School of Design and the Built Environment

Estimating and Reducing Road Carbon Emissions through Hybrid Life Cycle Assessment and Decomposition Analysis

Rui Jiang

0000-0001-5007-5746

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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.

Signature:

Date: 31/08/21

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ABSTRACT

Greenhouse gas (GHG) emissions have long been a worldwide concern due to their detrimental impacts on climate change, sea-level rise, and natural and human ecosystems. Australia has committed to reduce its national GHG emissions by 26–28% by 2030 relative to 2005 levels. The use, maintenance and rehabilitation (M&R) of road infrastructure is a significant source of GHG emissions. In addition, on-road vehicles contribute a large portion of national GHG emissions. In response to the need to achieve the emissions reduction target, Australian road authorities and policymakers are under increasing pressure to reduce GHG emissions from the road sector.

Estimating and understanding the GHG emissions of roads is the first step towards achieving effective emissions reduction. Life cycle assessment (LCA) is a widely adopted approach for estimating emissions of road infrastructure. Although road M&R is preferred over new construction by road agencies in Australia, existing LCA studies on roads have limited considerations to emissions from the use and M&R phases of roads. This thesis proposes and illustrates a structured hybrid LCA approach that can be adopted by road agencies to more fully evaluate carbon emissions from the use and M&R phases of roads. A path exchange LCA method and a tiered hybrid LCA method are integrated to increase accuracy. To illustrate this approach, a case study of a road network in Western Australia was considered. The results show that from 2017 to 2026, the global warming potential (GWP) of the targeted phases increased from 467.8 to 589.5 tCO_2-e/km. The use phase had much higher GWP than the M&R phase during the service life of roads, accounting for an average of 99.2% of the total GWP. In addition, heavy traffic roads in metropolitan areas and freeways with annual average daily traffic (AADT) greater than 20,000 vehicles are identified as the most carbon intensive. The adopted approach provides road agencies a structured and accurate hybrid LCA method for estimating GHG emissions from the use and M&R phases of road infrastructure.

Road agencies (e.g., Main Roads Western Australia) tend to make strategic maintenance plans for a road network based solely on pavement condition and maintenance budgets. With the increasing recognition of sustainability, it is imperative that pavement maintenance plans are established to achieve maximum sustainable

benefits. This thesis integrates environmental and social sustainability indicators into the traditional assessment of network-level pavement maintenance plans. A conceptual framework is developed based on a multi-attribute method by systematically considering road condition, and economic, environmental and social sustainability. The international roughness index, agency cost, GHG emissions, and road-user cost were adopted as key indicators, respectively, and a case study was used to demonstrate the usefulness of this framework. Based on an initial experiment in which equal weights were allocated to these four attributes, the 85 M plan (representing an annual maintenance budget of AUD 85 M) was identified as the optimal solution out of eight network-level pavement maintenance plans. The proposed framework provides a straightforward method for road agencies to select the most optimal network-level pavement maintenance plans.

In addition, to reduce road transport related emissions during road use, major policy innovation is needed in addition to the Emissions Reduction Fund. The basis for formulating relevant policies is an accurate estimate of emissions and an understanding of the factors that have led to changes in past emissions. As such, this thesis also investigated the factors affecting changes in the Australian road transport sector. To better inform policy, the U.S. road transport sector was examined as a reference. The energy-related carbon dioxide (CO_2) emissions of road transport in the U.S. (2008–2017) and Australia (2009–2017) were assessed from the perspective of passenger and freight transport, using a logarithmic mean Divisia index approach. The key findings include: 1) cars and light trucks (from passenger transport) and medium/heavy trucks (from freight transport) are significant contributors to road transport CO_2 emissions; 2) population has a dominant effect on the increase of CO_2 emissions from passenger transport, and the most effective strategy for emissions reduction in this sector is to improve energy intensity; and 3) gross domestic product (GDP) has contributed the most to the growth in CO_2 emissions from freight transport, and reduced freight transport intensity is effective at reducing CO_2 emissions in this sector. Based on these findings, several policy recommendations are proposed to inform CO_2 emissions reduction strategies for the road transport sector. Overall, this thesis has important implications for decision/policymakers seeking to reduce GHG emissions in the road sector at both local and national levels, thereby helping to green the sector and achieve current emissions reduction targets.

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LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AMDI	Arithmetic mean Divisia index
ANZSIC	Australian-New Zealand Standard Industrial Classification
BIM	Building information modelling
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CNG	Compressed natural gas
EIO-LCA	Environmental Input-Output Life Cycle Assessment
EOL	End-of-life
EPA	Environmental Protection Agency
ERF	Emissions Reduction Fund
FU	Functional unit
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
HCP	Highly cited paper
HDM-4	Highway Development and Management Model—version 4
HMA	Hot mixed asphalt
IDA	Index decomposition analysis
IO	Input-output
IPCC	Intergovernmental Panel on Climate Change
IRI	International roughness index
IS	Infrastructure sustainability
ISCA	The Infrastructure Sustainability Council of Australia
LCA	Life Cycle Assessment
LCCA	Life cycle costing analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LMDI	Logarithmic mean Divisia index
LPG	Liquefied petroleum gas
M&R	Maintenance and rehabilitation

MPD	Mean profile depth
MRWA	Main Road Western Australia
NAV	Net annual value
NPV	Net present value
OECD	Organisation for Economic Co-operation and Development
P-LCA	Process-based Life Cycle Assessment
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCC	Portland cement concrete
PXC	Path Exchange Hybrid LCA method
RAP	Reclaimed asphalt pavement
RR	Rolling resistance
SDA	Structural decomposition analysis
VMT	Miles travelled by vehicles
VOC	Vehicle operating cost
VTI	A model developed by the Swedish National Road and Transport Research Institute
WA	Western Australia
WMA	Warm mix asphalt
WSM	Weighted sum method

Chapter 1. Introduction

This chapter provides a brief introduction to this study. The context of this research field and motivation for conducting the study are first elaborated in Section 1.1. Section 1.2 and Section 1.3 analyse the problems and challenges faced by the field, and explain the overall research aim and objectives. Section 1.4 states the significance and contribution of this study. Section 1.5 provides an overview of the structure of the thesis and, finally, Section 1.6 summarises this chapter.

1.1 Context and Motivation

Greenhouse gas (GHG) emissions have long been a worldwide concern due to their detrimental impacts on climate change, sea-level rise, and natural and human ecosystems (Jonker et al., 2019). Reducing GHG emissions is, therefore, required and targeted by many countries. Australia, despite having a relatively small population (ranked 55th in the world in 2019), generates 1% of the world's GHG emissions (ranked 16th in 2018) (The World Bank, 2019; Union of Concerned Scientists, 2020). In addition, per capita GHG emissions in Australia were ranked 3rd in the world in 2018 (Union of Concerned Scientists, 2020). To acknowledge responsibility, Australia has committed to reduce its national GHG emissions by 26–28% by 2030 relative to the 2005 levels (Australian Government, 2015). With a growing economy and population, reducing the emissions intensity of the economic sectors is key to achieving this emissions reduction target (Australian Government, 2015). Following electricity and stationary energy (excluding electricity) sectors, transport is the third-largest sector for GHG emissions in Australia, and has the highest growth rate (Australian Government, 2020c; Climate Council, 2017). The transport sector accounted for 28.2% of national energy use in 2019 and 18.3% of national GHG emissions in 2020 (Australian Government, 2020a, c). In addition, transport energy efficiency in Australia was recently ranked second worst by one international scorecard (Climate Council, 2017).

Among all transport modes, road transport accounts for approximately 69.3% and 27.8% of Australian passenger and goods transport, respectively (AU BITRE, 2019). Rather than new construction, Australian road agencies prioritise maintenance and rehabilitation (M&R) of roads over new construction programmes (Department of Infrastructure and Regional Development, 2013). Every year, more than AUD 7 billion is spent by the Australian Government on maintaining and renewing the 877,650-km Australian road network (Department of Infrastructure and Transport, 2014; Statista, 2020). Such a large network accounted for nearly 84.5% and 75% of national transport GHG emissions and energy consumption during the use of roads in the fiscal year 2018-19, respectively (AU BITRE, 2019; Australian Government, 2020a). Car emissions alone produced half of the GHG emissions from the transport sector during the road use phase (Jiang et al., 2020), and emissions continue to increase due to rising vehicles numbers (Main Roads Western Australia, 2020). In addition, the construction and continuous maintenance of road infrastructure consume large amounts of materials and fuel, which are produced through highly carbon-intensive processes (Santos et al., 2015b). For example, the production of cement, a commonly used material in road work, generates 1% of Australia's total GHG emissions (CIF, 2013). The changing roughness of the road pavement during road use also influences emissions from on-road vehicles, which is a major source of emissions (Inyim et al., 2016). In response to the climate change policy, Australian road authorities are under increasing pressure to report the sustainability of roads and reduce their emissions. As such, special attention should be paid to both road infrastructure (e.g., road maintenance and pavement roughness change) and transport related emissions during use and M&R phases.

1.1.1 Infrastructure related emissions during road use and maintenance

- Estimation of infrastructure related emissions from road use and maintenance

Estimating and understanding the GHG emissions of roads is the first step towards achieving effective emissions reductions (Sandanayake et al., 2017). Life Cycle Assessment (LCA) is a widely adopted approach for estimating emissions from road infrastructure, based on lifecycle inputs, outputs and the potential environmental impacts of products/processes (ISO, 2006; Santero et al., 2011).

The current application of LCA in road evaluation often follows the ISO 14044 (2006) standard. In Australia, a guide for assessing the lifecycle GHG emissions of road infrastructure was prepared for road agencies by Transport Authorities Greenhouse

Group (TAGG, 2013), including a carbon gauge calculator tool. However, this workbook, along with the tool, focus on the material production and construction phases; although the M&R phase is covered, details on the calculation process are not adequate (PIARC, 2019). As road authorities currently favour M&R over new construction, a more detailed LCA model for the M&R phase is sorely needed (Department of Infrastructure and Regional Development, 2013). In addition, the use phase defined in the workbook only considers street lighting, traffic signals, and intelligent transport systems, such as variable speed signs and lane use signs (TAGG, 2013). Rolling resistance (RR), which is the most frequently considered use phase component in existing studies, is not, however, covered or modelled. Road agencies in Australia are, therefore, in need of a structured and practical LCA approach for the use and M&R phases of roads so that significant contributing factors and road segments can be identified for decision making.

