy	VOT ($: occupancy)	VOT ($: freight)	%
ASDG	2,687,652.3	65,082.39	2.42
ASIM	349,707.79	15,805.6	4.51
ASOG	1,010,755.9	17,057.74	1.68
ASRS	36,915.39	1,480.82	4.01
GrOL	58,407.37	11,184.22	19.14
RipSeal	333,451.74	38,788.9	11.63
Slurry	77,967.06	9,195.03	11.79
CS	2,002,273.7	227,599.05	11.36

Figure 6.3 presents the actual cost of the VOT calculation. Figure 6.3(a) displays the actual calculated cost of VOT, consisting of occupancy and freight value. Figure 6.3(b) displays the percentages of occupancy and freight in each strategy.



(a) VOT component cost

(b) VOT component percentage

Figure 6.3: VOT Cost and Percentage

6.5.2 Delay Time

The gap of RUC between the usual road situation, construction working phase and situation after treatment enabled calculation of the delay cost. Table 6.18 displays the fluctuation between the usual condition, under-construction situation and post-construction situation. It indicates that, if the speed limit drops to 40 km/h, all the treatment strategies' RUCs increase and improvement of roughness after treatment.

Table 6.18: RUC Fluctuations

	RUC ($/m^2)				
	Usual condition	**Under construction**	**Fluctuation**	**After improvement**	**Fluctuation**
ASDG	0.1990	0.3166	+66.66%	0.1362	-46.11%
ASIM	0.1352	0.2086	+54.29%	0.1243	-8.77%
ASOG	0.1844	0.3284	+78.09%	0.1670	-10.42%
ASRS	0.0645	0.1084	+68.06%	0.0639	-0.94%
GrOL	0.0071	0.0130	+83.09%	0.0063	-12.69%
RipSeal	0.0196	0.0358	+82.65%	0.0176	-11.36%
Slurry	0.0130	0.0249	+91.54%	0.0116	-12.07%
CS	0.0142	0.0261	+83.80%	0.0125	-13.6%

The results indicated that spray works have more influence on the increase of RUC in construction situations than do plant mix works. In particular, slurry caused a 91.54% increase over the usual situation. The road roughness corresponded to the VOC of the MFF road type, which required IRI data to calculate. The roughness improvement affected the VOC for users. The most affected strategy was ASDG at 46.11% of decrease, followed by CS at 13.6% and GrOL at 12.69%.

6.6 Summary

Maintenance strategy enables efficient management of road networks by setting standards in the road’s lifecycle. It provides targeted pavement performance, with the required treatments and budget. Thus, it is necessary for each road authority to develop long-term road maintenance standards and strategies. A maintenance strategy ensures appropriate and timely maintenance of a road network. A general maintenance policy enables the right treatment at the right time and in the right place. However, the strategy must be optimum to ensure efficient use of the allocated budget. Accounting for user costs has typically been undertaken by associating an estimated monetary value of costs then adding. For that reason, it is necessary to integrate RUC into the decision making for road maintenance.

Therefore, as a first step, this chapter modified the appropriate calculation method for Australian roads, considering vehicle classes, road types and regions. To calculate the unit rate of RUC, this study analysed 6,174 cases of road maintenance treatment data from MRWA, encompassing a total of 54,201,382 m^2. Based on the calculated results, mixing plant works had the greater effect on RUC in terms of absolute value. However, spray work reactions to circumstance changes were more severe. The detailed method of integrating RUC into the decision-making process will be the focus of the following chapter.

Chapter 7: Discussion and Implementations

7.1 Introduction

This chapter demonstrates that environmental and social impacts can be incorporated into decision making for road maintenance. It applies the calculated true costs based on the previous chapter's results, such as the environmental cost and value of RUC. Through a discussion with MRWA, this research selected three scenarios as the next step to verify the results based on the calculation results. The three scenarios included: (1) the LCCA of cost factors over a long period; (2) the budget allocation for road maintenance (rehabilitation); and (3) the evaluated weight of variables using the AHP, which is analysed with the normalised true cost of road maintenance factors to score and make final decisions on road maintenance strategy to enable an accurate result in practice. Figure 7.1 presents a framework of the verification process.

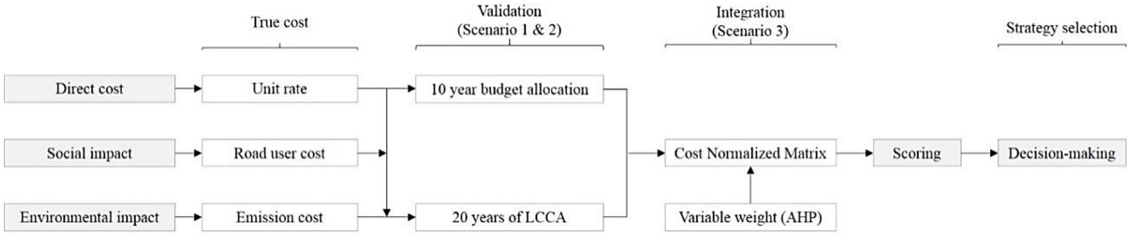


Figure 7.1: Framework of Verification and Implementation

7.2 Scenario 1: Lifecycle Cost Analysis of Alternatives

7.2.1 Background

RUC, consisting of VOT and VOC, is used as an indicator of the social impact of road maintenance activities. VOC is affected by roughness and speed, while VOT is only affected by the speed of the vehicle. It describes that uninterrupted freeway rehabilitation work reduces VOC by improving the roughness of the road. This research conducted one case study using MRWA data to analyse the lifecycle cost of different maintenance strategies over a 20-year lifecycle. The selected area was Region 7 (H018), which was the Metro area. The road was an uninterrupted freeway (MFF), with a total treated length of 4.85 km, which start chainage of the site from 27.28 km to end chainage of the site

32.13 km. The road width was 9.9 m, which led to a total of 48,015 m^2. The AADT was 18,229 and the roughness before treatment was 3.8.

7.2.2 Method

This research considered six alternatives of net present value (NPV) in a 20-year whole LCCA, calculated with a 7.0% discount rate. The six alternative options were:

1. Alternative 1: routine maintenance only (AUD\$3.33/m^2)
2. Alternative 2: rehabilitation treatment of RipSeal (AUD\$58/m^2)
3. Alternative 3: rehabilitation treatment of GrOL (AUD\$85/m^2)
4. Alternative 4: RUC after routine maintenance (AUD\$0.3492/m^2)
5. Alternative 5: RUC after RipSeal treatment (AUD\$0.0913/m^2)
6. Alternative 6: RUC after GrOL treatment (AUD\$0.0326/m^2).

Alternative 1 involved routine maintenance only Maintenance Management Information System (MMIS) defects. Therefore, the activity involved only routine maintenance, which entailed a cost of \$3.3/m^2. Alternatives 2 and 3 were treatment using RipSeal and granular overlay. The unit rate was adopted from the actual average cost for Region 7—MFF roads. These options were treated in the first year and final seal on three years after first treatment. Therefore, a fixed rate was used to calculate the routine maintenance year. However, to calculate the true cost of the alternatives, RUC and environmental cost were applied. Alternative 4 was the average RUC of the treatment strategy, and Alternatives 5 and 6 encompassed RUC after treatment with RipSeal and GrOL.

7.2.3 Result

Table 7.1 presents the detailed analysis results of LCCA. As described above, Alternatives 1 to 3 involved the selection of maintenance treatment, and Alternatives 4 to 6 involved LCCA of the RUC of each strategy chosen. The environmental cost was applied once for the year of construction.

Table 7.1: Twenty-year LCCA of Scenarios

Year	Alternative 1		Alternative 2		Alternative 3		Alternative 4		Alternative 5		Alternative 6	
	Activity	**Cost ($)**	**Activity**	**Cost ($)**	**Activity**	**Cost ($)**	**Activity**	**Cost ($)**	**Activity**	**Cost ($)**	**Activity**	**Cost ($)**
0	RM only	160,050	Rip and seal	2,784,870	Granular overlay	4,081,275	RUC	16,767	RUC	4,384	RUC	1,565
1	RM only	168,053	RM only	1,000	RM only	1,000	RUC	17,605	RUC	4,603	RUC	1,644
2	RM only	176,455	RM only	3,000	RM only	3,000	RUC	18,485	RUC	4,833	RUC	1,726
3	RM only	185,278	Final seal + RM	195,421	Final seal + RM	195,421	RUC	19,410	RUC	5,075	RUC	1,812
4	RM only	194,542	RM only	1,000	RM only	500	RUC	20,380	RUC	5,328	RUC	1,903
5	RM only	204,269	RM only	1,000	RM only	500	RUC	21,399	RUC	5,595	RUC	1,998
6	RM only	224,696	RM only	1,000	RM only	500	RUC	23,539	RUC	6,154	RUC	2,198
7	RM only	247,165	RM only	1,000	RM only	500	RUC	25,893	RUC	6,770	RUC	2,417
8	RM only	271,882	RM only	1,000	RM only	500	RUC	28,482	RUC	7,447	RUC	2,659
9	RM only	299,070	RM only	1,000	RM only	500	RUC	31,331	RUC	8,192	RUC	2,925
10	RM only	328,977	RM only	1,000	RM only	500	RUC	34,464	RUC	9,011	RUC	3,217
11	RM only	361,875	RM only	2,000	RM only	1,000	RUC	37,910	RUC	9,912	RUC	3,539
12	RM only	398,062	RM only	2,000	RM only	1,000	RUC	41,701	RUC	10,903	RUC	3,893
13	RM only	437,868	RM only	2,000	RM only	1,000	RUC	45,871	RUC	11,993	RUC	4,282
14	RM only	481,655	RM only	2,000	RM only	1,000	RUC	50,458	RUC	13,193	RUC	4,711
15	RM only	529,821	RM only	3,000	RM only	1,500	RUC	55,504	RUC	14,512	RUC	5,182
16	RM only	582,803	RM only	3,000	RM only	1,500	RUC	61,054	RUC	15,963	RUC	5,700
17	RM only	641,083	RM only	3,000	RM only	1,500	RUC	67,160	RUC	17,559	RUC	6,270
18	RM only	705,192	RM only	3,000	RM only	1,500	RUC	73,876	RUC	19,315	RUC	6,897
19	RM only	775,711	RM only	3,000	RM only	1,500	RUC	81,263	RUC	21,247	RUC	7,586
20	RM only	853,282	RM only	3,000	RM only	1,500	RUC	89,390	RUC	23,371	RUC	8,345

The NPV results indicated the 20-year whole LCCA of the cases selected, as displayed in Figure 7.2.

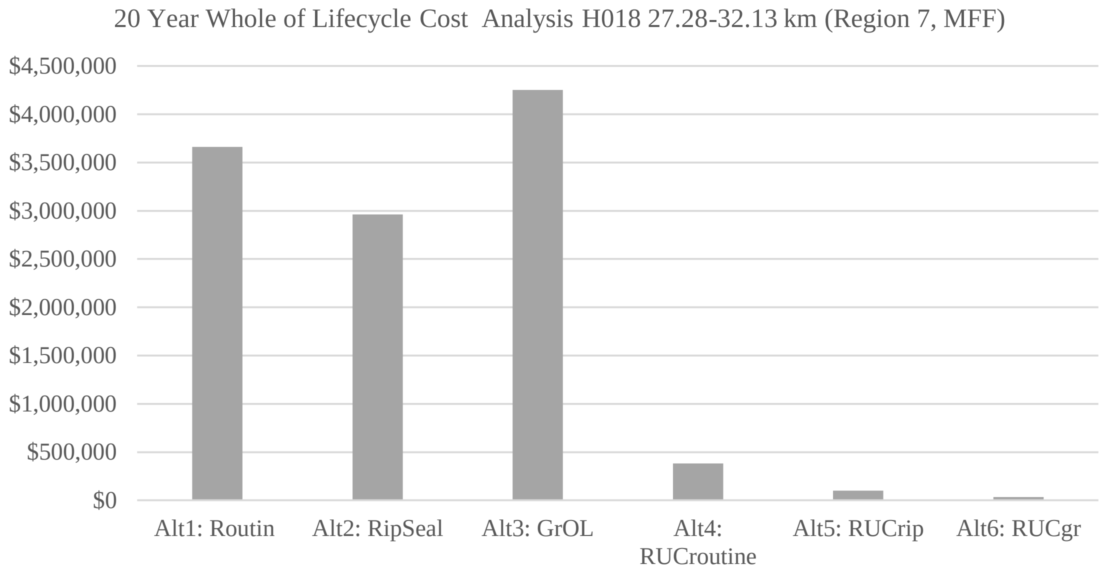


Figure 7.2: Twenty-year LCCA Results

Table 7.2 presents the total LCC model analysis results.

Table 7.2: LCC Model Analysis Results ($)

	Direct cost	**RUC**	**Environmental cost**	**Total**
Routine maintenance	3,661,518.06	383,580.63	–	4,045,098.69
RipSeal	2,961,335.36	100,288.98	3,896	3,065,520.34
GrOL	4,251,046.02	35,809.65	3,653	4,290,508.67

Comparing the total NPV of Alternatives 1 to 3 provided the most effective selection of maintenance strategies. However, the analysis results of Alternatives 4 to 6 indicated the costs saved through the road condition improvement and the cost savings of social cost. The cost gap between Alternatives 4 to 6 benefits savings from RUC by improving the road conditions. The rehabilitation work influenced the roughness of the road and helped reduce the costs to society. In addition, the total RUC was higher than the cost gap between the different scenarios' treatments. Thus, the RUC is a key factor for decision making in road asset management, and should be integrated into the decision-making model when selecting maintenance strategies.