Similar limitations and research needs have been identified by the academic community. Since the first peer-reviewed LCA study on roads was published in 1996, much attention has been paid to the material production and construction phases, with more than 50% of existing studies leaving out the M&R phase and, in particular, the use phase (Jiang and Wu, 2019). Such exclusion may lead to bias in results, affecting the establishment of accurate and relevant carbon reduction strategies (Inyim et al., 2016). According to Wu et al. (2014), the M&R of a road can contribute 5.6% of the total carbon emissions during its life cycle, which is above the 1% exclusion threshold set by the Publicly Available Specification 2050. In addition, the deterioration of road pavements during their use can result in additional fuel consumption and GHG emissions. Indeed, the global warming potential (GWP) linked to road roughness can be higher than that of material extraction and production, which is normally considered to be highest (Santero and Horvath, 2009). A possible reason for the exclusion of the use phase is a lack of a clear methodology for estimating the environmental impacts generated in this phase (Inyim et al., 2016). There is, therefore, a need to develop a structured LCA approach to evaluate emissions from the use and M&R phases of roads.

Recently, researchers started to realise such limitations and related research has been conducted. Process-based LCA (P-LCA) method is predominantly used in these studies. For example, Qian et al. (2013), Santos et al. (2015b), Lepech and Li

(2010),Chen et al. (2016) and Mao et al. (2017) all adopts a P-LCA method to investigate the use and/or M&R phases of roads. Possible reasons for its popularity are the maturity of the available tools and its high accuracy that can be achieved through itemised inputs and outputs for every process (Jiang and Wu, 2019). However, this method is costly and time-consuming and can lead to cut-off errors due to the exclusion of several 'unimportant' processes. Environmental input-output LCA (EIO-LCA) is able to provide a complete calculating framework, but it still faces disadvantages, such as a high level of sector aggregation and the use of nationally averaged data (Choi et al., 2016). As such, hybrid LCA methods have been explored in recent studies with the aim of accounting for individual processes to ensure accuracy while also using input-output (IO) data to complete the system boundary. For example, Batouli et al. (2017) used a hybrid LCA method to evaluate the whole lifecycle GWP of different pavement types, but a detailed explanation of the applied model was not provided. A similar limitation is also observed in Santos et al. (2017b). Enache and Stampfer (2015) also applied the hybrid LCA approach to evaluate GHG emissions from the construction and M&R phases of forest roads in Romania. Nevertheless, traffic delays and the use phase were not included. A structured hybrid LCA model is still in need for the use and M&R phases of roads.

- Integrating estimated emissions into road infrastructure maintenance decisions

Importantly, the estimated GHG emissions from the road use and M&R phases should be considered by decision-makers seeking to reduce emissions. The M&R of a road consists of routine maintenance, preservation and pavement rehabilitation (Torres-Machi et al., 2018). Routine maintenance often includes reactive and corrective actions that fix specific problems of safety concern (e.g., potholes); preservation is usually proactive and scheduled in advance, with periodical activities to slow down the deterioration of road pavements; and pavement rehabilitation requires structural enhancements and is often triggered when the service life or load carrying capacity of a road need to be upgraded (Torres-Machi et al., 2018). Generally, these activities require materials, equipment use and temporary road closure. In addition, the implementation of different M&R strategies will further influence the performance of roads during their use phase. Therefore, the assessment and selection of a road maintenance plan has a crucial influence on the economic, social and environmental characteristics of a community.

Road design and maintenance plans can be assessed based on several considerations including direct costs, such as design fees, construction and future maintenance, road-user costs, and other externalities, such as emissions and noise (Toole et al., 2007). The most commonly included assessment criterion in practice is agency cost, including the direct cost of materials, equipment and labour associated with the maintenance activities. Because agency costs have a direct impact on the financial performance of road agencies, it is common to evaluate maintenance activities along with pavement performance. Over the past few years, road-user costs—as an indicator of the social impact of road maintenance—have been included in some few studies (France-Mensah and O'Brien, 2019; Gao and Zhang, 2013); however, this remains a challenge because of several uncertainties (Giustozzi et al., 2012). For example, road-user costs do not have a traded market value and although calculation methods have been developed, they are mainly applied in the construction phase (Giustozzi et al., 2012). Given the rising recognition of the importance of sustainability, environmental issues have now become an addition consideration for the construction and infrastructure sectors (Wang et al., 2018). One of the most commonly adopted indicators in environmental assessment is GHG emissions, which are considered a significant contributor to global climate change (Wu et al., 2019). Based on these recent developments, it is imperative that the practices of evaluating maintenance decision should be improved from a cost-based approach to a more sustainable one.

Nevertheless, road agencies (e.g., Main Roads Western Australia, MRWA) tend to make strategic maintenance plans for road networks based solely on pavement conditions and maintenance budgets (Li, 2018). As environmental effects are not usually considered as direct costs to road agencies and, unlike agency costs, they do not pay for road-user cost, most road agencies are reluctant to change their way of decision-making on road maintenance plans (Giustozzi et al., 2012). In addition, studies that provide references for road agencies to concurrently consider these indicators are limited (France-Mensah and O'Brien, 2019). Over the past few years, researchers in the field of pavement management have started to take these factors into consideration. For example, a sustainability evaluation framework that includes pavement performance, maintenance cost and environmental consideration has been developed to evaluate the effectiveness of maintenance activities (Giustozzi et al., 2012). However, this previous work does not include road-user costs, which represents the social impact of maintenance on a wider community. More recently, a sustainable pavement management plan that includes a trade-off analysis of road condition, road-user costs and GHG emissions was developed (France-Mensah and O'Brien, 2019). This framework was developed and tested for the maintenance activities of road segments in a single year when maintenance activities are conducted. However, as road conditions continuously deteriorate and require constant maintenance over their use phases, life cycle costing analysis (LCCA) should be employed to evaluate assets over their useful life cycle (Beatty, 2002). Salman et al. (2020) considered life cycle cost in their pavement maintenance selection framework together with technical, environmental and social considerations; however, their framework was developed for a single road segment. Compared with local governments and contractors who may focus on the performance of a single road segment, road agencies usually make maintenance plans to maximise network performance. As such, for road agencies, pavement maintenance plans at a network level are expected to be more valuable. A straightforward approach that guides road agencies in the integration of sustainability indicators in their network-level pavement maintenance decisions is, therefore, needed.

1.1.2 Transport related emissions during road use and maintenance

In addition to infrastructure related emissions, transport related emissions from on-road vehicles during the use phase of roads are a major contributor to road emissions. To reduce GHG emissions from the road transport sector, many countries have launched a range of policies and strategies, such as mandatory vehicle emissions standards and increasing the use of renewable fuels (Climate Council, 2017; U.S. EPA, 2020). In Australia, the Emissions Reduction Fund (ERF) is provided by the government to reduce GHG emissions. As Shahiduzzaman and Layton (2015) point out, major policy innovation is needed to reach the emissions reduction goal. In 2014, the Australian climate change authority identified three opportunities to reduce transport emissions (Climate Change Authority, 2014). The first is to reduce the use of carbon-containing fuel and improve the emissions intensity of the light vehicle fleet by improving the design of new vehicles. Second is to switch the use of conventional fuels to alternative fuels, such as electricity, biofuels including ethanol and biodiesel, and natural gas. Lastly, the travelling demand could be made more efficient if more people shifted from driving to walking or taking public transport. This could be achieved by upgrading public transport infrastructure, improving urban planning decisions such as the location of employment and community service, and providing streetscapes that encourage walking.

In response to these opportunities, several policies for reducing GHG emissions from light vehicles have been recommended. These include the ERF that 'purchases' the reductions of emissions, mandatory vehicle emissions standards, fuel consumption labelling and differential registration fees according to emissions intensity (Climate Change Authority, 2014). Similarly, the Climate Council (2017) proposed three key strategies to lower car-related emissions, namely shifting from cars to public transport, electrifying transport and powering it with 100% renewable energy, and mandating GHG emissions standards for cars. Crucially, the establishment of relevant policies to achieve emissions reduction relies on the accurate estimation of emissions and the identification of key influencing factors that have driven changes in emissions in the past. As such, many studies have been conducted to address this. For example, Wang et al. (2011) analysed the carbon dioxide (CO_2) emissions from the transport sector in China and found that per capita economic activity and transport modal shifting were the two biggest factors driving significant increases in CO_2 emissions. In the road transport sector, Lu et al. (2007) decomposed carbon emissions from highway transport of Germany, Japan, South Korea and Taiwan into five factors—emission coefficient, fuel intensity, vehicle ownership, population intensity and economic growth. Their study reports that while economic growth and the increase of vehicle ownership contribute significantly to the increase of carbon emissions, population intensity (i.e., population growth per unit gross domestic product (GDP)) helps reduce carbon emissions during the same period. He et al. (2020) investigated the road transport GHG emissions of the Asia Pacific region, projecting a peak by 2040 and recommending that measures should be taken to improve fuel efficiency and traffic management. However, no such investigations have been conducted for Australia. The factors underlying changes in GHG emissions from the road transport sector and the effectiveness of emissions reduction policies and strategies remain unclear.

1.2 Problem Statement

Based on the context and motivation outlined in Section 1.1, three main research problems were addressed, as follows:

Research problem 1 – few LCA studies have considered the use and M&R phases when evaluating road infrastructure, which can lead to biased results and affect the establishment of accurate and relevant GHG emissions reduction strategies. One important reason for this is the current lack of mature methodologies. A structured and practical LCA approach for estimating GHG emissions from the use and M&R phases of roads is, therefore, needed. Furthermore, most of the studies that have evaluated the use and M&R phases of roads have adopted a P-LCA methodology, yet, due to the exclusion of several processes, cut-off errors can occur. As an alternative, the hybrid LCA approach can improve the accuracy of results by completing the system boundary; however, few, if any, hybrid LCA models have been proposed specifically for the estimation of GHG emissions from the use and M&R phases of road infrastructure.

Research problem 2 – LCA-based estimates of the GHG emissions from the use and M&R phases of roads can help road agencies reduce emissions only when they are used in real-life decision-making. However, road agencies tend to consider road conditions and agency costs when selecting a network-level pavement maintenance plan. Environmental sustainability and social performance, which are attracting increasing concern, are rarely taken into consideration. Environmental and social sustainability could, therefore, be overlooked. It is imperative that environmental and social sustainability indicators are better integrated into traditional decision-making frameworks so that maximum sustainable benefits can be achieved.

Research problem 3 – existing LCA studies on road infrastructure are mostly conducted at a project or network level; LCA is not well suited for national-level estimation (Klöpffer, 2014). Therefore, currently, LCA results have limited implications for policymaking aimed at achieving national emissions reduction targets. Road transport related emissions, which represent a large contributor to overall Australian GHG emissions, have significant potential for emissions reduction. As such, the factors driving changes in GHG emissions from the Australian road transport sector need to be identified to inform policymaking. In addition, due to the limited emissions reduction policies currently implemented in Australia, comparisons with other countries with similar political, economic and geographical characteristics should prove highly useful.

Therefore, this research mainly targets three questions:

- What are the sources of lifecycle GHG emissions of road infrastructure during its use and M&R phases? How can a structured hybrid LCA model be established to evaluate these emissions?
- How to embed the emissions evaluation results into road agencies' decision-making frameworks to reduce infrastructure related GHG emissions and maximise sustainable benefits?
- What are the factors that drive changes in GHG emissions from the Australian road transport sector and how do they inform policymaking to reduce transport related GHG emissions?

1.3 Research Aim and Objectives

This study aims to identify GHG emissions reduction opportunities in the use and M&R phases of Australian roads and provide recommendations at both the practical/local and policy/national levels. Both infrastructure and transport related emissions during these phases are targeted. To achieve this aim, four objectives are selected:

Objective 1 – conducts an intensive review on existing studies related to road emissions evaluation and reduction.

Objective 1 includes understanding the status quo of research on road emissions evaluation and reduction through the following three activities: 1) a systematic review of the current development and implementation of LCAs in road infrastructure and LCA studies on the use and M&R phases of roads; 2) a review of existing studies on the evaluation and selection of road infrastructure maintenance plans; and 3) a review of current studies related to the decomposition analysis of road transport emissions during the use of roads.

Objective 2 – proposes and illustrates a hybrid LCA approach that can be used by road agencies to estimate GHG emissions specifically for the use and M&R phases of road infrastructure.

This objective includes developing a novel LCA approach for an accurate evaluation of road infrastructure related emissions from the use and M&R phases. It is addressed by 1) proposing a structured hybrid LCA approach to evaluate GHG emissions from the use and M&R phases of road infrastructure, and 2) demonstrating the proposed approach with a case study.

Objective 3 – proposes and demonstrates a straightforward method for road agencies to integrate the proposed hybrid LCA approach in evaluating and selecting the optimal network-level pavement maintenance plan.

This objective targets the reduction of road infrastructure related emissions from the use and M&R phases through the two following steps: 1) developing a conceptual framework able to help select sustainable network-level pavement maintenance plans based on pavement condition, maintenance costs, road-user costs and environmental considerations. The hybrid LCA approach developed under Objective 2 is integrated in this framework; and 2) demonstrating the use of the conceptual framework for network-level pavement maintenance plans with a case study.

Objective 4 – identifies the influencing factors that contribute to changes in CO_2 emissions from the Australian road transport sector and provide recommendations for policymaking based on comparisons with other countries with similar characteristics, specifically the U.S.

This objective targets the evaluation and reduction of road transport related CO_2 emissions during the use phase. CO_2 emissions are exclusively investigated due to data accessibility and their high proportion of GHGs. The U.S. is selected because of four reasons. First, the U.S. is one of the leading countries in cutting carbon emissions while still growing its economy (Aden, 2016). Second, the U.S. and Australia share a similar carbon emissions reduction target, both aiming to reduce carbon emissions by 26%-28% relative to 2005 levels, by 2025 and 2030, respectively (Jiang et al., 2020; Shahiduzzaman and Layton, 2015). Third, it has similar characteristics to Australia, such as its federal system of government which may influence policy implementation, developed economy, and the distribution of cities and populations (i.e., densely populated cities in the east and less populated cities in the west), which may affect transport intensity (Ribeiro et al., 2019). In addition, state-level data for the U.S. are easy to access. Three steps are followed to achieve this objective, specifically: 1) an evaluation of the CO_2 emissions of the road transport sectors in the U.S. and Australia; 2) the identification and comparison of the factors contributing to changes in the CO_2 emissions of these countries; and 3) the proposal of strategies that can be adopted to help the Australian road transport sector achieve its emissions reduction target.

In summary, objective 1 provides a solid basis for the other three objectives by reviewing existing methods and applications of related studies. Objectives 2 and 3 target infrastructure related GHG emissions during the use and M&R of roads from a project/local perspective. The former one proposes a hybrid LCA method for accurate evaluation of such emissions; and the latter one establishes a framework for road agencies to use the proposed LCA method in real-life decision making. Objective 4 focuses on the reduction of transport related GHG emissions during road use from a sectoral/national perspective. Overall, this research should provide implications for decision/policymakers seeking to reduce GHG emissions in the road sector.

1.4 Significance and Contribution of This Research

GHG emissions from the road sector have been a major environmental concern for many countries including Australia. This research is expected to help road agencies and policymakers evaluate and reduce GHG emissions in this sector. Special focus has been given to the use and M&R phases, considering Australian road agencies' preference for M&R and the high contributions of these phases.

The significance and contribution of this research is three-fold. First, this study is one of the first to propose a hybrid LCA method specifically for evaluating GHG emissions from the use and M&R phases of road infrastructure. In existing studies, the P-LCA method is the most widely adopted approach, which can lead to biased results due to its incomplete system boundary. The proposed hybrid LCA method is, therefore, expected to increase the accuracy of the results. In addition, existing LCA studies on single road projects have limited applicability for road agencies who typically make decisions based on the performance of entire road networks. The proposed approach is, therefore, demonstrated for a road network in Western Australia (WA). The results obtained from this case study (e.g., the identification of the most carbon-intensive road segments in a network) have further implications for road authorities when evaluating M&R priorities and funding allocation.

Second, at the network and local levels, this study is among the first to integrate road conditions, economic, environmental and social sustainability simultaneously in the assessment of network-level pavement maintenance plans. In conventional evaluation of such plans, typically only road condition and economic performance are considered whilst environmental and social sustainability are rarely included, limiting the realisation of sustainable benefits. One important factor here is the lack of mature methods available to road agencies. The proposed framework presented here provides a straightforward method for road agencies to incorporate environmental and social sustainability into their evaluations to support sustainable development. In addition, a case study of a road network in WA is used to demonstrate the usefulness and applicability of the proposed framework.

Finally, at the national level, this study addresses the fact that no existing studies have identified those factors driving changes in carbon emissions from Australia's road transport sector. On-road vehicles are one of the most significant emissions contributors in many countries including Australia. Yet, whilst many countries (e.g., European countries, the U.S., and China) have developed a range of policies to reduce carbon emissions from road transport, Australia has been conservative in this respect. To achieve the ambitious national emissions reduction target, major policy innovation is needed. Therefore, this study identifies the key drivers of change in carbon emissions so that effective policies can be made accordingly. Policy recommendations are also proposed that are expected to provide a solid reference for policymakers seeking to achieve the national emissions reduction target.

1.5 Thesis Structure

The structure of this thesis is presented in Figure 1-1.

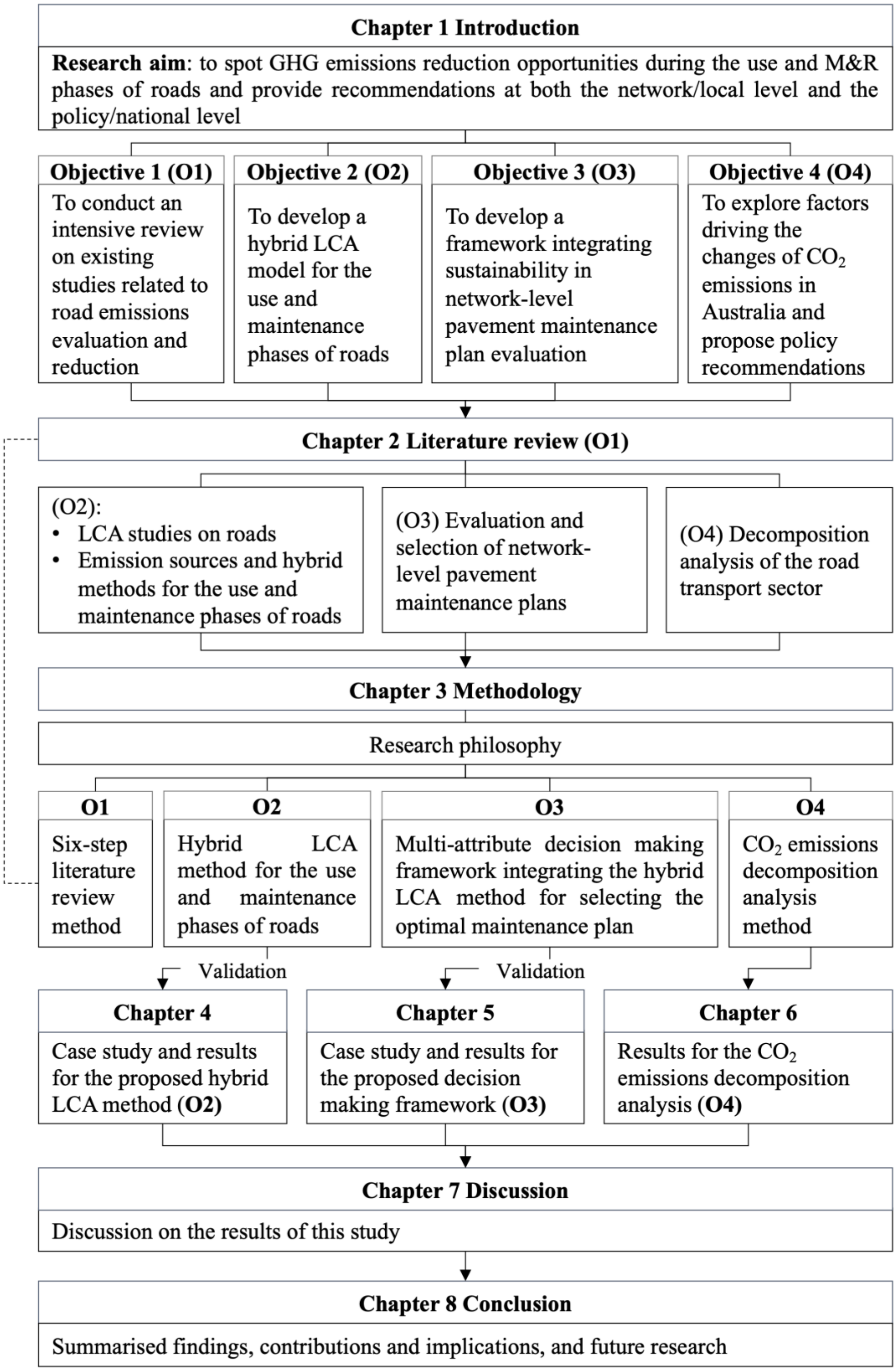

Figure 1-1: Thesis structure

Chapter 1 presents an introduction to the study including the background and motivation of the research. Along with a research problem statement, the overall aim and specific objectives are also stated. This chapter also summarises the wider significance and contribution of the work.

Chapter 2 is a review of related literature (Objective 1). Three topics are targeted according to the three objectives stated in Chapter 1, namely LCA studies on roads, pavement maintenance decision-making, and decomposition analysis of carbon emissions.