7.3 Scenario 2: Allocating Maintenance Budgets for Rehabilitation

7.3.1 Background and Method

Maintenance budget allocation is critical to ensure that various asset types are adequately maintained. Maintenance budget allocation at the state network level is based on factors that include the direct cost of maintenance and the pavement performance improvement. Using the LCC approach, this research developed an integrated approach to evaluate budget allocation, considering the effects of roadworks on road users. The RUC of all road segments in Western Australia was recalculated following the method in Chapter 3. The RUC was integrated with the direct cost to the road agency to identify the optimal budget level for rehabilitation. The research included the assumptions of no traffic growth over the next 10 years and a capital rate of 7%. The eight budget allocation scenarios for rehabilitation were analysed with the following budgets: AUD$50 million, $60 million, $70 million, $85 million, $95 million, $105 million, $115 million and $125 million. Table 7.3 presents a simple example of the analysed results for the AUD$50 million budget allocation.

Table 7.3: AUD$50 Million Budget Allocation

Year	Resurfacing ($)	Rehabilitation ($)	VOC ($)	RUC ($)
2016	61,952,870.00	6,933,590.00	18,382,667.24	37,229,795.24
2017	49,823,626.00	176,209.40	18,385,728.68	37,232,856.68
2018	48,555,241.00	1,444,565.00	18,385,728.68	37,232,856.68
2019	46,441,210.00	3,558,709.00	18,389,003.15	37,236,131.15
2020	43,928,975.00	6,070,820.00	18,392,310.20	37,239,438.20
2021	45,210,679.00	4,788,511.00	18,395,625.87	37,242,753.87
2022	45,911,545.00	4,088,237.00	18,398,939.43	37,246,067.43
2023	42,597,291.00	7,402,332.00	18,401,836.46	37,248,964.46
2024	43,431,198.00	6,568,598.00	18,405,043.72	37,252,171.72
2025	46,074,878.00	3,924,592.00	18,408,341.68	37,255,469.68
2026	321,225,495.00	768,204,470.00	18,411,774.22	37,258,902.22
Total	**795,153,008.00**	**813,160,633.40**	**202,356,999.33**	**409,675,407.33**

7.3.2 Result

Table 7.4 displays the total budget and RUC of percentage.

Table 7.4: Budget and RUC of Scenarios

Maintenance budget scenario ($)	Total budget ($)	Total RUC ($)	%	Total cost ($)
50 million	1,608,313,641.40	409,675,407.33	25.47	2,017,989,049
60 million	1,542,375,321.40	409,701,376.14	26.56	1,952,076,698
70 million	1,470,919,040.10	409,699,904.80	27.85	1,880,618,945
85 million	1,336,935,062.50	409,698,643.28	30.64	1,746,633,706
95 million	1,336,935,062.50	409,698,182.28	31.25	1,746,633,245
105 million	1,305,335,660.00	409,698,013.43	31.39	1,715,033,673
115 million	1,333,685,740.00	409,696,254.91	30.72	1,743,381,995
125 million	1,349,150,859.00	409,695,839.25	30.37	1,758,846,698

The results indicated that the budget scenario of $105 million was the most effective strategy, which is a total of $1,715,033,673, considering both rehabilitation cost and RUC. The second-best option seemed to be a budget of $115 million at a total of $1,743,381,995. Figure 7.3 presents the annual rehabilitation budget scenario.

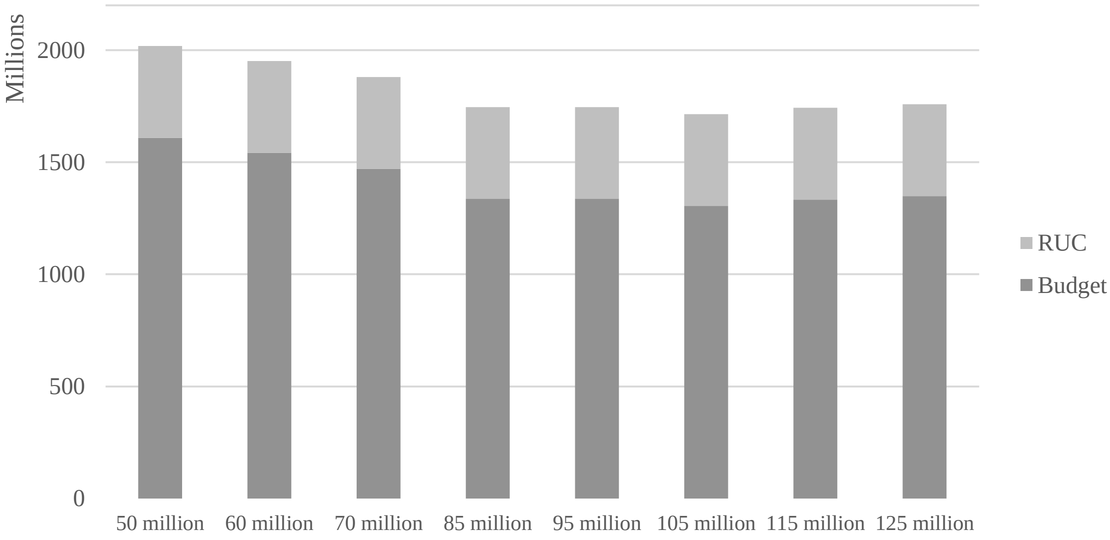


Figure 7.3: Annual Rehabilitation Budget Scenario

With a discount rate of 7%, the results indicated that the total lifecycle cost of the road network for the $105 million budget scenario was relatively lower than that of the other scenarios. Thus, this research concluded that the optional budget level for rehabilitation costs should be $105 million annually in this analysis.

7.4 Scenario 3: Selecting Optimal Maintenance Strategies

7.4.1 Background

AHP is a decision-making method proposed by Saaty (1980) through McGraw-Hill. It classifies problems that include multiple objectives, multiple evaluation criteria and multiple decision-making subjects, and classifies the elements in the upper class by pair comparison to determine the importance or weight of each element. The overall ranking is determined by calculating the total score. Based on the calculation through previous chapters, the actual cost of eight strategies is analysed in Table 7.5. The results include the unit rate, environmental cost and RUC for three conditions (usual road, under construction and after treatment) in AUD/m^2. The results present the average value of eight regions in Western Australia.

Table 7.5: Final Result of Variable Calculation (\$/m^2)

	Unit rate	Environmental	RUC_u	RUC_c	RUC_a
ASDG	45.45	0.33	0.20	0.32	0.14
ASIM	58.87	0.43	0.14	0.21	0.14
ASOG	49.25	0.33	0.18	0.33	0.17
ASRS	130.12	1.04	0.06	0.11	0.06
GrOL	71.87	0.20	0.01	0.01	0.01
RipSeal	49.5	0.27	0.02	0.04	0.02
Slurry	13.59	0.19	0.01	0.02	0.01
CS	6.31	0.06	0.01	0.03	0.01

7.4.2 Method

The first step was to model the AHP structure with five evaluation criteria—unit rate, environmental cost and three types of RUC. The eight evaluation targets' overall hierarchical structures were the treatment strategies. Figure 7.4 presents the evaluation criteria hierarchy.

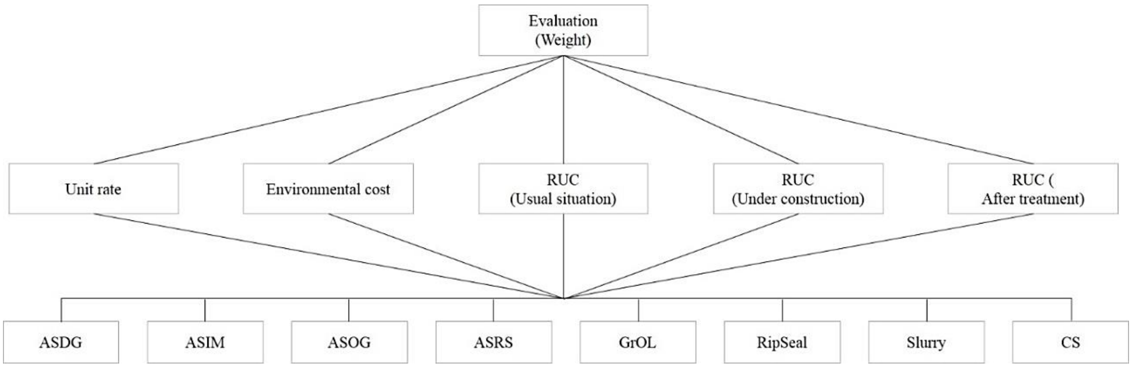


Figure 7.4: Evaluation Criteria Hierarchy

Each pair of evaluation elements constituting a hierarchy was paired with each other to evaluate the relative importance from the viewpoint of the superior type. The next step was to normalise the five variables of unit rate, environmental cost and three types of RUC for the eight strategies, based on the calculation result. Table 7.6 presents the normalisation process of the unit rate for instance that divides the sum of the columns to adjust the importance of each pair of evaluation values. Row averaging provided the weights for the evaluation criteria. The results of the normalised matrix were calculated with the factors' weight of importance to determine the maintenance decision making.

Table 7.6: Normalisation Process of Unit Rate

Unit rate	ASDG	ASIM	ASOG	ASRS	GrOL	RipSeal	Slurry	CS	**Weight**
ASDG	1	1.29527	1.083608	2.862926	1.581298	1.089109	0.299010	0.138834	0.066042
ASIM	0.772040	1	0.836589	2.210294	1.220826	0.840836	0.230848	0.107185	0.050987
ASOG	0.922843	1.195330	1	2.64203	1.459289	1.005076	0.275939	0.128122	0.060946
ASRS	0.349293	0.452429	0.378497	1	0.552336	0.380418	0.104442	0.048494	0.023068
GrOL	0.632392	0.819118	0.685265	1.810491	1	0.688744	0.189091	0.087797	0.041764
RipSeal	0.918182	1.189293	0.994949	2.628687	1.451919	1	0.274545	0.127475	0.060638
Slurry	3.344371	4.331862	3.623988	9.574687	5.288447	3.642384	1	0.464312	0.220868
CS	7.202853	9.329635	7.805071	20.62124	11.38986	7.844691	2.1553724	1	0.475688
Total	**15.14197**	**19.61294**	**16.40797**	**43.35035**	**23.94397**	**16.49126**	**4.5276**	**2.102219**	**1**

Likewise, the emissions of environmental cost and RUC were normalised, as displayed in Table 7.7.

Table 7.7: Final Normalised Result

	Unit rate	**Environmental cost**	**RUC$_u$**	**RUC$_c$**	**RUC$_a$**
ASDG	0.066042	0.073794	0.013008	0.013686	0.018465
ASIM	0.050987	0.056446	0.018584	0.020854	0.018465
ASOG	0.060946	0.073839	0.014454	0.013271	0.015206
ASRS	0.023068	0.023561	0.043362	0.039813	0.043085
GrOL	0.041764	0.124903	0.260169	0.437941	0.258508
RipSeal	0.060638	0.089282	0.130085	0.109485	0.129254
Slurry	0.220868	0.127512	0.260169	0.218970	0.258508
CS	0.475688	0.430663	0.260169	0.145980	0.258508

Through scoring each strategy, the importance of the factors, including the five variables, could be calculated for decision making. The below matrix displays the scoring activity.

$$\begin{array}{lc} & \begin{array}{ccccc} \text{Unit rate} & \text{Env. cost} & \text{RUC}_u & \text{RUC}_c & \text{RUC}_a \end{array} \\ \begin{array}{l} \text{ASDG} \\ \text{ASIM} \\ \text{ASOG} \\ \text{ASRS} \\ \text{GrOL} \\ \text{RipSeal} \\ \text{Slurry} \\ \text{CS} \end{array} & \left[\begin{array}{ccccc} 0.066042 & 0.073794 & 0.013008 & 0.013686 & 0.018465 \\ 0.050987 & 0.056446 & 0.018584 & 0.020854 & 0.018465 \\ 0.060946 & 0.073839 & 0.014454 & 0.013271 & 0.015206 \\ 0.023068 & 0.023561 & 0.043362 & 0.039813 & 0.043085 \\ 0.041764 & 0.124903 & 0.260169 & 0.437941 & 0.258508 \\ 0.060638 & 0.089282 & 0.130085 & 0.109485 & 0.129254 \\ 0.220868 & 0.127512 & 0.260169 & 0.218970 & 0.258508 \\ 0.475688 & 0.430663 & 0.260169 & 0.145980 & 0.258508 \end{array}\right] \end{array} \left[\begin{array}{c} \text{Unit rate importance score} \\ \text{Env. importance score} \\ \text{RUC}_\text{u} \text{ importance score} \\ \text{RUC}_\text{c} \text{ importance score} \\ \text{RUC}_\text{a} \text{ importance score} \end{array}\right]$$

To score each strategy to determine the most appropriate decision making, the true cost can be calculated through the cost and importance of weight. To check the results' consistency in scoring, the consistency ratio (CR) can be calculated, which is a comparison of the consistency index (CI) and random consistency index (RI):

$$CR = CI/RI$$

$$CI = (\lambda_{\max} - n) / n\text{-}1$$

$\lambda_{max} = \sum XiWi / n$ (*n:* number of variables)

If the value of the consistency ratio is smaller than or equal to 10%, the inconsistency is acceptable. If the consistency ratio is greater than 10%, the subject judgements should be revised. Table 7.8 presents the *RI* of variables (*n*).