Chapter 3 outlines the methodology for this research. The philosophy underpinning the methods are first presented, followed by the research design. The methods adopted for each research objective outlined in Chapter 1 are then explained. Broadly speaking, a literature review method is used for the critical review presented in Chapter 2 (Objective 1); a hybrid LCA approach is proposed for the estimation of GHG emissions specifically from the use and M&R phases of road infrastructure (Objective 2); a multi-attribute decision-making framework is developed to integrate sustainability indicators into traditional assessment of network-level pavement maintenance plans, and the proposed hybrid LCA approach is integrated in this framework (Objective 3); and a logarithmic mean Divisia index (LMDI) decomposition analysis method is adopted to analyse the factors influencing changes in CO_2 emissions in the Australian and U.S. road transport sectors (Objective 4). The reasons for the selection of different approaches, and the data collection and analysis methods, are also provided in this chapter.

Chapter 4 presents a case study in WA to illustrate the usefulness of the proposed hybrid LCA approach for the estimation of GHG emissions from the use and M&R phases of road infrastructure (Objective 2).

Chapter 5 demonstrates the use of the conceptual framework developed to integrate sustainability indicators into traditional assessment of network-level pavement maintenance plans (Objective 3) through a case study in WA. Pavement condition, maintenance costs, road-user costs and environmental considerations that are considered in the framework, and the weighted sum results for decision-making, are analysed separately.

Chapter 6 presents the results of an evaluation and decomposition analysis of energy-related CO_2 emissions from the Australian and U.S. road transport sectors (Objective 4). Factors influencing change in CO_2 emissions are identified for passenger and freight transport, respectively.

Chapter 7 discusses the results of the objectives that are presented in Chapter 4-6. Recommendations for reducing the GHG emissions of the M&R and use phases of road networks are presented as a reference for road agencies. In addition, by comparing the factors influencing emissions and the emissions reduction policies in Australia and the U.S., policy recommendations are proposed. The broader value of this thesis in supporting the greening of the road sector is also discussed in this chapter.

Chapter 8 presents the conclusions of the research, elaborating on its wider contribution and implications. The limitations of the research are also examined along with recommendations for future research.

1.6 Chapter Summary

This chapter provides an introduction to the background and motivation of the research. The research problem, aim and objectives were explained. The significance and contribution of the research were carefully stated. This chapter also outlined the structure and the relationships between the remaining thesis chapters to aid readability and navigation.

Chapter 2. Literature Review

This chapter provides a review of current studies related to the research presented in the rest of the thesis. Based on the research aim and objectives stated in Chapter Chapter 1, existing studies on the LCA of roads, the evaluation and decision making of network-level pavement maintenance plans, and decomposition analysis of emissions in the road transport sector are summarised.

Section 2.1 reviews LCA studies on roads including mainstream LCA methods and typical LCA procedures. The emissions sources from the use and M&R phases of roads and the hybrid LCA methods used are discussed in Section 2.2 to address Objective 2. Section 2.3 summarises previous studies that evaluates network-level pavement maintenance plans. Special focus is placed on those indicators that have been adopted in existing studies and the methods used to combine multiple indicators for decision-making, informing Objective 3. In addition, Section 2.4 reviews current studies on decomposition analysis of road transport sector emissions. Factors that influence changes in GHG emissions from the road transport sector and mainstream decomposition analysis methods are discussed to inform Objective 4. Finally, Section 2.5 provides a summary of this chapter.

2.1 Life Cycle Assessment of Roads

This section presents a critical literature review of existing LCA studies on roads. The aim is to provide an overview of related studies, identify mainstream LCA methods and present the state-of-the-art following typical LCA application procedures. Detailed information for the review method is provided in Section 3.3.

LCA refers to the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). The lifecycle perspective avoids shifts in environmental burdens between different lifecycle phases of roads, i.e., material production, construction, M&R, use and end-of-life (EOL) phases (Klöpffer, 2014). Unlike other sectors (e.g., the building sector), the use of LCA in road assessment is still in its infancy. The first LCA study on roads was conducted in the 1990s (Roudebush, 1996), and over the last two decades, LCA has attracted increasing interest as a means of evaluating the environmental sustainability of road infrastructure.

Following the literature review method described in Section 3.3, 199 peer-reviewed journal papers were retrieved. A preliminary analysis of the 199 identified papers published from 2003 to 2019 (Section 3.3) was conducted to provide descriptive information of these studies including their publication year, journal, and general classification. Figure 2-1 illustrates the temporal distribution of the publications, showing that LCA on roads has attracted substantial research interest since 2012, illustrating growing interest in this research area.

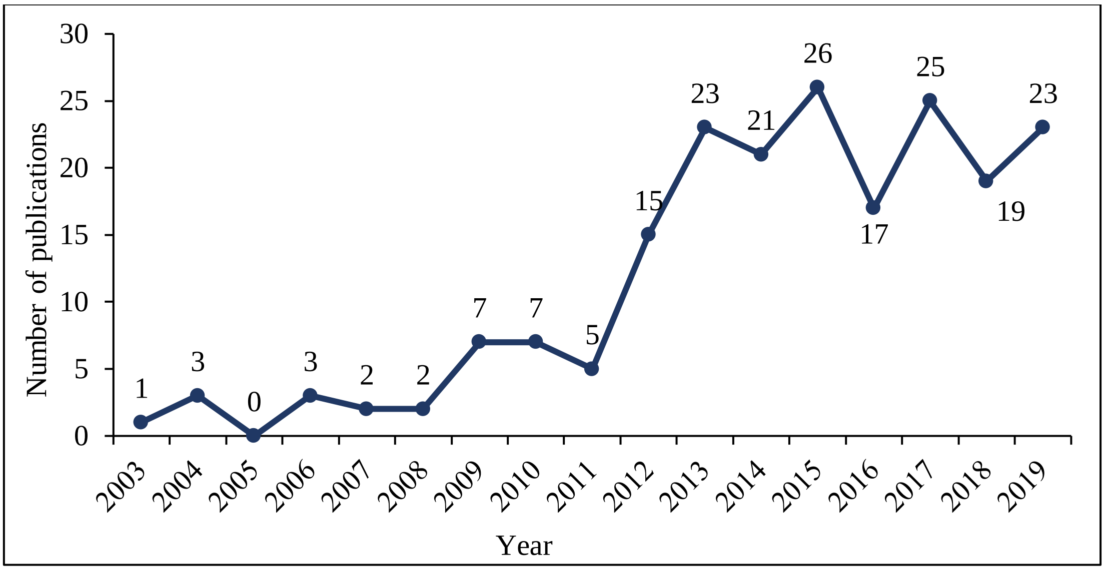

Figure 2-1: Distribution of retrieved publications by year

Figure 2-2 illustrates the distribution of the publication by journal. In total, 50 journals have published relevant papers, with the highest numbers published in the Journal of Cleaner Production (41), Transportation Research Record: Journal of the Transportation Research Board (21), and Transportation Research Part D: Transport and Environment (19).

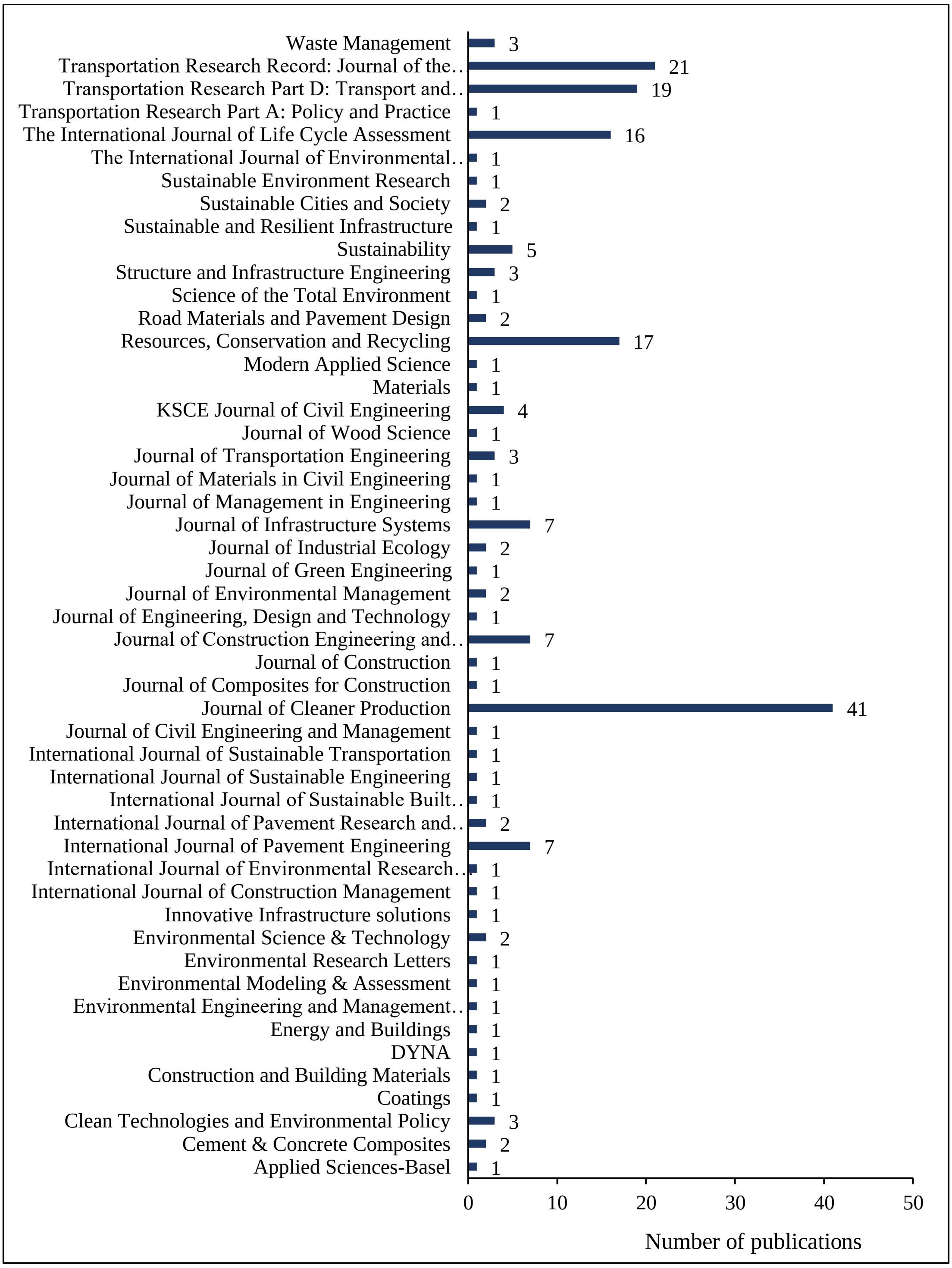

Figure 2-2: Distribution of retrieved publications by journal

In general, two main themes were identified based on the stated goals of these publications, namely the application of LCA in roads (113, 56.8%) and the development of LCA modelling for roads (77, 38.7%). Table 2-1 presents the description of these two main themes. In the application theme, the study goal was the application of LCA to evaluate roads or road materials following the LCA processes defined in ISO 14044 (2006). Among these studies, 94 targeted road structures, whereas the remaining 19 targeted materials. In the modelling development theme, the study purpose was to develop a LCA tool for roads or a method for calculating certain new impacts that were often excluded from previous studies (e.g., traffic delay and rolling resistance, RR). Based on the research aims and objectives, the 94 papers focussing on the application of LCA to roads were targeted first. Table 2-1 and Figure 2-3 present the definitions and distributions of the themes, respectively, which show that the evaluation of materials has attracted immense research interest.