Table 7.8: Random Consistency Index

n	2	3	4	5	6	7	8	9	10
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

7.4.2.1 Scoring Application: A Case Study

Each pair of evaluation elements constituting a hierarchy was evaluated in terms of their relative importance from the viewpoint of the upper evaluation criteria through the subjective judgement or questionnaire of the evaluator. Table 7.9 presents the dual rating scale for the importance of the evaluation criteria.

Table 7.9: Assessing the Importance of the Evaluation Criteria

Descriptive evaluation	Quantification
Very high	5
High	3
Moderate	1
Low	1/3
Very low	1/5

This study assessed the relative excellence of the eight maintenance strategies for the evaluation criteria, and calculated the weight of each evaluation criterion through using the simple calculation method of AHP. The calculation method displayed the sum of each column in the last row of the evaluation table pair, and then divided each of the above significances by the column sum below. This involved a type of normalisation process that adjusted the importance, or size, of each pair of evaluation values. The average of the rows indicated the weight of the criteria. The weights shown in Table 7.10 represent the relative importance of the effects of the five evaluation criteria selected to evaluate the eight maintenance strategies for overall excellence. The value of consistency ratio was 0.050, which indicated that consistency was acceptable.

Table 7.10: Weight of Variables

	Unit rate	Environmental cost	RUC_u	RUC_c	RUC_a	**Weight**
Unit rate	1	0.941	1.310	0.523	0.794	**0.152**
Environmental cost	1.063	1	1.442	0.693	0.659	**0.165**
RUC_u	0.763	0.693	1	0.261	0.255	**0.091**
RUC_c	1.913	1.442	3.826	1	3.302	**0.376**
RUC_a	1.260	1.518	3.915	0.303	1	**0.216**

Based on the calculation using the same method and procedure as described above, the weight (importance) of the remaining evaluation objects could be obtained from the viewpoint of each evaluation factor. It was then necessary to assess which of the eight maintenance strategies was the best. Based on the above matrix results and the weights shown in the table, the total score for each strategy was calculated by multiplying:

$$\begin{array}{c} \\ \text{ASDG} \\ \text{ASIM} \\ \text{ASOG} \\ \text{ASRS} \\ \text{GrOL} \\ \text{RipSeal} \\ \text{Slurry} \\ \text{CS} \end{array} \left[\begin{array}{ccccc} \text{Unit rate} & \text{Env. cost} & RUC_u & RUC_c & RUC_a \\ 0.066042 & 0.073794 & 0.013008 & 0.013686 & 0.018465 \\ 0.050987 & 0.056446 & 0.018584 & 0.020854 & 0.018465 \\ 0.060946 & 0.073839 & 0.014454 & 0.013271 & 0.015206 \\ 0.023068 & 0.023561 & 0.043362 & 0.039813 & 0.043085 \\ 0.041764 & 0.124903 & 0.260169 & 0.437941 & 0.258508 \\ 0.060638 & 0.089282 & 0.130085 & 0.109485 & 0.129254 \\ 0.220868 & 0.127512 & 0.260169 & 0.218970 & 0.258508 \\ 0.475688 & 0.430663 & 0.260169 & 0.145980 & 0.258508 \end{array} \right] \times \begin{bmatrix} 0.152 \\ 0.165 \\ 0.091 \\ 0.376 \\ 0.216 \end{bmatrix} = \begin{bmatrix} 0.032532 \\ 0.030584 \\ 0.031037 \\ 0.035616 \\ 0.271136 \\ 0.104871 \\ 0.216457 \\ 0.277766 \end{bmatrix}$$

In this case, the important factor to be considered was RUC during maintenance work and the improved road condition after the treatment. The weight of RUC_c was highest at 0.376, followed by RUC_a at 0.216. The final result comparing the score of the eight strategies' results indicated that CS was highest at 0.28, and GrOL was second highest at 0.27. In summary, CS was the best maintenance treatment for this case.

7.4.2.2 The Regional Problem

This research found that emission values indicated a significant difference between the different regions. RUC was affected by road type, speed, roughness and AADT. Although the AADT was different in every region, it did not influence the strategy in the region. This simply means that, if a strategy has been selected and fixed, and the decision is considering which region to choose, this will influence the decision making. However, emissions are affected by the detailed process of the strategy, which influences the raw materials, manufacture, placement and transportation. The research found that plant mix works are more affected by transportation than spray works. To enable more accurate decision making, this research provides more specific detail of the environmental cost for each region. Adopting the environmental cost of the specific region will provide a more accurate result when determining the strategy. Table 7.11 presents the normalised environmental cost ($/m^2) impact for each region.

Table 7.11: Environmental Cost for Each Region

	RA1	**RA2**	**RA5**	**RA6**	**RA7**	**RA8**	**RA11**	**RA14**
ASDG	0.091271	0.096257	0.079743	0.050866	0.100941	0.096336	0.07067	0.078297
ASIM	0.064136	0.072647	0.061473	0.038669	0.080484	0.074733	0.051449	0.060826
ASOG	0.083555	0.095755	0.080491	0.050829	0.105948	0.092071	0.068174	0.078702
ASRS	0.027816	0.032647	0.026081	0.015601	0.036331	0.033309	0.021206	0.025313
GrOL	0.109393	0.090258	0.118139	0.150499	0.076073	0.088448	0.092938	0.121323
RipSeal	0.090415	0.087238	0.091686	0.074316	0.081134	0.08695	0.111697	0.091574
Slurry	0.153326	0.192965	0.143289	0.081036	0.228922	0.199319	0.111697	0.138491
CS	0.380089	0.332233	0.399099	0.538185	0.290168	0.328834	0.47217	0.405474

As described, RUC is influenced by road type, speed limit, roughness and AADT. Thus, RUC is not affected by region when deciding which treatment to apply. However, if the decision making is about which region to treat first, then the RUC of each region must be considered. The AADT influences the RUC result and differs in each region. For instance, the Metropolitan Region 7 had high AADT and a much higher RUC than did the other regions. In summary, this research suggests to applicate below a score of RUC in three different conditions—usual road condition, under-construction condition and post-improvement condition—when making maintenance decisions among the different regions. Table 7.12 displays the weight score of the different regions.

Table 7.12: Regional Weight of RUC (Normalised $/m^2)

	RUC$_u$	**RUC$_c$**	**RUC$_a$**
RA 1	0.16853	0.16364	0.1627
RA 2	0.0401	0.0404	0.03591
RA 5	0.16363	0.16437	0.1733
RA 6	0.23076	0.22667	0.23425
RA 7	0.00724	0.00806	0.00808
RA 8	0.1228	0.11914	0.11776
RA 11	0.14417	0.15679	0.13575
RA 14	0.12276	0.12093	0.13225

7.4.3 Result

According to the calculation and analysis of social impacts, to obtain accurate results, it is most reasonable to distinguish by region. RUC is affected by road condition and AADT, in addition, the unit rate and environment impacts were strongly influenced by region because of the condition of regions and the distance of the transportation. As a result, this research presents the following end result. The final metrics consist of observations that consider the overall average of the state and the results for all eight regions.

7.4.3.1 The State Result

The state matrix result was calculated through the eight regions, with 6,304 cases for environmental cost and 6,174 cases for RUC. The final outcome of the results was:

$$
\begin{array}{lccccc}
 & \text{Unit rate} & \text{Env. cost} & \mathrm{RUC}_u & \mathrm{RUC}_c & \mathrm{RUC}_a \\
\text{ASDG} & 0.066042 & 0.073794 & 0.013008 & 0.013686 & 0.018465 \\
\text{ASIM} & 0.050987 & 0.056446 & 0.018584 & 0.020854 & 0.018465 \\
\text{ASOG} & 0.060946 & 0.073839 & 0.014454 & 0.013271 & 0.015206 \\
\text{ASRS} & 0.023068 & 0.023561 & 0.043362 & 0.039813 & 0.043085 \\
\text{GrOL} & 0.041764 & 0.124903 & 0.260169 & 0.437941 & 0.258508 \\
\text{RipSeal} & 0.060638 & 0.089282 & 0.130085 & 0.109485 & 0.129254 \\
\text{Slurry} & 0.220868 & 0.127512 & 0.260169 & 0.218970 & 0.258508 \\
\text{CS} & 0.475688 & 0.430663 & 0.260169 & 0.145980 & 0.258508
\end{array}
$$

7.4.3.2 Region 1

The Great Southern region centre was Albany (452 km), and the final outcome of the results was:

$$
\begin{array}{lccccc}
 & \text{Unit rate} & \text{Env. cost} & \mathrm{RUC}_u & \mathrm{RUC}_c & \mathrm{RUC}_a \\
\text{ASDG} & 0.054904 & 0.091271 & 0.013637 & 0.015557 & 0.017452 \\
\text{ASIM} & 0.050987 & 0.064136 & 0.020047 & 0.023609 & 0.019088 \\
\text{ASOG} & 0.060946 & 0.083555 & 0.01471 & 0.014991 & 0.014238 \\
\text{ASRS} & 0.023068 & 0.027816 & 0.042085 & 0.045453 & 0.037245 \\
\text{GrOL} & 0.041764 & 0.109393 & 0.373811 & 0.375657 & 0.381758 \\
\text{RipSeal} & 0.060638 & 0.090415 & 0.138148 & 0.137337 & 0.135736 \\
\text{Slurry} & 0.220868 & 0.153326 & 0.204993 & 0.199568 & 0.203604 \\
\text{CS} & 0.475688 & 0.380089 & 0.192569 & 0.187828 & 0.190879
\end{array}
$$

7.4.3.3 Region 2

The Southwest region centre was Bunbury (165 km) and the final outcome of the results was:

$$\begin{array}{c|ccccc|} & \text{Unit rate} & \text{Env. cost} & \text{RUC}_u & \text{RUC}_c & \text{RUC}_a \\ \text{ASDG} & 0.087764 & 0.096257 & 0.013494 & 0.015526 & 0.017498 \\ \text{ASIM} & 0.065613 & 0.072647 & 0.019871 & 0.023558 & 0.019178 \\ \text{ASOG} & 0.053897 & 0.095755 & 0.014572 & 0.014968 & 0.01427 \\ \text{ASRS} & 0.021871 & 0.032647 & 0.041651 & 0.045377 & 0.037275 \\ \text{GrOL} & 0.043117 & 0.090258 & 0.377832 & 0.376924 & 0.380409 \\ \text{RipSeal} & 0.067071 & 0.087238 & 0.137037 & 0.137337 & 0.135463 \\ \text{Slurry} & 0.15679 & 0.192965 & 0.206627 & 0.197849 & 0.205703 \\ \text{CS} & 0.503875 & 0.332233 & 0.188916 & 0.188462 & 0.190204 \end{array}$$

7.4.3.4 Region 5

The Goldfield-Esperance region centre was Kalgoorlie (597 km) and the final outcome of the results was:

$$\begin{array}{c|ccccc|} & \text{Unit rate} & \text{Env. cost} & \text{RUC}_u & \text{RU0.0C}_c & \text{RUC}_a \\ \text{ASDG} & 0.050787 & 0.079743 & 0..13788 & 0.01556 & 0.017437 \\ \text{ASIM} & 0.04063 & 0.061473 & 0.019709 & 0.023586 & 0.019122 \\ \text{ASOG} & 0.050787 & 0.080491 & 0.014438 & 0.014991 & 0.014235 \\ \text{ASRS} & 0.017665 & 0.026081 & 0.041186 & 0.045402 & 0.037251 \\ \text{GrOL} & 0.034825 & 0.118139 & 0.377944 & 0.373902 & 0.382443 \\ \text{RipSeal} & 0.051868 & 0.091686 & 0.136703 & 0.138181 & 0.13341 \\ \text{Slurry} & 0.203148 & 0.143289 & 0.20726 & 0.198636 & 0.20488 \\ \text{CS} & 0.550289 & 0.399099 & 0.188972 & 0.189741 & 0.191222 \end{array}$$

7.4.3.5 Region 6

The Kimberley region centre is Kununurra (3,208 km) and Derby (2,512 km). The final outcome of the results was:

$$\begin{array}{cc}
 & \begin{array}{ccccc} \text{Unit rate} & \text{Env. cost} & \text{RUC}_u & \text{RUC}_c & \text{RUC}_a \end{array} \\
\begin{array}{c} \text{ASDG} \\ \text{ASIM} \\ \text{ASOG} \\ \text{ASRS} \\ \text{GrOL} \\ \text{RipSeal} \\ \text{Slurry} \\ \text{CS} \end{array} &
\left[\begin{array}{ccccc}
0.054303 & 0.050866 & 0.013313 & 0.015461 & 0.017365 \\
0.049778 & 0.038669 & 0.019653 & 0..23448 & 0.019007 \\
0.054303 & 0.050829 & 0.014366 & 0.014908 & 0.01416 \\
0.021643 & 0.015601 & 0.041271 & 0.045163 & 0.037014 \\
0.042667 & 0.150499 & 0.378316 & 0.382008 & 0.383602 \\
0.054303 & 0.074316 & 0.137569 & 0.136839 & 0.136117 \\
0.213333 & 0.081036 & 0.206354 & 0.195068 & 0.200934 \\
0.50967 & 0.538185 & 0.189158 & 0.187106 & 0.191801
\end{array}\right]
\end{array}$$

7.4.3.6 Region 7

The Metropolitan region centre is Perth city (25 km) and the final outcome of the results was:

$$\begin{array}{cc}
 & \begin{array}{ccccc} \text{Unit rate} & \text{Env. cost} & \text{RUC}_u & \text{RUC}_c & \text{RUC}_a \end{array} \\
\begin{array}{c} \text{ASDG} \\ \text{ASIM} \\ \text{ASOG} \\ \text{ASRS} \\ \text{GrOL} \\ \text{RipSeal} \\ \text{Slurry} \\ \text{CS} \end{array} &
\left[\begin{array}{ccccc}
0.069686 & 0.100941 & 0.013445 & 0.015523 & 0.017533 \\
0.064819 & 0.080484 & 0.019795 & 0.023553 & 0.019217 \\
0.097982 & 0.105948 & 0.014513 & 0.014964 & 0.014304 \\
0.056176 & 0.036331 & 0.04151 & 0.045347 & 0.037349 \\
0.049567 & 0.076073 & 0.378877 & 0.377254 & 0.379444 \\
0.072642 & 0.081134 & 0.136837 & 0.137438 & 0.135486 \\
0.300945 & 0.228922 & 0.206319 & 0.197705 & 0.20548 \\
0.288182 & 0.290168 & 0.188703 & 0.188216 & 0.191188
\end{array}\right]
\end{array}$$

7.4.3.7 Region 8

The Wheat Belt region centre is Northam (99.7 km) and Narrogin (180 km). The final outcome of the results was:

$$\begin{array}{cc} & \begin{array}{ccccc} \text{Unit rate} & \text{Env. cost} & \text{RUC}_u & \text{RUC}_c & \text{RUC}_a \end{array} \\ \begin{array}{c} \text{ASDG} \\ \text{ASIM} \\ \text{ASOG} \\ \text{ASRS} \\ \text{GrOL} \\ \text{RipSeal} \\ \text{Slurry} \\ \text{CS} \end{array} & \left[\begin{array}{ccccc} 0.07605 & 0.096336 & 0.013554 & 0.015477 & 0.017382 \\ 0.037619 & 0.074733 & 0.019942 & 0.023497 & 0.019034 \\ 0.047024 & 0.092071 & 0.014628 & 0.014922 & 0.014187 \\ 0.016356 & 0.033309 & 0.041906 & 0.045229 & 0.037061 \\ 0.032245 & 0.088448 & 0.377158 & 0.379527 & 0.382404 \\ 0.048025 & 0.08695 & 0.137693 & 0.137466 & 0.133538 \\ 0.188097 & 0.199319 & 0.206539 & 0.19616 & 0.205192 \\ 0.554584 & 0.328834 & 0.188579 & 0.187723 & 0.191202 \end{array}\right] \end{array}$$

7.4.3.8 Region 11

The Pilbara region centre is Port Headland (1,663 km) and the final outcome of the results was:

$$\begin{array}{cc} & \begin{array}{ccccc} \text{Unit rate} & \text{Env. cost} & \text{RUC}_u & \text{RUC}_c & \text{RUC}_a \end{array} \\ \begin{array}{c} \text{ASDG} \\ \text{ASIM} \\ \text{ASOG} \\ \text{ASRS} \\ \text{GrOL} \\ \text{RipSeal} \\ \text{Slurry} \\ \text{CS} \end{array} & \left[\begin{array}{ccccc} 0.049453 & 0.07067 & 0.013419 & 0.015483 & 0.017433 \\ 0.044508 & 0.051449 & 0.019766 & 0.023484 & 0.019117 \\ 0.055634 & 0.068174 & 0.014482 & 0.014925 & 0.014217 \\ 0.019351 & 0.021206 & 0.041318 & 0.045286 & 0.037166 \\ 0.038149 & 0.092938 & 0.384913 & 0.379106 & 0.385357 \\ 0.056818 & 0.111697 & 0.135432 & 0.136791 & 0.135589 \\ 0.222538 & 0.111697 & 0.203148 & 0.198041 & 0.203383 \\ 0.513549 & 0.47217 & 0.187522 & 0.186883 & 0.187738 \end{array}\right] \end{array}$$

7.4.3.9 Region 14

The Mid-West-Gascoyne region centre is Carnarvon (907 km) and Geraldton (431 km). The final outcome of the results was:

$$\begin{array}{cc} & \begin{array}{ccccc} \text{Unit rate} & \text{Env. cost} & RUC_u & RUC_c & RUC_a \end{array} \\ \begin{array}{c} \text{ASDG} \\ \text{ASIM} \\ \text{ASOG} \\ \text{ASRS} \\ \text{GrOL} \\ \text{RipSeal} \\ \text{Slurry} \\ \text{CS} \end{array} & \begin{bmatrix} 0.080003 & 0.078297 & 0.013554 & 0.015571 & 0.017631 \\ 0.039975 & 0.060826 & 0.019942 & 0.023633 & 0.019336 \\ 0.049968 & 0.078702 & 0.014628 & 0.015017 & 0.014392 \\ 0.01738 & 0.025313 & 0.041906 & 0.045525 & 0.03762 \\ 0.034264 & 0.121323 & 0.377158 & 0.376075 & 0.379958 \\ 0.04797 & 0.091574 & 0.137693 & 0.137297 & 0.135699 \\ 0.177797 & 0.138491 & 0.206539 & 0.198844 & 0.205383 \\ 0.552644 & 0.405474 & 0.188579 & 0.188038 & 0.189979 \end{bmatrix} \end{array}$$

7.5 Developed Framework

This Chapter shows the calculation result for various scenarios based on extending the consideration of social and environmental factors in the maintenance stage. Figure 7.5 is the final integrated decision making framework incorporating social and environmental factors.

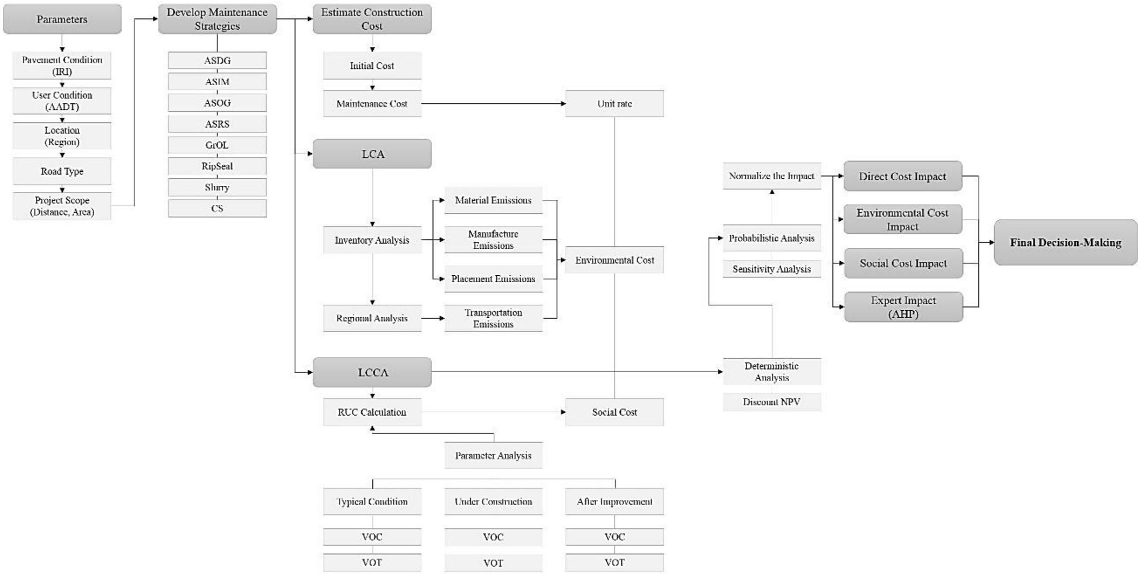


Figure 7.5 The Final Developed Framework

7.6 Summary

This chapter has validated the inclusion of social costs into the LCA of road infrastructures. The true cost of road maintenance has been calculated based on the previous chapters’ results and innovatively integrated the social and environmental impacts into the decision making process using three scenarios: (1) the Life Cycle Cost Analysis of maintenance decisions over 20 years; (2) the appropriate budget allocation for road maintenance (rehabilitation), considering the impact of the maintenance to the whole community; and (3) the true cost of road maintenance activities for easy assessment of maintenance activities in practice. Finally, this Chapter finalised metric for State average and eight different metrics value of each, which can provide accurate result on decision making of road maintenance.

Chapter 8: Conclusion

8.1 Introduction

This chapter presents the summary, conclusions and recommendations of this study. Limitations of this research and suggestions for future research are also presented in this Chapter.

8.2 Summary of Research Findings

In this section, the research findings of four research objectives are summarised.

8.2.1 Research Findings for Objective 1

Objective 1 is to investigate the current decision making process in road maintenance by identifying all relevant cost indicators.

The basic concepts, principles, and theory were analysed through literature review. The review found that true costs, considering environmental and social impacts are limited due to reasons at various levels, including economic, organizational, and so on. Therefore, the process of road maintenance, methods to calculate the environmental and social impacts of road maintenance, and influencing factors of road maintenance have been reviewed.

Through the comprehensive literature review, 19 influencing cost-related factors of road maintenance have been identified, including 11 environmental and social influencing factors. The survey aims to find out the importance of each influencing factor on road maintenance decision making. Also, the survey investigates the reasons leading to the limited consideration of environmental and social factors.

The main summarised research findings for this research objective 1 are:

- Direct costs and site conditions are ranked higher than other environmental and social impacts.
- The primary factors causing difficulty in incorporating social impacts into road maintenance are budgets, realising benefits and lack of expertise.
- Although the importance of influencing factors were slightly different for different types of organisations, both government agency and private company highlight budget limitation as the most significance influencing factor.

- The environmental and social impacts receive limited consideration in Australia when making maintenance decisions.

8.2.2 Research Findings for Objective 2

Objective 2 is to develop an innovative and improved model to accurately calculate the environmental cost of road maintenance in Western Australia.

The emission values have been calculated with Australia-specific data, including Australia-specific emission factors. The detailed processes of eight road maintenance strategies have been analysed to calculate the environmental impact, in terms of carbon emissions, from the extraction of raw materials, manufacturing, placement, and transportation. The result shows that due to the large geographic scale in Western Australia, the transportation of materials has the highest impact on the emission values.

The main summarised research findings for research objective 2 are:

- The ASRS has the highest emissions value followed by the ASIM, and CS has the lowest emissions value.
- The highest environmental cost is ASRS, and CS has the lowest environmental cost.
- Transportation has the largest impact on the environmental impact of maintenance strategies, followed by the use of raw materials.

8.2.3 Research Findings for Objective 3

The research objective 3 is to develop an innovative and improved mathematical model to accurately calculate the RUC of roads in Australia.

The vehicle operation cost and value of time (freight and occupants) have been calculated with Australia-specific parametric values by referring to eight strategies, eight regions, five road types, and various speed limits as well. The final result of road user cost has been categorized into three different situations including the usual condition, under construction situation, improvement after treatment condition. The result is useful for road agencies to identify the social cost of maintenance activities and integrate it in the decision making process.

The main summarised research findings for research objective 3 are:

- During the usual situation, ASDG has the highest RUC while GrOL, Slurry and CS has the same lowest cost.

- During the under construction situation (speed 40 km/h), ASOG has the highest RUC while GrOL has the lowest cost.
- After treatment of IRI improvement, ASOG has the highest RUC while GrOL, Slurry and CS has the same lowest RUC.

8.2.4 Research Findings for Objective 4

The research objective 4 is to innovatively integrate environmental cost and RUC into making maintenance decisions for road projects.

This research calculated the true cost of maintenance activities based on direct cost, environmental cost and road user cost. In order to demonstrate the integration of these cost elements, this research use three scenarios: (1) the Life Cycle Cost Analysis of maintenance decisions over 20 years; (2) the appropriate budget allocation for road maintenance (rehabilitation), considering the impact of the maintenance to the whole community; and (3) the true cost of road maintenance activities for easy assessment of maintenance activities in practice.

The main summarised research findings for research objective 4 are:

- The environmental and social cost of maintenance activities can be integrated into the lifecycle cost analysis of maintenance. Through the LCC model analysis of the case study, it is recommended that RipSeal is selected as the optimal maintenance strategy, with an estimated value of $ 3, 065,520 (AUD), which is $ 979,578 lower than routine maintenance and $ 1,224,988 lower than GrOL.
- The allocation of annual maintenance budget scenario result shows that the budget scenario of $105 million was the most effective strategy to bring the total maintenance value to $1,715,033,673, which is $ 2,834,832 lower than 115 million budget scenario and $ 3,159,957 lower than 95 million budget scenario.
- To assist the easy adoption of the results, the weighting of eight maintenance strategies about their true cost implications were provided.

8.3 Contributions to Theory and Knowledge

This research shows that the indirect cost elements of road maintenance activities, including environmental and social costs can be measured quantitatively and integrated effectively into decision-making. Previous studies mostly assessed the environmental and social impact of road design and construction while this thesis demonstrated that they can also be integrated into the maintenance stage, especially in countries and regions where new road construction is very limited.

8.3.1 Understanding Sustainable Road Maintenance

Currently, maintenance decisions are made based on two factors: direct cost and improvement to the overall road network health. However, as the concept of sustainable development has been widely recognised, it is necessary to understand the concept of sustainable road maintenance. Based on the triple bottom line, this thesis reviewed the economic, social and environmental aspects of road maintenance and identified the importance of these aspects in road maintenance. The current decision making process in road maintenance was also evaluated and the reasons leading to the low adoption of environmental and social aspects of maintenance were identified. The primary factors causing difficulty in incorporating environmental and social impacts into road maintenance are budgets, measuring benefits and lack of expertise.