Table 2-1: Classification of the retrieved publications based on their stated goals

Classification		Description of the classifications	Publication
Typical application	Road evaluation	To evaluate the environmental impacts of a road project	26
	Alternative design	To compare different designs for a given road, such as rehabilitation methods, maintenance schemes and various lifespan designs	19
	Material evaluation	To evaluate the environmental impacts of a material, such as a mixture, an additive, or an eco-friendly material (e.g., industrial by-products, recycled materials, and other modified materials)	51
	Material comparison	To compare different materials, such as concrete versus asphalt, and different asphalt products	17
Modelling development	Framework/tool development	To develop a framework or calculation tool for road evaluation	24
	LCC + LCCA	To develop a method that integrates LCA and lifecycle cost analysis (LCCA) in road evaluation	23
	New impacts	To develop a method to capture new impacts that are rarely considered in previous studies, including traffic congestion, albedo effects, rolling resistance, carbonation, noise, and lighting	30
Other		The goal of the study is not included in the above classifications	9

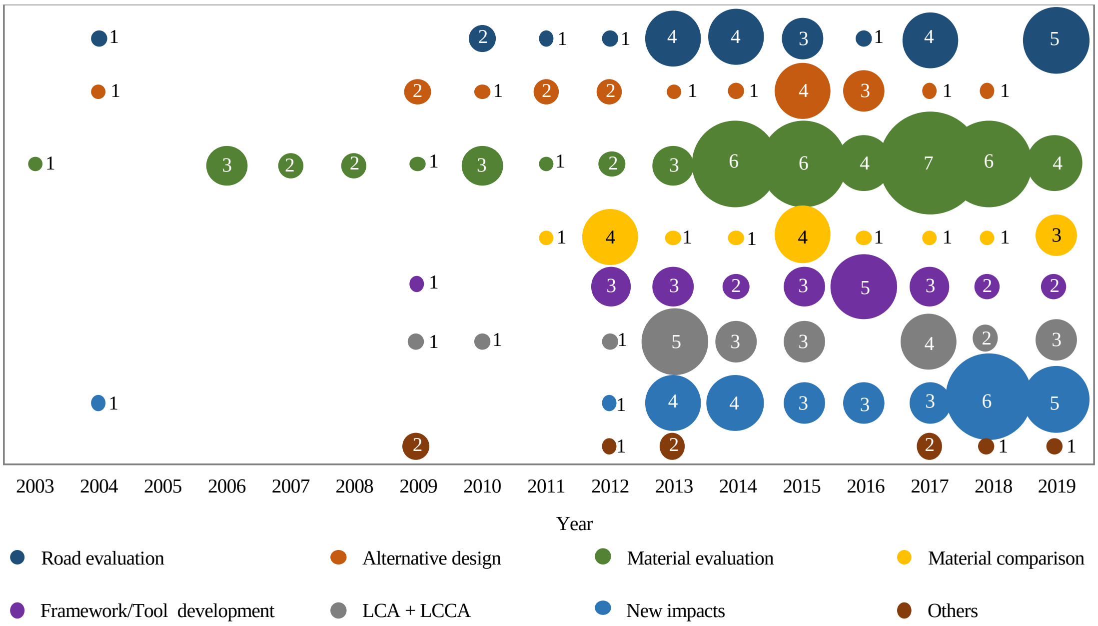

Figure 2-3: Distribution of retrieved publications by theme and year

Notes: the size of the circles reflects the number of publications. LCA is short for life cycle assessment and LCCA means life cycle costing analysis.

2.1.1 Mainstream life cycle assessment methods

Mainstream LCA methods include P-LCA, EIO-LCA, and hybrid LCA methods, as is the case in other sectors (e.g., the building sector) (Santos et al., 2017b). P-LCA defines the system boundary by processes and divides the target system into a series of process flows to model the inputs and outputs of every process (Horvath and Hendrickson, 1998). Similar to the building sector, this approach has been widely adopted in environmental evaluations of roads (e.g., Abd Rashid and Yusoff, 2015; Chiu et al., 2008; Chowdhury et al., 2010; Huang et al., 2009), with 67 (71.3%) of the retrieved studies using this method. However, this method requires data on consumption and environmental output for every process, which is labour- and time-intensive. Therefore, P-LCA is often expensive and time-consuming, especially for complex systems that encompass thousands of processes (Suh et al., 2004). This approach also has a risk of excluding a large number of inputs for upstream processes, which may have a significant effect on the total inventory (Choi et al., 2016).

To simplify LCA and generate more comprehensive results, EIO-LCA has been proposed. In EIO-LCA, the boundary often spans the global economy, which includes the entire chain of suppliers (Suh et al., 2004). When producing the products in a sector, inputs, which are the outputs of other sectors, are required. Because each sector has environmental impacts per dollar of output, the overall environmental impacts can be quantified by summing the products of the inputs and the environmental impacts of the corresponding sectors (Horvath and Hendrickson, 1998). Although EIO-LCA is able to improve the completeness of the traditional method, it faces problems including the age of input-output data, homogeneity assumption, the use of nationally averaged data, and high levels of sector aggregation (Choi et al., 2016; Hendrickson et al., 2006). As can be observed in Table 2-2, EIO-LCA has not been fully embraced, with only six studies conducted for the evaluation of roads (6.4%).

Hybrid LCA, which combines the two methods by using IO data to complement the processes excluded in P-LCA, was later proposed (Bullard et al., 1978; Suh et al., 2004). The main advantage of this approach is that it improves the completeness of P-LCA while improving the reliability of EIO-LCA (Bullard et al., 1978). Table 2-2 summarises the advantages and disadvantages of each of these three methods.

It is also worthy of mentioning that recent studies in the building sector are proposing to integrate LCA with building information modelling (BIM) to simplify the data acquisition process of LCA (Soust-Verdaguer et al., 2017). Two main directions of the integration are identified. One is to generate a bill of quantity from the BIM model and then apply the quantity information in LCA calculation. The other is to perform LCA in the BIM environment with a LCA plug-in tool (Roberts et al., 2020; Wastiels and Decuypere, 2019). Although such research has not been seen in the transport sector, this trend could provide valuable reference especially for countries like Australia where BIM is promoted mainly in the infrastructure sector rather than in the building sector (Jiang et al., 2021).

Table 2-2: Pros and cons of existing LCA methods

Comparison	Methods	Pros	Cons	Frequency
Process-based LCA (P-LCA)	• Identifies the input and output in each process of production of a product or service[1] • Provides assessment for specific processes[1]	• Can obtain detailed results for each process[1] • Has advantages when evaluating the use and end-of-life (EOL) phases[2] • Allows comparison of specific products[2]	• Setting a system boundary is difficult[3] • Cut-off errors[1,3,4] • Unable to capture circularity effects[1] • Costly and time-consuming[1,3]	67 (71.3%)
EIO-LCA	• Provides an assessment of the whole economic system[1] • Quantifies interrelationships between various sectors of the economy[1]	• The analysis boundary is the whole economy; no cut-off errors[1] • Solves the problem of circularity effects[1] • Less costly and faster[1] • Reflects direct and indirect interactions between different economic sectors; provides both economic and sector-wide results[1]	• Unable to reflect particular processes owing to the heterogeneousness of sectors and the use of national average data[3] • Homogeneity and linearity assumptions[4] • Aged input-output data[3,4] • High levels of sector aggregation[3,4]	6 (6.4%)

Comparison	Methods	Pros	Cons	Frequency
Hybrid LCA	Usually combines the two methods by using IO data to complement the upstream processes, which are often excluded in traditional P-LCA[3]	• Overcomes the problem of the costly, time-consuming, or missing data of P-LCA[3,4,5] • Reduces cut-off errors of P-LCA and improves the consistency across the phases of the road life cycle[3,4,5] • Improves the reliability of EIO-LCA[3,4,5]	• Lack of standard methodological framework[5] • Lack of mature tool[5]	11 (11.7%)

Note:

[1] Hendrickson et al. (2006); [2] Choi et al. (2016); [3] Suh et al. (2004); [4] Bullard et al. (1978); [5] Crawford et al. (2018).

This table is based on 84 papers; 10 papers were excluded as methods were not reported in these cases.

2.1.2 Application of life cycle assessment methods in road assessment

Complying with ISO 14044 (ISO, 2006), a typical LCA study often follows the following four steps: 1) defining goal and scope, clarifying system boundaries, and determining functional units (FUs); 2) compiling the life cycle inventory (LCI) by allocating the inputs (resources) and outputs (e.g., emissions) through the life cycle; 3) assessing the potential life cycle environmental impact of the target system (which is referred to as LCIA); and 4) interpreting the results from the LCIA to draw conclusions and make recommendations. Each step is investigated in the following sections to examine the current common practices and identify limitations in existing studies, so that future directions can be proposed accordingly for further improvement.

2.1.2.1 Goal and scope definition

The goal of a LCA plays a vital role in defining the functional unit (FU), setting the system boundary, and selecting the data sources (Loijos et al., 2013). Existing LCA studies on roads are usually limited to four types of goals—evaluating the environmental impact of roads, alternative designs, pavement materials, and alternative materials. In addition, the majority of the studies examined (89, 94.7%) were conducted based on a project-level analysis; few have investigated the impacts of roads in a network context to inform policymaking at the network level. Therefore, the implications of these studies are limited to the project level and, as such, offer limited value to road planners and policymakers seeking to identify optimal solutions at a network or national level.