8.3.2 Evaluating Sustainable Road Maintenance

This thesis developed an innovative framework to evaluate the environmental and social costs of maintenance strategies. In order to successfully achieve this, two separate models were developed for the evaluation of environmental impact and social impact of road maintenance activities. For the evaluation of environment impact, this study proposed the use of carbon emissions as the indicator given the importance of global climate change. The life cycle assessment approach method adopted in this study made a valuable contribution to knowledge in terms of defining the system boundaries of maintenance activities and identifying and calculating Australia-specific emission factors for maintenance. In addition, this study proposed a method to calculate the road user cost before, during and after maintenance, which is also considered as a significant contribution to knowledge.

8.3.3 Implementing Sustainable Road Maintenance

This thesis proposed the implementation of sustainable road maintenance strategies at two levels: macro level (state level) and micro level (project level). At the macro level, the method and process of integrating environmental and social cost into budget allocation made a valuable contribution to the decision making process of road maintenance. In addition, at the project level, this thesis demonstrated a method and process to select optimal maintenance strategy. More importantly, the true cost of each type of maintenance strategy was investigated by integrating direct cost, environmental cost and social cost.

8.4 Contributions to Practice

This research demonstrated how the methodology and tools developed in the study can be implemented in practical cases. This allows road agencies to capture the ever-changing requirements for economic, environmental and social considerations. The proposed innovative model is expected to achieve a new maintenance paradigm that will enable road agencies to develop treatments tailored to the actual behaviour and conditions of the road, achieve cost-effective maintenance and provide environmental benefits. The main practical contributions of this study include:

8.4.1 Understanding the Current Maintenance Process in Australia

This research investigated the current situation of road maintenance decision-makings from road agencies, contractors and research organisations. One practical contribution of this study is the identification of the difference of perceptions from road agencies, contractors and research organisations. While environmental and social impacts may have higher priority for research organisations, they are not usually considered for road agencies and contractors. The results of this thesis will be useful for road agencies and contractors to make changes to accommodate sustainable road maintenance in their daily activities, for example, by addressing budget limitation and providing more training on sustainability.

8.4.2 Providing Tools and Values to Assess Sustainable Road Maintenance in Australia

This research provided various values and tools to assess the environmental and social costs of road maintenance. The costs are categorised by many groups, such as regions, maintenance strategies and road types so that road agencies may refer to the values and tools that may be suitable for their decision makings. In addition, the values and tools developed in this thesis are based on Australia-specific data, meaning that the results can be usefully adopted without further modification for decision making, providing practical assistance for sustainable road maintenance decisions.

8.4.3 Selecting Truly Sustainable Maintenance Activities

This research provided true cost of road maintenance considering both direct cost and indirect cost. Additionally, it innovatively integrated the social and environmental impacts into the decision making process using three scenarios: (1) the Life Cycle Cost Analysis of maintenance decisions over 20 years; (2) the appropriate budget allocation for road maintenance (rehabilitation), considering the impact of the maintenance to the whole community; and (3) the true cost of road maintenance activities for easy assessment of maintenance activities. These scenarios were selected based on an in-depth discussion with road agency in Western Australia and it is believed that they represent problems that other road agencies will also face. The process and method therefore made practical contributions for road agencies to standardise their decision making process.

8.5 Limitations and Suggestions

Due to the limitations of the data, the results were restricted to Western Australia and some regional cases have been assumed for the analysis. Also, questionnaire survey was conducted in small sample size. Although the method is applicable to other countries and regions, it is recommended that region-specific factors are adopted to identify the true environmental and social cost of road maintenance in that specific region.

Additionally, this study excluded the accident cost in road user cost, because it is difficult to quantify the cost element of road accident based on the data that were available at the time of this study. However, accident cost is considered as one important element of road user cost and it is recommended that future studies should consider developing a detailed method to quantify accident cost that may be affected by road maintenance activities. Also, this study did not consider bus passenger occupancy in average annual daily traffic because of lack of information.

More importantly, it should be noted that this study focused on the integration of cost-related factors into the decision making process of road maintenance. One important non-cost factor of road maintenance is the performance of maintenance strategies, which was not included in this study. The reason is that the deterioration of pavement is a well investigated research area and the results of road deterioration results can be usefully integrated with this study to make effective maintenance decisions. It is therefore recommended that future studies should combine the cost and non-cost factors of road maintenance for effective decision making.

8.6 Conclusion

The cost of road maintenance represents a significant amount of public funds. The effective use of these funds has the potential to save millions of dollars for road users. The successful implementation of a road maintenance strategy will need to be supported by a decision making process that does not only require limited director cost, but also minimised cost to the whole community.

To maximise the benefits to the whole community, it is essential that agencies understand the skills to calculate the environmental and social cost of maintenance activities and be able to integrate these cost elements into the decision making process. This thesis provides the detailed methods on the calculation of carbon emissions and road user cost in the maintenance stage, which are used to represent environmental impact and social impact of road maintenance. This thesis also provides useful case studies demonstrating how these cost elements can be integrated into the decision making process, including selecting the best maintenance scenario and allocating maintenance budget. It is believed that the successful implementation of the results of this thesis can help road agencies understand and calculate the true cost of maintenance activities and make effective maintenance decisions in the future.

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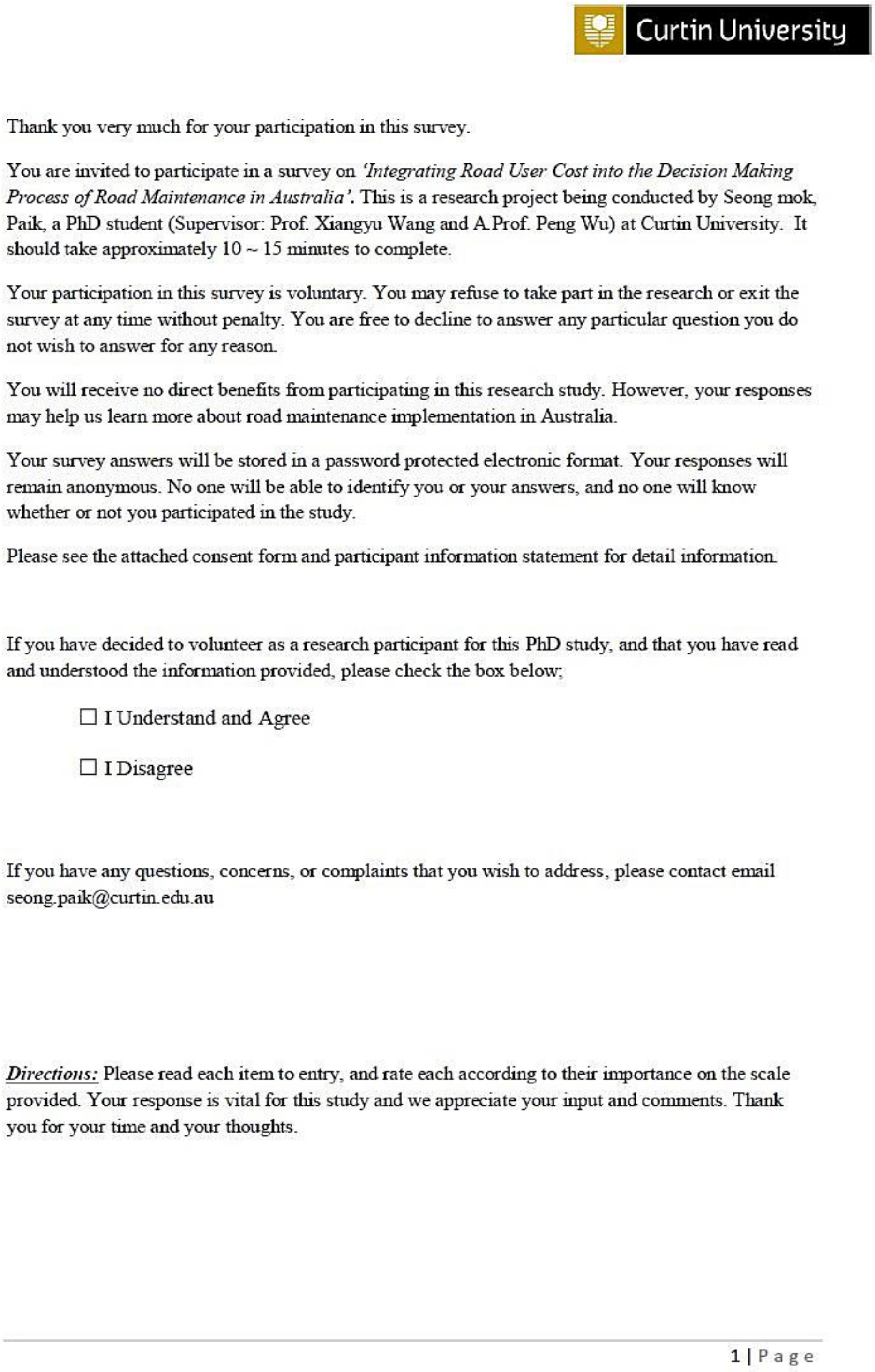
Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.

Appendix 1



Curtin University

Thank you very much for your participation in this survey.

You are invited to participate in a survey on *'Integrating Road User Cost into the Decision Making Process of Road Maintenance in Australia'*. This is a research project being conducted by Seong mok, Paik, a PhD student (Supervisor: Prof. Xiangyu Wang and A.Prof. Peng Wu) at Curtin University. It should take approximately 10 ~ 15 minutes to complete.

Your participation in this survey is voluntary. You may refuse to take part in the research or exit the survey at any time without penalty. You are free to decline to answer any particular question you do not wish to answer for any reason.

You will receive no direct benefits from participating in this research study. However, your responses may help us learn more about road maintenance implementation in Australia.

Your survey answers will be stored in a password protected electronic format. Your responses will remain anonymous. No one will be able to identify you or your answers, and no one will know whether or not you participated in the study.

Please see the attached consent form and participant information statement for detail information.

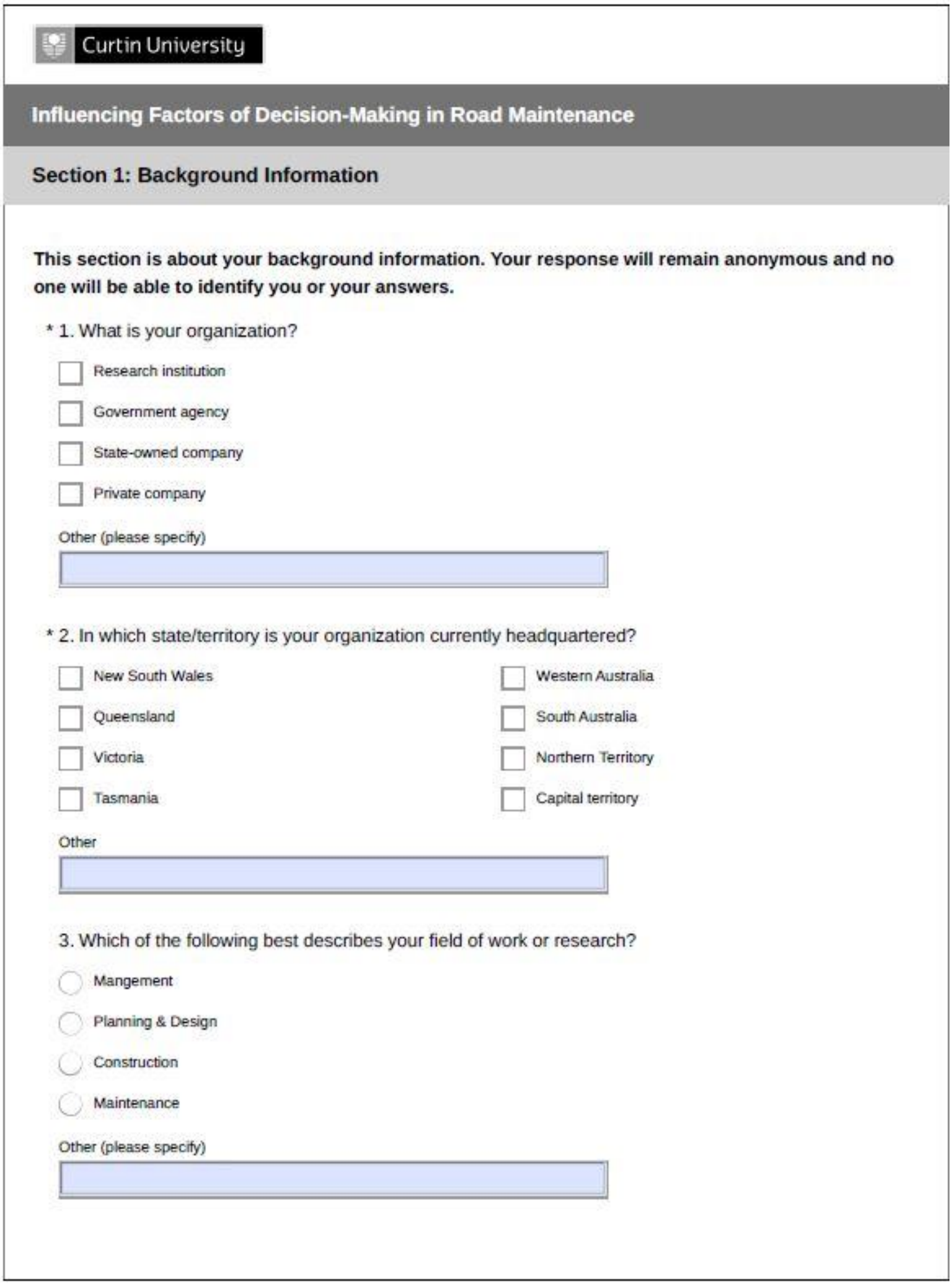
If you have decided to volunteer as a research participant for this PhD study, and that you have read and understood the information provided, please check the box below;

☐ I Understand and Agree

☐ I Disagree

If you have any questions, concerns, or complaints that you wish to address, please contact email seong.paik@curtin.edu.au

Directions: Please read each item to entry, and rate each according to their importance on the scale provided. Your response is vital for this study and we appreciate your input and comments. Thank you for your time and your thoughts.



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Influencing Factors of Decision-Making in Road Maintenance

Section 1: Background Information

This section is about your background information. Your response will remain anonymous and no one will be able to identify you or your answers.

* 1. What is your organization?

☐ Research institution

☐ Government agency

☐ State-owned company

☐ Private company

Other (please specify)

* 2. In which state/territory is your organization currently headquartered?

☐ New South Wales

☐ Queensland

☐ Victoria

☐ Tasmania

☐ Western Australia

☐ South Australia

☐ Northern Territory

☐ Capital territory

Other

3. Which of the following best describes your field of work or research?

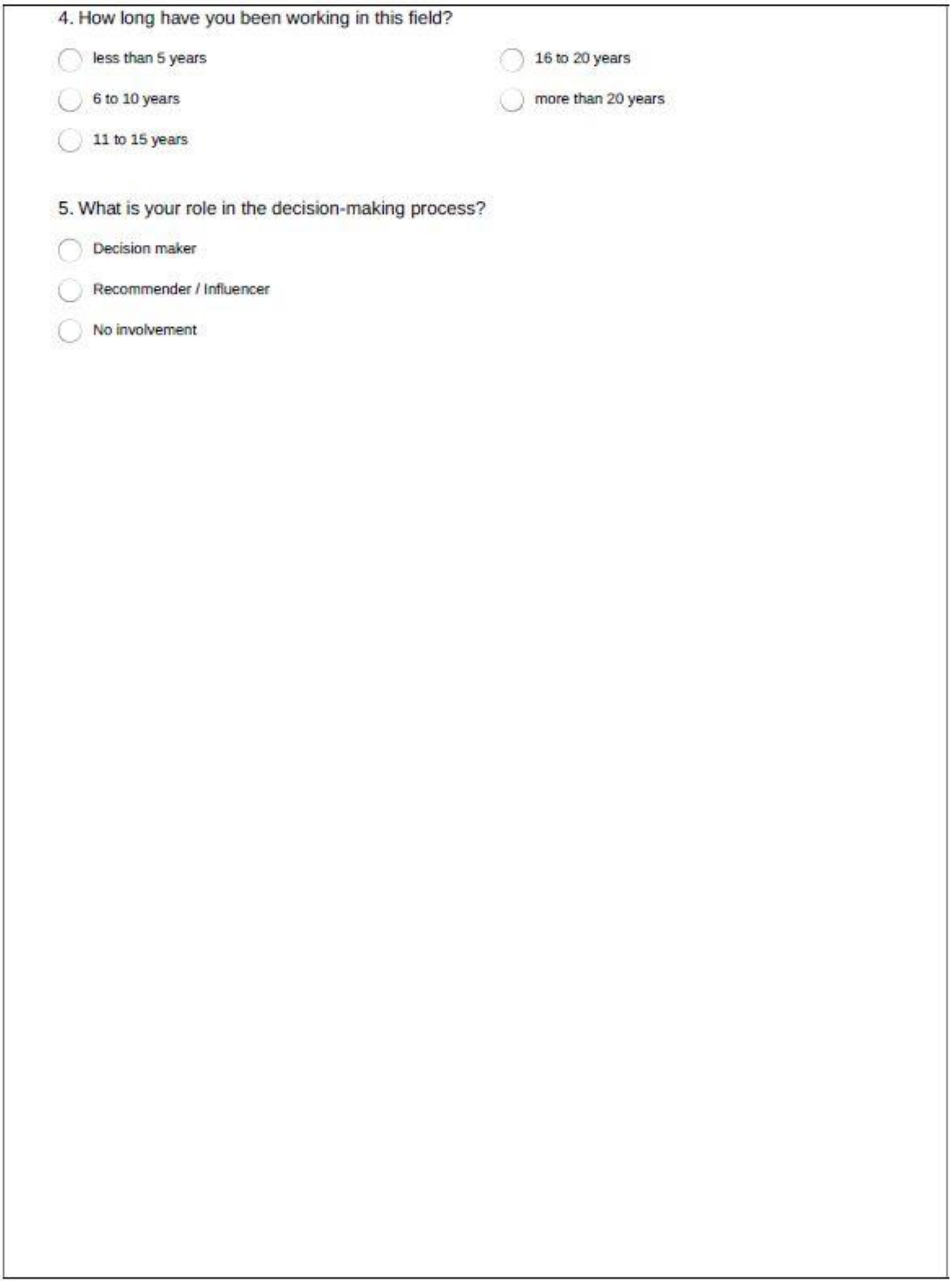
○ Mangement

○ Planning & Design

○ Construction

○ Maintenance

Other (please specify)

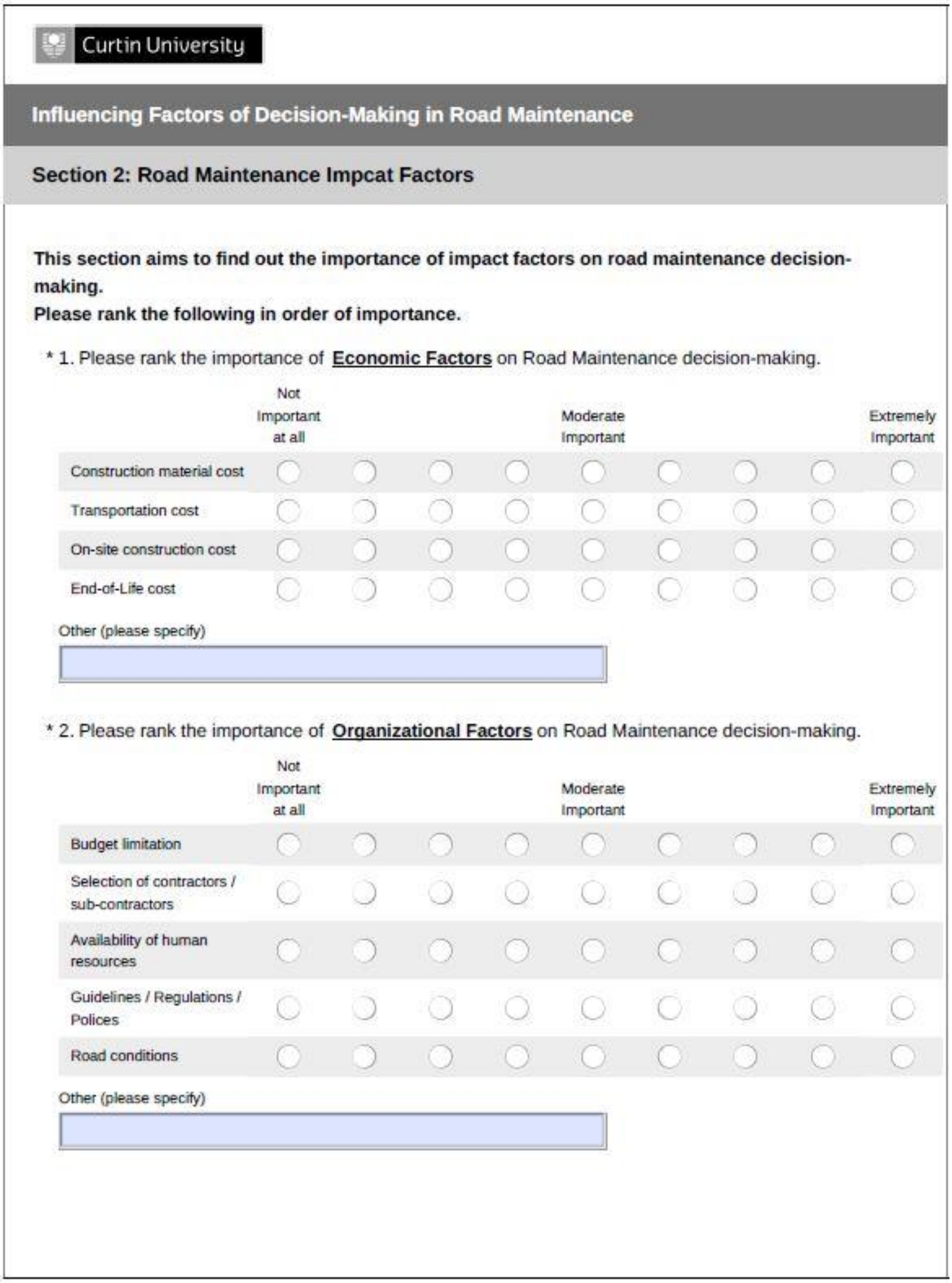


4. How long have you been working in this field?

○ less than 5 years
○ 6 to 10 years
○ 11 to 15 years
○ 16 to 20 years
○ more than 20 years

5. What is your role in the decision-making process?

○ Decision maker
○ Recommender / Influencer
○ No involvement



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Influencing Factors of Decision-Making in Road Maintenance

Section 2: Road Maintenance Impcat Factors

This section aims to find out the importance of impact factors on road maintenance decision-making.
Please rank the following in order of importance.

* 1. Please rank the importance of **Economic Factors** on Road Maintenance decision-making.

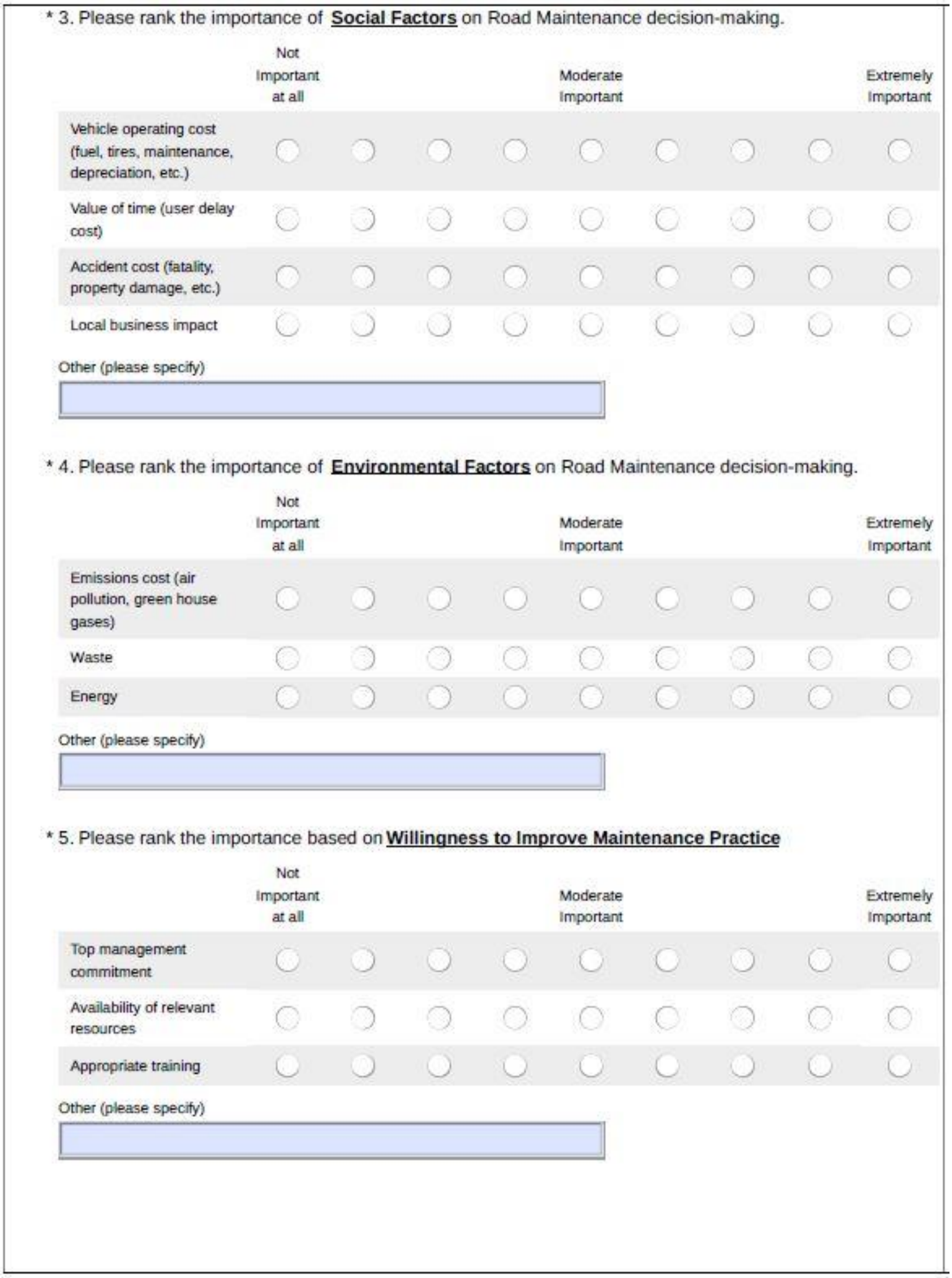
	Not Important at all				Moderate Important				Extremely Important
Construction material cost	○	○	○	○	○	○	○	○	○
Transportation cost	○	○	○	○	○	○	○	○	○
On-site construction cost	○	○	○	○	○	○	○	○	○
End-of-Life cost	○	○	○	○	○	○	○	○	○

Other (please specify)

* 2. Please rank the importance of **Organizational Factors** on Road Maintenance decision-making.