As with applying LCA in other sectors, such as the buildings sector, various FUs have been used in LCA studies on roads, making it difficult to compare results across studies (Anand and Amor, 2017; Säynäjoki et al., 2017). In total, 68 studies (72.3%) used road length metrics, e.g., km, lane-km, and lane-mile, while 11 (11.7%) used the treatment area, e.g., m^2, as the FU, where the scope of these studies involved the surface or wearing course of the pavement. Another FU is the entire road project, which is usually used when evaluating the environmental impact of a specific strategy (e.g., a road closure scheme during rehabilitation and emission control strategy) on a given road project. For example, Hanson and Noland (2015) compared the vehicle emissions when adopting various staging approaches for a rehabilitation project. Other studies have also used volume (e.g., m^3 or yd^3) to evaluate the impacts of earthworks or recycling materials (e.g., Capony et al., 2013).

The use of these FUs has limitations, however. A lane mile or a m^2 cannot be used as a standard FU (Cass and Mukherjee, 2011). As AzariJafari et al. (2016) point, out, information related to road specifications should include region, lane width, shoulder width, thickness, roadway type, pavement type, and analysis period. They argue that road functions cannot be appropriately reflected if the adopted FU does not include the roadway classification, lane width, and number of lanes. Appendix B presents the goals of the reviewed studies, together with the FUs of the twenty most-cited papers and two recent publications with more than 10 citations (referred to as the 22 highly cited papers, HCPs). Based on these studies, a systematic presentation of road specifications is rarely provided in their FUs.

In addition, it is reported that the lack of consideration of the pavement condition is also a shortfall of existing studies (Inyim et al., 2016). Unlike other products or services, the condition of a pavement often deteriorates over long service life, which directly influences the function of a road. For example, pavement roughness is an important indicator for the serviceability of roads (Al-Omari, 1994) and can cause up to 70% variation in the fuel-consumption impacts caused by on-road vehicles (Batouli and Mostafavi, 2017). Therefore, an FU that integrates the changeable condition and performance of road pavements is required (Batouli and Mostafavi, 2017; Inyim et al., 2016).

In addition, there are six phases during a road's life cycle to be considered when defining the system boundary of a LCA—materials extraction and production, materials transport, construction, use, M&R, and EOL phases. The materials extraction and production phase usually includes the processes for manufacturing the road materials, from the acquisition of raw materials to the final material production (i.e., mixing plant operations). The construction phase considers all preservation and construction activities, including the combustion of fuels by the paving equipment. Materials transport from manufacturing plants to construction sites have been integrated into the construction phase (e.g., Zhang et al., 2010) but also treated as a separate phase (e.g., Kayo et al., 2015) depending on the specific aims of the study. The M&R phase deals with three types of maintenance treatment, namely maintenance, preservation, and rehabilitation. In addition, EOL treatments include the demolition, debris transport, recycling, and final disposal at the end of a road's service life (Celauro et al., 2015). However, there is no common agreement on what should be included in the use phase. For example, Loijos et al. (2013) only considered the effects of albedo, carbonation, roughness, and lighting, but excluded vehicle emissions. In contrast, Treloar et al. (2004) not only included vehicle emissions but also considered the manufacture, use, and maintenance of vehicles.

The materials extraction, transport, and construction phases are commonly included life cycle phases, in 91 (96.8%), 59 (62.8%), and 81 (86.2%) of the reviewed studies, respectively. The use, M&R, and EOL phases are less frequently considered, in 28 (29.8%), 55 (58.5%), and 32 (34.0%) of the reviewed studies, respectively. Table 2-3 presents a summary of the 22 HCPs. The EOL phase is usually excluded as the total demolition and disposal of infrastructure is not common practice or is not permitted by the relevant national maintenance policies, such as in Italy (Celauro et al., 2015). More importantly, the exclusion of the use phase from most of the existing studies is seen as a significant shortfall owing to its important contribution to GWP via its impact on roughness, structure, and albedo (Santero et al., 2011). This general omission is attributed to the limitations of the impact assessment method for the use phase, and the common assumption that different roads generate the same impacts during this phase (Inyim et al., 2016).

It should be noted that in this research the discussion of system boundary is from a life cycle perspective, which is based on ISO 14044 (2006). With the development of LCA, the concept of system boundary has been expanded. Two other types of system boundary can also be considered, namely that between the technical system and the natural environment (e.g., when agriculture is included) and between the studied technological system and other technological systems (e.g., when the studied product has multiple functions) (Finnveden et al., 2009). For road infrastructure, these types of system boundary are not discussed in related studies possibly because they are less relevant.

Table 2-3: Summary of highly cited Life Cycle Assessment (LCA) studies on roads: system boundary (life cycle perspective)

Studies	**System boundary (life cycle perspective)**					
	Material production	Transport	Construction	Use	M&R	EOL
Chiu et al. (2008)	√	√	×	×	√	×
Treloar et al. (2004)	√	×	√	√	√	×
Chowdhury et al. (2010)	√	×	×	×	×	×
Birgisdottir et al. (2006)	√	√	√	×	√	×
Birgisdottir et al. (2007)	√	√	√	×	√	×
Wang et al. (2012b)	√	√	×	√	√	×
Huang et al. (2009)	√	√	×	×	√	×
Vidal et al. (2013)	√	√	√	√	√	√
Carpenter et al. (2007)	-	-	-	-	-	-
Cass and Mukherjee (2011)	√	×	√	×	×	×
Yu and Lu (2012)	√	×	√	√	√	√
Olsson et al. (2006)	√	√	√	√	×	×
Loijos et al. (2013)	√	×	√	√	√	√
Jullien et al. (2006)	√	-	√	×	×	×
Anastasiou et al. (2015)	√	√	√	×	√	√
Aurangzeb et al. (2014)	√	√	√	×	√	×
Oliver-Sola et al. (2009)	√	√	√	×	√	○
Roth and Eklund (2003)	-	-	-	-	-	-

Notes:

1. √ – included; ○ – limited consideration; - – not specified; × – not included;

2. The twenty most highly cited papers and two recent, highly cited publications with more than 10 citations are included.

2.1.2.2 Life Cycle Inventory (LCI)

The choice of data sources is an important decision in LCA studies (Martínez-Rocamora et al., 2016). The International EPD® System categorises data into three types for the LCI phase—primary, secondary, and tertiary data. Primary data refer to first-hand data usually obtained by on-site surveys and field investigations. Secondary data can be obtained from the literature, including published articles, annual environmental reports, and commercial databases. Tertiary data, or other generic data, are often available through statistical averages (Moretti et al., 2017).

Typically, a LCA requires project (input) and emissions data. To obtain input data, primary data from field investigations and interviews with contractors or equipment manufacturers are preferred (e.g., Cass and Mukherjee, 2011). However, first-hand data for material production and construction activities are not always complete (Gulotta et al., 2019), for which secondary data can be employed. For emissions data, primary data are extremely difficult to obtain, and only Kang et al. (2014) and Al-Qadi et al. (2015) used self-developed local or regional databases. Alternatively, Ecoinvent, U.S. LCI databases, the Athena database, and the published literature are important sources of secondary data. The use of different sources can lead to differing results even for the same product, compromising comparability across studies. In addition, not all materials are included in the available databases, especially recycled materials, which may lead to inaccuracies in the assessment results (dos Santos et al., 2017). Similar findings are also reported for building LCA (Säynäjoki et al., 2017). More importantly, a significant number of the reviewed studies (30, 31.9%) did not report their data sources, resulting in high uncertainty in the LCI results. Appendix C lists the data sources of the 22 HCPs.

The selection of LCA tools is usually related to the adopted LCI method. Most of the reviewed papers that adopted the P-LCA method used SimaPro or GaBi software (e.g., Farina et al., 2017; Giani et al., 2015; Vidal et al., 2013). For EIO-LCA, the most commonly adopted tools are the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), which is a spreadsheet-based LCA and LCCA program designed to assess the environmental and economic impacts of pavement and roads, and the Economic Input–Output Life Cycle Assessment model, which is an online tool designed to make EIO-LCA quick, easy to use, and free. For hybrid LCA, however, there is no widely adopted tool, which may be one of the reasons for its lack of application (Crawford et al., 2018). Unlike the building sector where uncertainties arising from LCA tools have been widely discussed and highlighted (e.g., Emami et al., 2019), only dos Santos et al. (2017) provide a comparative study on LCA tools for roads. These authors conclude that results can vary significantly even when the same phases are considered with the same materials and equipment use. In addition, 37 (39.4%) of the reviewed studies do not report the specific tools used. Therefore, some degree of caution is required when selecting LCA tools and the reporting of such choices needs to be improved (dos Santos et al., 2017). Appendix C summarises the LCA methods and tools employed in the 22 HCPs.

2.1.2.3 Life cycle impact assessment (LCIA)

LCIA connects the LCI results to environmental impacts by assigning the results to selected impact categories (ISO, 2006). According to Van den Heede and De Belie (2012), there are two main impact analysis methods. The first involves a damage-oriented method represented by Eco-indicator 99, which focusses on endpoint environmental damages (i.e., where the actual environmental effects or damages occur), such as damage to ecosystem quality, human health, and mineral and fossil resources. The second approach is a problem-oriented or midpoint method, of which CML 2001 is a representative example, for quantitative modelling within the early stages of the cause-effect chain. For example, a road's climate change effect can be calculated by an endpoint method to produce environmental damage to human health, or by a midpoint method (i.e., kg of CO_2 equivalent, CO_2-e). To offer users the choice of the level of results, methods that combine midpoint and endpoint approaches are also available, such as ReCiPe, which is a fusion of CML 2001 and Eco-indicator 99.

Of the reviewed literature, only 18 (19.1%) papers report the chosen method of impact assessment. In these studies, many (17) adopted a midpoint method, including the CML 2001 midpoint method (4 papers), the ReCiPe midpoint method (8 papers), the TRACI midpoint method (2 papers), and three other midpoint methods. The popularity of the ReCiPe may be attributed to the fact that it incorporates widely used SimaPro software (Vidal et al., 2013) and is convenient for combining both impact assessment methods. Other publications, which did not report the method of impact assessment, commonly adopted midpoint methods for selecting midpoint impact categories, such as GWP, acidification, and eutrophication, as well as others. Similar preference for the midpoint approach is also reported in other sectors (e.g., Yi et al., 2014). This is likely because the endpoint approach requires a high level of expertise and is subject to much higher levels of uncertainty than the midpoint approach. Nevertheless, the midpoint approach may not provide the results that decision-makers really expect (Bare et al., 2000). Therefore, Bare et al. (2000) suggested that a consistent framework is needed to present both sets of results, either in a combined or parallel approach. It should also be noted that selecting impact categories and conducting an impact assessment are mandatory elements of an LCA study (ISO, 2006); however a standardised way of reporting these results is lacking.

Many studies offer a simple quantification of outputs without impact assessment. For example, Cass and Mukherjee (2011) calculated the GHG emissions for highway construction without conducting a further impact assessment. Such omission of the impact assessment step can lead to difficulties in the decision-making process because the simple estimation of gas emissions cannot provide intuitive information (Inyim et al., 2016). A similar limitation can also be seen in comparison studies, such as in Yu and Lu (2012). However, an LCI study alone is not suitable for comparative assertions (ISO, 2006).

As summarised in Appendix C, other studies have attempted to interpret results using impact assessment, but the selected impact categories are extremely varied, which makes it difficult to conduct a cross-comparison between studies. Such a varied choice of impact categories may be a function of the range of categories employed in different LCA tools, as shown in Table 2-4. Of the reviewed studies, GHG emissions and energy consumption were the most consistently used assessment metrics. Other widely used categories are damage to ecosystems and human health. In comparison, little consideration has been given to natural resources such as land use.

Table 2-4: An overview of impact categories of different life cycle impact assessment (LCIA) methods

Method	Impact/Damage categories
CML (Midpoint)	**Obligatory impact categories**: Depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification, and eutrophication. **Optional impact categories**: Loss of life support function, loss of biodiversity, freshwater sediment ecotoxicity, marine sediment ecotoxicity, impacts of ionising radiation, malodorous air, noise, waste heat, casualties, lethal, non-lethal, depletion of biotic resources, desiccation, and malodorous water
TRACI (Midpoint)	Ozone depletion, global warming, smog formation, acidification, eutrophication, human health (cancer), human health (non-cancer), human health criteria pollutants, eco-toxicity, and fossil fuel depletion
ReCiPe (Midpoint)	Climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, fossil fuel depletion
ReCiPe (Endpoint)	Damage to human health, damage to Ecosystem diversity and damage to resources availability
Eco-indicator 99 (Endpoint)	Damage to mineral and fossil resources, Damage to ecosystem quality, Damage to human health

(Reference: Karim, 2011; Van den Heede and De Belie, 2012)

Furthermore, few authors have explained their reasons for choosing certain impact categories, without clarifying whether the selection was consistent with the goal and scope of the study. For example, Santos et al. (2015b) adopted eight impact categories whereas Santos et al. (2017b) only considered four categories, without providing reasons for inclusion or exclusion. Of the reviewed studies, only two, i.e., Fitch et al. (2013) and Veran-Leigh et al. (2019), provide reasons for selecting each of the chosen impact categories.

2.1.2.4 Life cycle interpretation

Life cycle interpretation comprises three components—identifying significant issues; checking completeness, consistency, and sensitivity; and drawing conclusions and recommendations (ISO, 2006).

A sensitivity analysis is a compulsory element in the life cycle interpretation phase, which estimates the effects of a chosen method or data on the LCA results. Its aim is to evaluate the reliability of the final results by quantifying the extent to which the results are affected by uncertainties arising from data, the allocation methods, or the LCIA calculation. A supplementary uncertainty analysis is often used to quantify uncertainties including model inaccuracy, input uncertainty, and data variability (ISO, 2006). However, few studies have reported such results, indicating high uncertainties in the reported results. In total, 32 of the reviewed studies (34.0%) conducted a sensitivity analysis, typically on the effects of transport management and traffic growth (e.g., Mendoza et al., 2012; Yu and Lu, 2012). In addition, only 17 studies (18.1%) conducted an uncertainty analysis. Thus, very few studies complied with ISO (2006) requirements, which state that sensitivity analysis is mandatory and uncertainty analysis should supplement the results. For example, Wang et al. (2012b) implemented a sensitivity analysis without clearly reporting the results. Giani et al. (2015) implemented a separate uncertainty analysis without conducting a sensitivity analysis. This suggests a need for a clearer definition and guidance for sensitivity and uncertainty analyses based on the ISO 14044 (2006) standard.

In addition, based on the research goals of published studies with an application theme, most aim to draw conclusions relating to the comparison of different life cycle phases, pavement types and/or paving technologies. As such, each phase in the life cycle of a road is identified to contribute differently to its overall environmental impacts. As can be observed from Appendix D, most studies identify the material extraction and production phase as the main contributor to overall carbon emissions and energy consumption. In this phase, the cement production process is highlighted as the main contributor (e.g., Choi et al., 2016; Loijos et al., 2013; Oliver-Sola et al., 2009; Weiland and Muench, 2010), and the importance of the use phase has also been highlighted (e.g., Chen et al., 2016). According to Araujo et al. (2014), the impact of the use phase on the environment was approximately 700-times higher than the construction phase. The use phase also dominates the environmental performance for roads with high traffic volumes (Santos et al., 2015b).

The comparison of pavement materials, such as asphalt and concrete, has also attracted much research attention, although no general conclusion has been drawn. For example, Weiland and Muench (2010) and Yu and Lu (2012) investigated rehabilitation alternatives; the former authors argued that hot mixed asphalt pavement (HMA) had a higher energy use and Portland cement concrete (PCC) had a higher GWP, whilst the latter authors concluded that PCC was better than HMA in both energy use and GWP performance. Such discrepancies may reflect impacts from the use phase and EOL phase being overlooked by Weiland and Muench (2010), whereas Yu and Lu (2012) considered the whole life cycle except for the transport of materials. More widely agreed results may be that asphalt pavement offers a reduction in GWP whilst concrete has an advantage in pavement energy demand (e.g., Dumitrescu et al., 2014; Gschosser and Wallbaum, 2013; Gschosser et al., 2012; Weiland and Muench, 2010). It should also be noted that most studies include no or had limited consideration of the use phase, except for Yu and Lu (2012), which might influence the results.

Reclaimed asphalt pavement (RAP) and warm mix asphalt (WMA) are commonly investigated eco-friendly technologies. RAP allows a reduction of the use of virgin materials and WMA is used to lower the production temperature of asphalt mixtures (Giani et al., 2015). Using RAP has significant potential for reducing the eco burden of both rehabilitation (Chiu et al., 2008; Turk et al., 2016) and initial construction projects (Aurangzeb and Al-Qadi, 2014; Aurangzeb et al., 2014), especially when combined with HMA (Giani et al., 2015; Vidal et al., 2013). However, existing studies provide contrasting results on the impacts of using a high RAP content. Aurangzeb and Al-Qadi (2014) and Aurangzeb et al. (2014) showed that reductions in energy and

GHG could be achieved with an increase in RAP content up to 30%, 40%, and 50%. In contrast, Saeedzadeh et al. (2018) reached the opposite conclusion, suggesting that a high RAP content leads to higher environmental burdens. In the case of WMA, Liu et al. (2014) and Mazumder et al. (2016) indicate that WMA is more beneficial to the environment than HMA. However, Tatari et al. (2012), Vidal et al. (2013), and Anthonissen et al. (2015) argue that this was not necessarily true because of the significant influences of additives, especially the synthetic zeolites.

2.1.3 Summary

- *Goal and scope definition*

Mostly project-oriented research. Over 90% of the reviewed papers are project oriented and very few investigate the impacts of roads in a network context, limiting their value for policymakers including road authorities (Zhang et al., 2013). The cumulative emissions of the road network of a region/nation remain unclear, and it is difficult to capture the regional disparities in emissions under the existing LCA framework (Chen et al., 2017). Therefore, region-specific strategies for reducing emissions are not easily developed. Another limitation of the focus on project-level LCA is that road maintenance works are often planned in isolation to achieve an optimal solution for the project (Galatioto et al., 2015). Whereas at the network level, as Santos et al. (2017a; 2018) have suggested, decisions are much more complicated by budget considerations. It is, therefore, recommended that future research needs to consider the road network as a whole, so that useful conclusions can be drawn for policymaking.

Inconsistent selection and definition of FUs. Various FUs have been used by existing studies, which makes comparisons difficult. To improve comparability across studies, consistency in the use of FUs needs to be increased (Inyim et al., 2016). In addition, the currently used FUs are insufficient to reflect the changing functions of roads. It is, therefore, recommended that the definition of a FU should reflect the evolving performance of roads, so that their real-time functions can be accounted for (Batouli and Mostafavi, 2017).

Lack of consideration of post-construction phases. The road use and M&R phases can have significant environmental impacts (Santero and Horvath, 2009; Wu et al., 2014), and yet only a few studies have considered these phases. Evidently, a method for accurately deciding the maintenance measures for the whole life cycle of a road—associated with constantly changing circumstances—remains lacking. In addition, the impact sources of the use phase are not consistently defined, and methods for this phase are insufficiently developed. Future studies are recommended to fully capture these phases, so that more reliable outcomes can be delivered (Inyim et al., 2016). Furthermore, unlike common products, roads can undergo rehabilitation multiple times and, therefore, may not have a clear life cycle. This suggests a need to further examine the life cycle of roads and, in particular, whether and how the EOL phase should be included in LCA (Batouli and Mostafavi, 2017).

- *LCI*

Limited reporting of data sources and LCA tools. Different databases and LCA tools have been used in existing studies, which leads to differing results even for the same product and processes (dos Santos et al., 2017). However, most authors are not aware of such uncertainties and do not report the data source and LCA tool choices. Future studies are recommended to consider such uncertainty via sensitivity and uncertainty analysis (Emami et al., 2019). There is also a need for studies that compare the results generated from different data sources or LCA tools, so that their respective uncertainties can be identified.

- *LCIA*

Lack of standardised LCIA procedure. The exclusion of the impact assessment phase, limited reporting of LCIA methods, and inconsistent selection of impact categories are identified as current limitations of LCIA, which makes comparisons across existing studies challenging (Inyim et al., 2016). A standardised LCIA procedure is, therefore, needed to raise awareness of the LCIA step and guide the selection of LCIA methods and impact categories.

- *Life cycle interpretation*

Lack of sensitivity and uncertainty analysis. A large amount of uncertainty exists in LCA including parameter (input) and data uncertainties in the LCI step and methodological uncertainties in the LCIA step (Bare et al., 2000). The general low level of awareness, and lack of sensitivity and uncertainty considerations, indicate that high uncertainties likely exist in the results presented in existing publications. Future studies should conduct such analyses to ensure reliability.

2.2 Life Cycle Assessment of the Maintenance and Use Phases of Roads

In an LCA study, the M&R phase usually estimates emissions from on-site equipment and embodied emissions of construction materials. In addition, emissions due to traffic delay caused by M&R work are also typically included (Loijos et al., 2013). The emission sources of the use phase usually include vehicle life cycles, on-road vehicles, and the impact of pavement performance changes, such as RR, deflection, albedo, and carbonation. Vehicle life cycles have only been considered by Treloar et al. (2004), who provide one of the earliest studies to consider the use phase. On-road vehicle emissions are more frequently considered, as road traffic is considered to be a component of road operations (Treloar et al., 2004). However, this has been recently challenged. For example, Loijos et al. (2013) attributed the emissions from normal traffic to vehicle life cycles and only considered emissions directly caused by the pavement (e.g., pavement roughness, pavement albedo, and carbonation). This approach is also supported by Fernandez-Sanchez et al. (2015) and Yu and Lu (2012). In rare cases, lighting is also considered as an emission source in road operations (e.g., Fernandez-Sanchez et al., 2015).