	Not Important at all				Moderate Important				Extremely Important
Budget limitation	○	○	○	○	○	○	○	○	○
Selection of contractors / sub-contractors	○	○	○	○	○	○	○	○	○
Availability of human resources	○	○	○	○	○	○	○	○	○
Guidelines / Regulations / Polices	○	○	○	○	○	○	○	○	○
Road conditions	○	○	○	○	○	○	○	○	○

Other (please specify)



* 3. Please rank the importance of **Social Factors** on Road Maintenance decision-making.

	Not Important at all				Moderate Important				Extremely Important
Vehicle operating cost (fuel, tires, maintenance, depreciation, etc.)	○	○	○	○	○	○	○	○	○
Value of time (user delay cost)	○	○	○	○	○	○	○	○	○
Accident cost (fatality, property damage, etc.)	○	○	○	○	○	○	○	○	○
Local business impact	○	○	○	○	○	○	○	○	○

Other (please specify)

* 4. Please rank the importance of **Environmental Factors** on Road Maintenance decision-making.

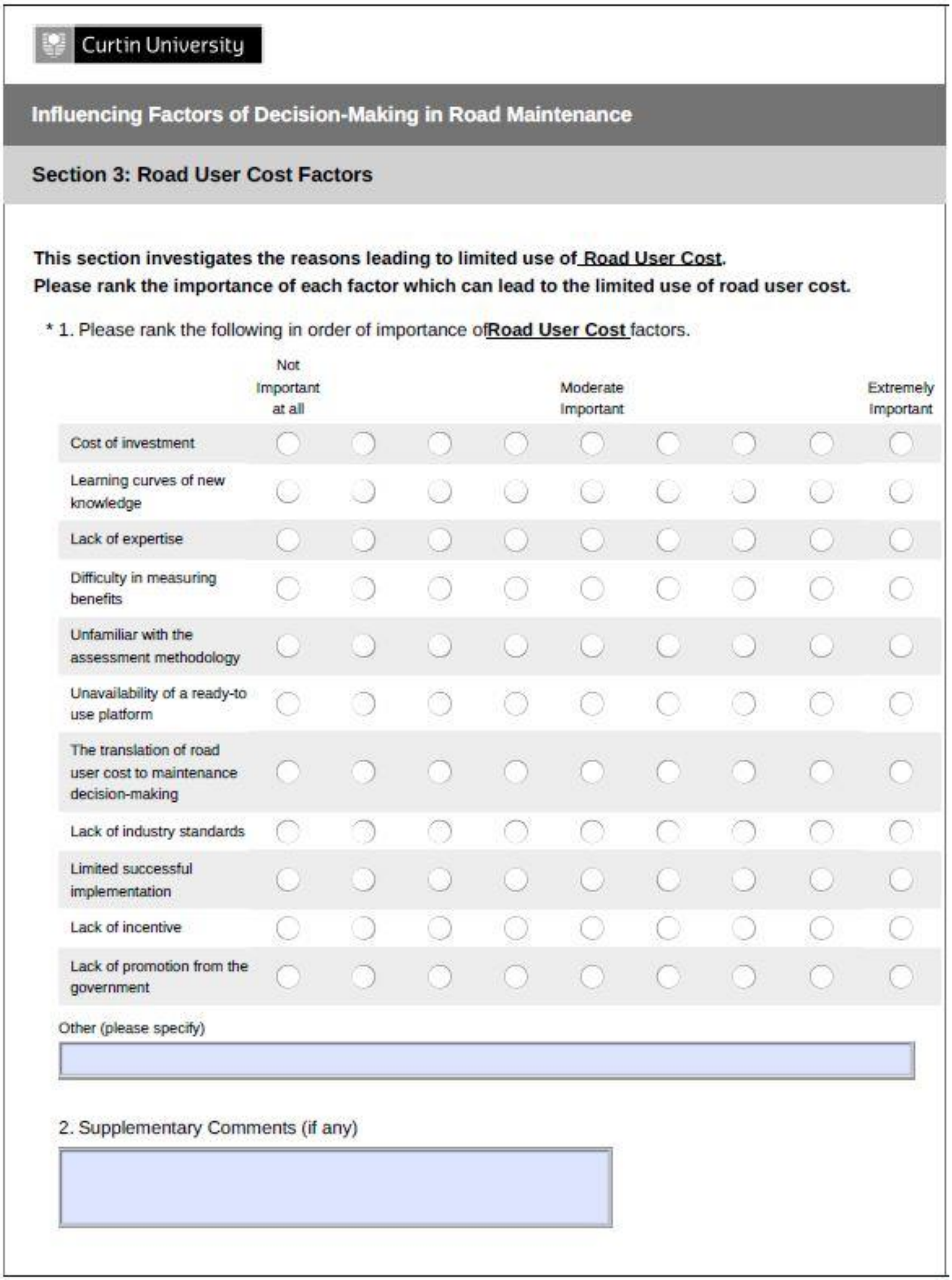
	Not Important at all				Moderate Important				Extremely Important
Emissions cost (air pollution, green house gases)	○	○	○	○	○	○	○	○	○
Waste	○	○	○	○	○	○	○	○	○
Energy	○	○	○	○	○	○	○	○	○

Other (please specify)

* 5. Please rank the importance based on **Willingness to Improve Maintenance Practice**

	Not Important at all				Moderate Important				Extremely Important
Top management commitment	○	○	○	○	○	○	○	○	○
Availability of relevant resources	○	○	○	○	○	○	○	○	○
Appropriate training	○	○	○	○	○	○	○	○	○

Other (please specify)



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Influencing Factors of Decision-Making in Road Maintenance

Section 3: Road User Cost Factors

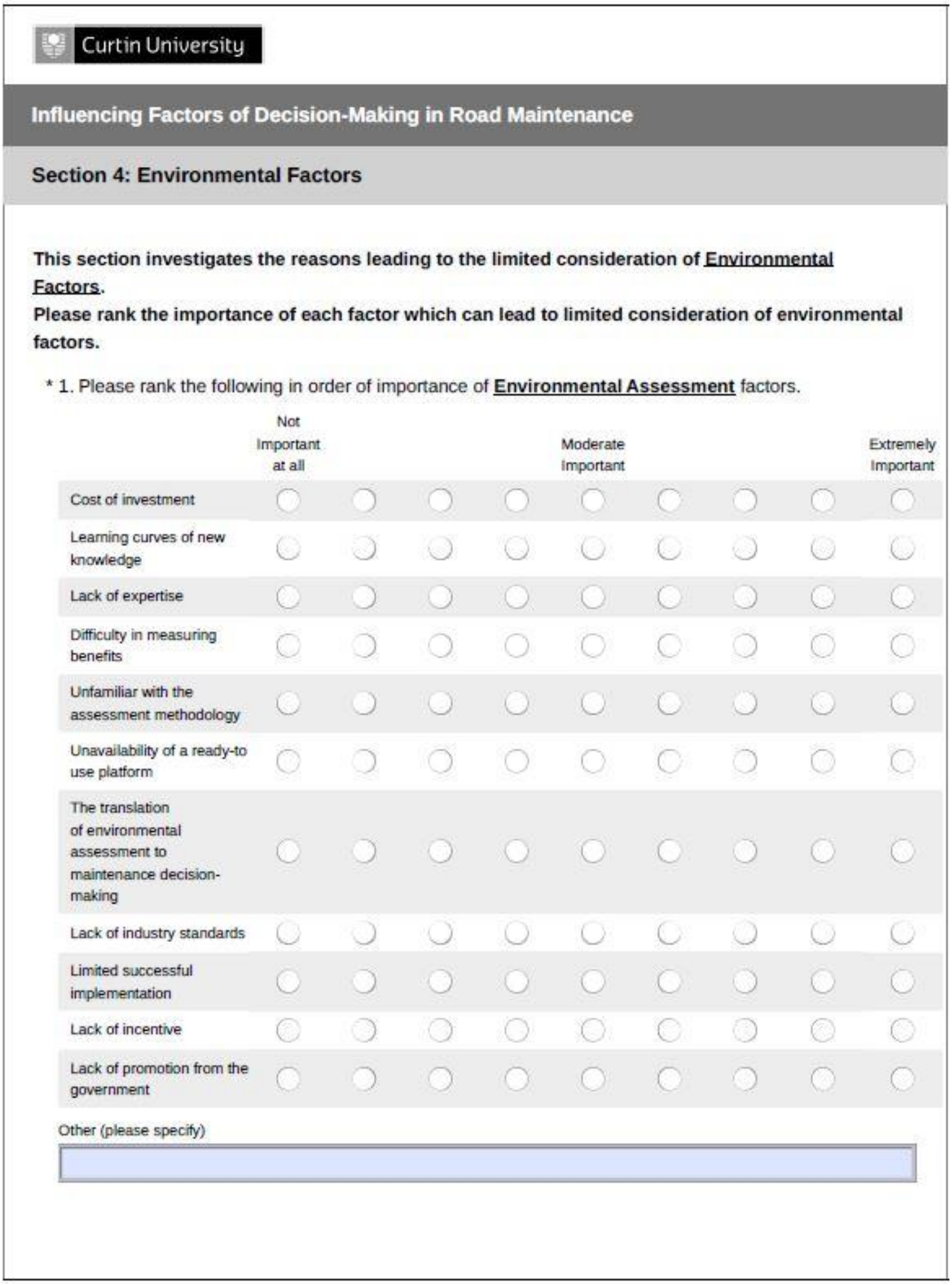
This section investigates the reasons leading to limited use of Road User Cost.
Please rank the importance of each factor which can lead to the limited use of road user cost.

* 1. Please rank the following in order of importance of**Road User Cost** factors.

	Not Important at all				Moderate Important				Extremely Important
Cost of investment	○	○	○	○	○	○	○	○	○
Learning curves of new knowledge	○	○	○	○	○	○	○	○	○
Lack of expertise	○	○	○	○	○	○	○	○	○
Difficulty in measuring benefits	○	○	○	○	○	○	○	○	○
Unfamiliar with the assessment methodology	○	○	○	○	○	○	○	○	○
Unavailability of a ready-to use platform	○	○	○	○	○	○	○	○	○
The translation of road user cost to maintenance decision-making	○	○	○	○	○	○	○	○	○
Lack of industry standards	○	○	○	○	○	○	○	○	○
Limited successful implementation	○	○	○	○	○	○	○	○	○
Lack of incentive	○	○	○	○	○	○	○	○	○
Lack of promotion from the government	○	○	○	○	○	○	○	○	○

Other (please specify)

2. Supplementary Comments (if any)



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Influencing Factors of Decision-Making in Road Maintenance

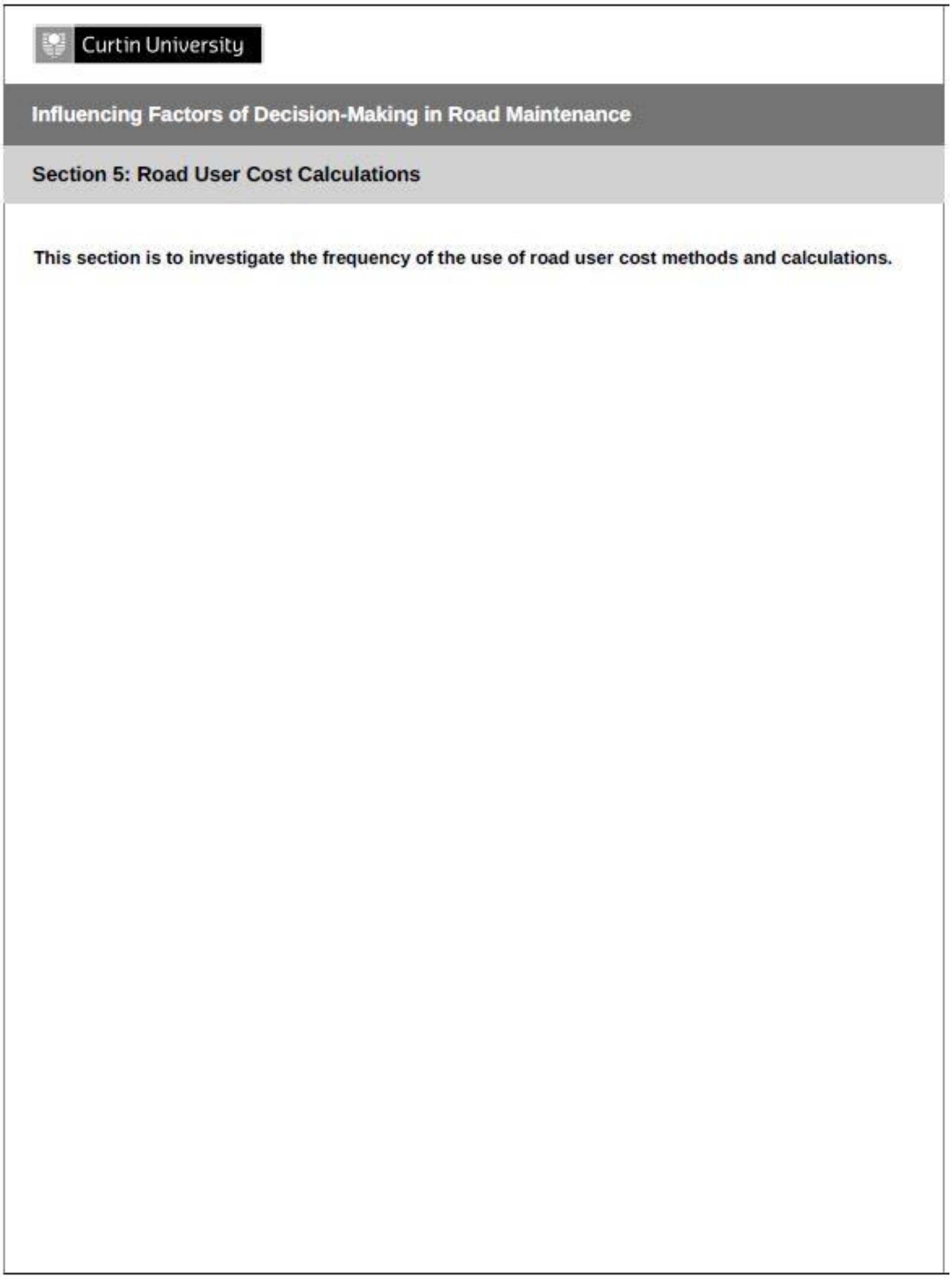
Section 4: Environmental Factors

This section investigates the reasons leading to the limited consideration of Environmental Factors.
Please rank the importance of each factor which can lead to limited consideration of environmental factors.

* 1. Please rank the following in order of importance of **Environmental Assessment** factors.

	Not Important at all				Moderate Important				Extremely Important
Cost of investment	○	○	○	○	○	○	○	○	○
Learning curves of new knowledge	○	○	○	○	○	○	○	○	○
Lack of expertise	○	○	○	○	○	○	○	○	○
Difficulty in measuring benefits	○	○	○	○	○	○	○	○	○
Unfamiliar with the assessment methodology	○	○	○	○	○	○	○	○	○
Unavailability of a ready-to use platform	○	○	○	○	○	○	○	○	○
The translation of environmental assessment to maintenance decision-making	○	○	○	○	○	○	○	○	○
Lack of industry standards	○	○	○	○	○	○	○	○	○
Limited successful implementation	○	○	○	○	○	○	○	○	○
Lack of incentive	○	○	○	○	○	○	○	○	○
Lack of promotion from the government	○	○	○	○	○	○	○	○	○

Other (please specify)



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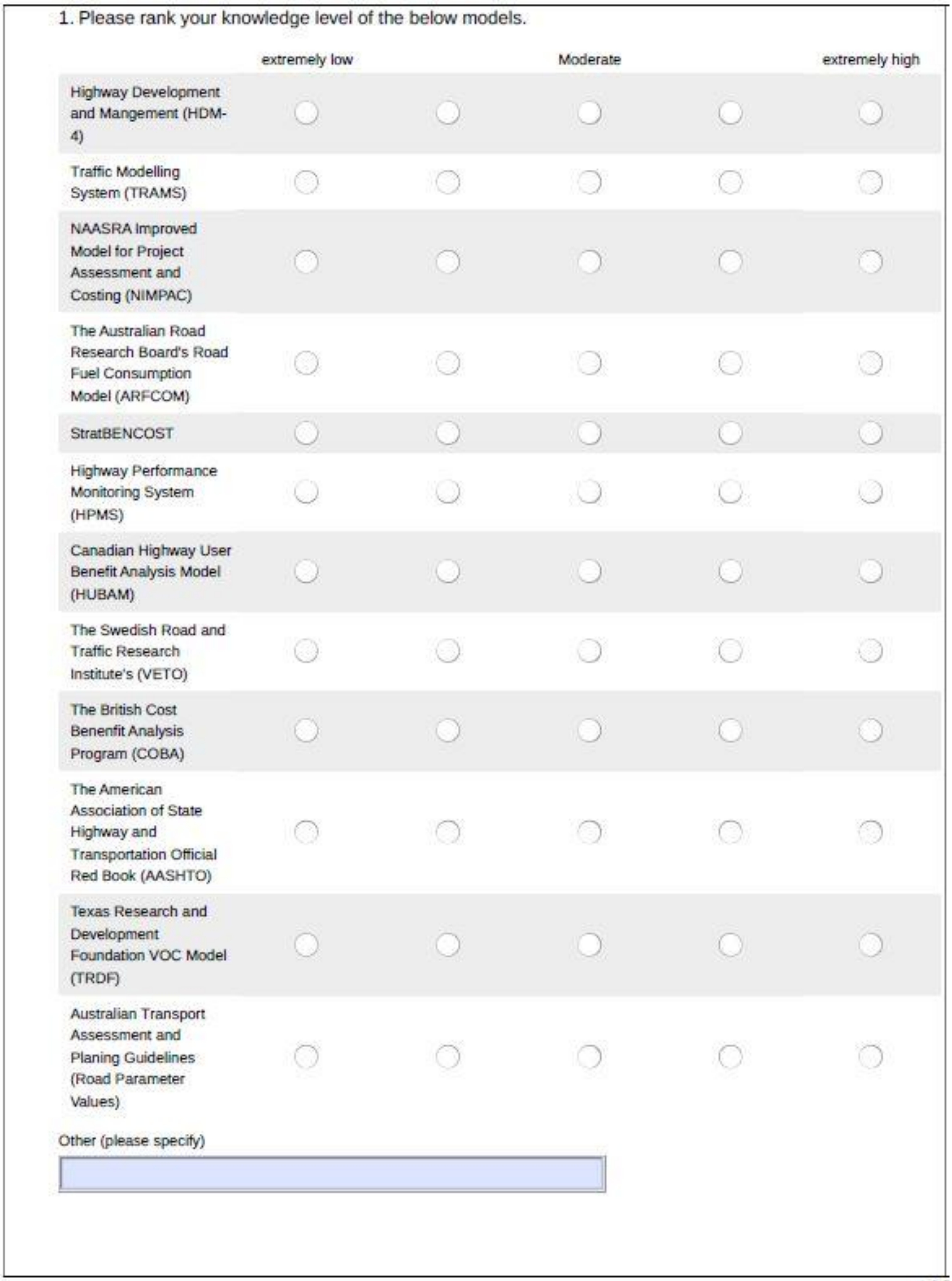
Influencing Factors of Decision-Making in Road Maintenance

Section 5: Road User Cost Calculations

This section is to investigate the frequency of the use of road user cost methods and calculations.



1. Please rank your knowledge level of the below models.

	extremely low		Moderate		extremely high
Highway Development and Mangement (HDM-4)	○	○	○	○	○
Traffic Modelling System (TRAMS)	○	○	○	○	○
NAASRA Improved Model for Project Assessment and Costing (NIMPAC)	○	○	○	○	○
The Australian Road Research Board's Road Fuel Consumption Model (ARFCOM)	○	○	○	○	○
StratBENCOST	○	○	○	○	○
Highway Performance Monitoring System (HPMS)	○	○	○	○	○
Canadian Highway User Benefit Analysis Model (HUBAM)	○	○	○	○	○
The Swedish Road and Traffic Research Institute's (VETO)	○	○	○	○	○
The British Cost Benenfit Analysis Program (COBA)	○	○	○	○	○
The American Association of State Highway and Transportation Official Red Book (AASHTO)	○	○	○	○	○
Texas Research and Development Foundation VOC Model (TRDF)	○	○	○	○	○
Australian Transport Assessment and Planing Guidelines (Road Parameter Values)	○	○	○	○	○

Other (please specify)

Appendix 2

Curtin University

Office of Research and Development

GPO Box U1987
Perth Western Australia 6845

Telephone +61 8 9266 7863
Facsimile +61 8 9266 3793
Web research.curtin.edu.au

06-Sep-2017

Name: Peng Wu
Department/School: Department of Construction Management
Email: Peng.Wu@curtin.edu.au

Dear Peng Wu

RE: Ethics Office approval
Approval number: HRE2017-0602

Thank you for submitting your application to the Human Research Ethics Office for the project **Integrating Road User Cost into the Decision Making Process of Road Maintenance in Australia**.

Your application was reviewed through the Curtin University Negligible risk review process.

The review outcome is: **Approved**.

Your proposal meets the requirements described in the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research (2007)*.

Approval is granted for a period of one year from **06-Sep-2017** to **05-Sep-2018**. Continuation of approval will be granted on an annual basis following submission of an annual report.

Personnel authorised to work on this project:

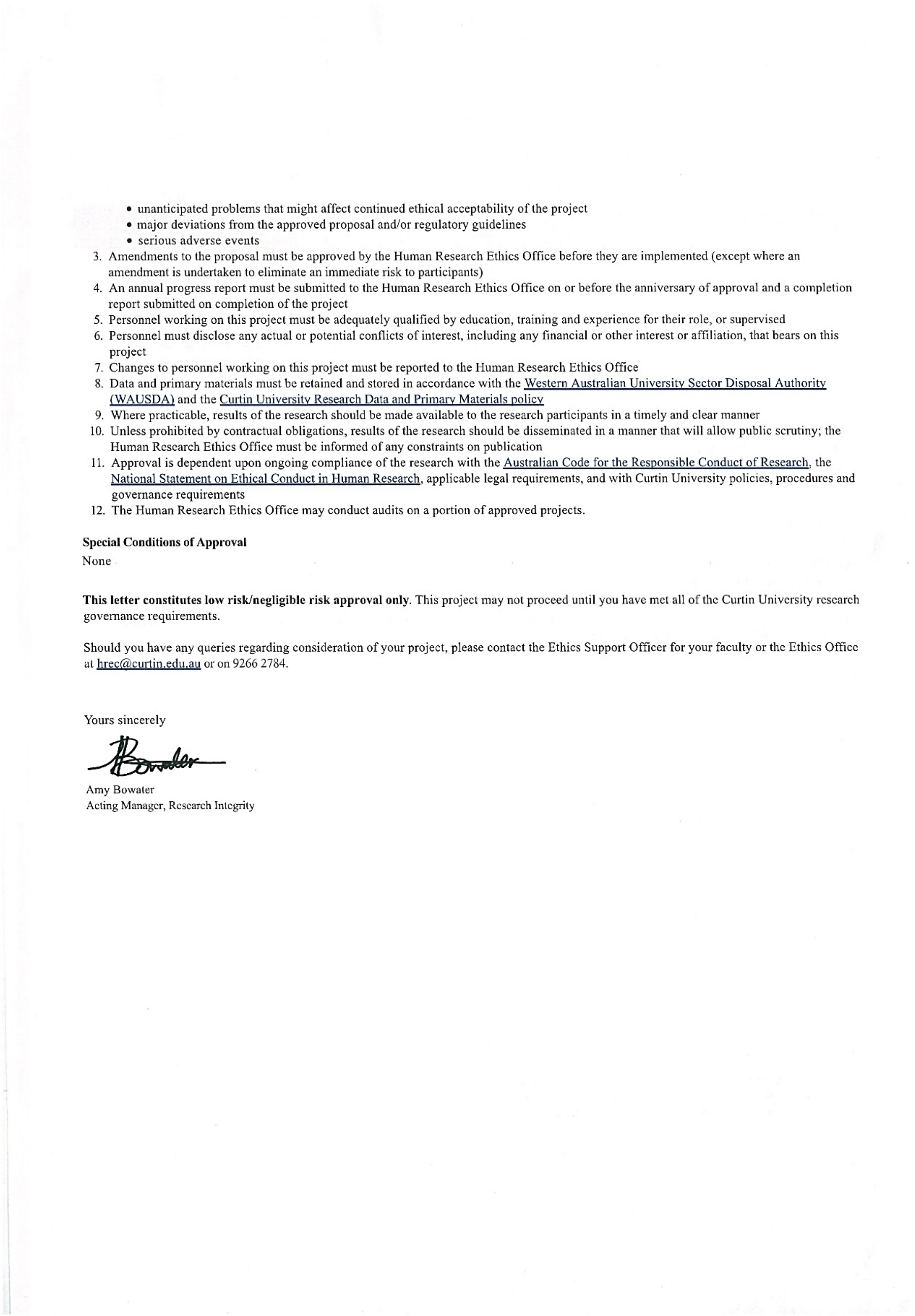
Name	Role
Wu, Peng	CI
Paik, Seong mok	Student

Approved documents:

Document

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:
    - proposed changes to the approved proposal or conduct of the study



- unanticipated problems that might affect continued ethical acceptability of the project
- major deviations from the approved proposal and/or regulatory guidelines
- serious adverse events

3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)
4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion report submitted on completion of the project
5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
9. Where practicable, results of the research should be made available to the research participants in a timely and clear manner
10. Unless prohibited by contractual obligations, results of the research should be disseminated in a manner that will allow public scrutiny; the Human Research Ethics Office must be informed of any constraints on publication
11. Approval is dependent upon ongoing compliance of the research with the Australian Code for the Responsible Conduct of Research, the National Statement on Ethical Conduct in Human Research, applicable legal requirements, and with Curtin University policies, procedures and governance requirements
12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Special Conditions of Approval

None

This letter constitutes low risk/negligible risk approval only. This project may not proceed until you have met all of the Curtin University research governance requirements.

Should you have any queries regarding consideration of your project, please contact the Ethics Support Officer for your faculty or the Ethics Office at hrec@curtin.edu.au or on 9266 2784.

Yours sincerely

Amy Bowater
Acting Manager, Research Integrity