Four existing hybrid LCA methods were identified that can be used to evaluate emissions, namely the path exchange hybrid (PXC), tiered, integrated, and matrix augmentation methods, as summarised in Table 2-5 (Crawford et al., 2018). When assessing the emissions of roads, only the PXC and tiered hybrid methods have been applied. The integrated hybrid method has not proved popular, possibly because of its high complexity and high data and time demands (Baboulet, 2009; Strømman et al., 2009; Yu and Wiedmann, 2018). In comparison, the matrix augmentation method modifies the IO matrix to generate new sector(s) from an existing one. However, the generated sector is proportional to the original one, thus limiting its benefits (Crawford et al., 2018). The modification of the IO matrix can also lead to unexpected results, which increases inaccuracies and uncertainties in the final results (Jiang et al., 2014).

The tiered hybrid method uses detailed process-based data to evaluate the use phase and important upstream processes, and complete other processes with IO data (Baboulet, 2009). This method is widely accepted, possibly because it improves the conventional P-LCA method by simply adding IO data to cover missing processes (Strømman et al., 2009). However, because it is a process-based analysis framework, the tiered method is still subject to cut-off errors, and the hybridisation also bring the risk of double-counting (Yu and Wiedmann, 2018). To this end, the PXC method is proposed to avoid these drawbacks (Baboulet, 2009). However, the limitation of applying this method in the use and M&R phases is that it has an IO-based analysis framework, meaning that establishing an IO model is fundamental, while fuel use due to traffic delays and the use phase is difficult to fit into an economic sector. Therefore, a hybrid LCA which combines the PXC and tiered methods may be the most suitable approach for targeting the evaluation of the use and M&R phases of roads.

Table 2-5: Pros and cons of four hybrid LCA methods

Methods	Description	Pros	Cons
Tiered hybrid LCA	• Process-based analysis framework • Applies process data in prominent downstream processes and IO data for upstream processes where process data are not available	Reduces the cut-off error of the P-LCA method	• Some level of truncation error • Risk of double-counting
Path exchange (PXC) hybrid LCA	• EIO-based analysis framework • Disaggregates an IO matrix to mutually exclusive economic sectors and modifies specific sectors with process data	• Fit for normalisation because of the clearly defined framework of applying the method • Provides a comprehensive approach for hybridising process and IO data • Enables the analysis of the emissions from the supply chain	• Complex and need to deal with an enormous amount of data • Time-consuming
Matrix Augmentation	• EIO-based analysis framework • Modifies the IO matrix to create additional 'sector(s)' of the economy first and then modifies the matrix with available process data	Resolves the aggregation error found in conventional EIO-LCA	The modification of the matrix can lead to unexpected impacts on the results
Integrated hybrid LCA	• Process-based analysis framework • Generates a technology matrix with process data and then connects to the IO table	• Reduces the cut-off error of the P-LCA method • Fit for normalisation because of the clearly defined framework of applying the method • Provides a structured approach for hybridising process and IO data	• Risk of double-counting • Compiling the cut-off matrices requires a large amount of data and time

Reference: Crawford et al. (2018).

2.3 Road Maintenance Decision-Making

2.3.1 Indicators to consider

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 focusses on activities related to the repair of defects of the road structure and associated facilities (Veith and Bennett, 2006). The evaluation of road maintenance involves the consideration of many factors. The most common considerations are economic cost and pavement conditions (Torres-Machi et al., 2018) . The economic cost of road maintenance is commonly equated to agency costs (Pittenger et al., 2012). In road maintenance, this can include materials, equipment and labour usage in activities such as preventative maintenance, routine maintenance and other rehabilitation or restoration activities (France-Mensah and O'Brien, 2019). Cost indicators, following the process of road pavement maintenance, include raw materials, mainly asphalt (which may include HMA and WMA), aggregate, sand, crushed brick/glass/concrete, and RAP, if any, followed by the cost of mixing plant operations. When mixed asphalt is produced, transport and on-site placement are needed (Santos et al., 2017a), requiring equipment such as bulldozers, compactors, dumpers and excavators. Following the LCCA approach commonly adopted in road design and construction evaluation, data on agency costs can be obtained from historical records and current bids. If these sources of data are not available, expert judgement can also be employed.

Pavement condition is also one of the most commonly adopted criteria when evaluating maintenance strategies. Pavement condition improvement after maintenance has, for example, been a dominant factor influencing road maintenance plans (Arif et al., 2016). Usually, road agencies collect several road condition indexes (e.g., roughness, friction, rutting, cracking, and faulting) compiled into a single score to assess the quality of road pavement (Bektas et al., 2015). However, this can be time-consuming and costly. Among these different indicators, road roughness is a key factor related to the serviceability of a road (Al-Omari and Darter, 1994). In addition, road roughness usually decreases immediately after maintenance, and increases as roads deteriorate. Therefore, road roughness is the most commonly used metric to assess pavement performance when developing road pavement maintenance plans (France-Mensah and O'Brien, 2019). To represent road roughness, the international roughness index (IRI) is applied as a standard index, where the smaller the IRI value, the smoother the pavement. Data on the IRI of roads before and after maintenance are often documented and updated by road agencies. There are also empirical formulas to estimate IRI overtime (Gao and Zhang, 2013).

Environmental aspects are attracting increasing attention when planning pavement maintenance strategies for road network as many countries are mandating the environmental sustainability evaluation of major projects (Giustozzi et al., 2012). GHG emissions are one of the most important indicators. In road maintenance, life cycle emissions mainly come from the production and transport of materials, on-site maintenance work, traffic delays, and fuel combustion due to RR. Traffic delays are usually caused by speed restrictions along the work zone and/or road closures, which can lower road capacity (Huang et al., 2009). Reduced speeds lead decrease fuel efficiency and, thus, extra fuel is consumed, generating more emissions than during normal use. When the road capacity of a work zone is lower than the traffic demand, vehicles need to stop and queue or detour over longer distances, further increasing emissions. RR is the result of the interaction between tires and the pavement when the engine keeps tires rolling (Santos et al., 2015b). Therefore, additional fuel will be combusted to overcome the RR on rough pavements (Trupia et al., 2017). To evaluate life cycle carbon emissions, P-LCA and EIO-LCA methods are usually adopted. As both methods have advantages and disadvantages, hybrid LCA methods are receiving increasing research interest (Crawford et al., 2018). As such, both EIO and process data are needed to enable such evaluations. EIO data can often be obtained from government reports and relevant statistics, while process data, such as the amounts of materials and equipment used, can be collected from material manufacturers and contractors. However, collecting first-hand data can be costly and time-intensive. In such cases, secondary data can be retrieved from the literature and authorised reports.

Social costs, or road-user costs, are less frequently considered because of the complexity of their calculation and the limited impacts on road agencies compared to agency costs (Giustozzi et al., 2012). Road-user costs often include travel delay costs, vehicle operating costs (VOCs), and crash costs (Batouli et al., 2017). Similar to traffic delay emissions, travel delay costs are generated because of traffic delays in work zones. Due to reduced speeds, queueing in line, and/or detours, road users have to spend more time travelling than usual, thereby wasting valued time. VOCs comprise fuel consumption, vehicle repair and maintenance, and tire wear, which are impacted by many factors including travel distance, type of vehicles, traffic volume, traffic composition, pavement surface type, and pavement conditions (Batouli et al., 2017; Chatti and Zaabar, 2012; Gao and Zhang, 2013). Generally, the rougher the pavement, the higher the VOC (Zaabar and Chatti, 2014). Moreover, crash costs can be impacted by many factors, such as crash rates and crash severity (Transport and Infrastructure Council, 2016). Whilst there are several models and rich data available for the modelling of travel delay costs and VOCs, data and the existing models for crash costs remain scarce (Gao and Zhang, 2013). In addition, the relationships between maintenance treatment and accident rates are unclear (Giustozzi et al., 2012; Santos et al., 2017a). Crash costs are, therefore, often not considered when developing road pavement maintenance plans.

2.3.2 Methods for combining multiple indicators

To combine multiple indicators in road maintenance planning, several methods can be adopted to achieve an optimal performance. One option is to consider the Pareto optimal when there are no other alternatives that can improve the results of one objective without compromising the performance of another (Wu et al., 2012). For example, Wei and Tighe (2004) developed a decision tree to integrate various technical and economic indicators for determining the most cost-effective preventive maintenance treatment. However, their study was cost-oriented and did not fully consider sustainability. To combine environmental and economic assessments for optimising pavement maintenance plans, Yu et al. (2013) used a dynamic programming method to link LCA and LCCA models. Yu et al. (2015) also seek to integrate road performance, cost and environmental indicators for the optimisation of pavement maintenance plans. They used genetic algorithms to generate a Pareto set to select the optimal solution. However, both of these studies are conducted at the project level, whereas road agencies often focus on the maintenance and performance of entire road networks. As such, Giustozzi et al. (2012) proposed a multi-attribute approach that can be implemented at the network level, which considered both environmental impact and costs with road performance. A similar method was used by Patidar (2007) to facilitate multi-objective optimisation of investment at a network level based on technical performance, agency costs, and user-costs. As Wu et al. (2012) conclude, no single multi-objective optimisation method is perfect in all factors, such as user-friendliness, information and data availability, and the costs of implementing the method. The multi-attribute decision making approach is, therefore, considered most suitable as it can be applied at the network level and road agency preferences can be quantified in the decision-making process (Wu et al., 2012) .

2.4 Decomposition Analysis of Carbon Emissions

2.4.1 Factors influencing road transport emissions

A consideration of road transport is critical to achieve emissions reduction targets within the transport sector. As such, a number of studies have been conducted to evaluate the key emissions drivers. Table 2-6 lists some example studies along with their research focus and the identified influencing factors.

Table 2-6: A list of studies investigating the factors influencing road transport emissions

Study	Country	Target	Influencing factors
Kwon (2005)	UK	Passenger	Emission coefficient; Fuel structure; Fuel intensity; Occupancy rate; Distance per person; Population.
Lu et al. (2007)	Taiwan, Germany, Japan, and South Korea	Road Transport	Emission factor; Population intensity; Vehicle ownership; Fuel intensity; Economic growth.
Papagiannaki and Diakoulaki (2009)	Greece and Denmark	Passenger	Ownership effect; Distance; Fuel mix; Car capacity change; Car engine change; Population.
Wang et al. (2012c)	China	Freight	Carbon intensity; Vehicle technology level; Vehicle load; Transport company size; Number of transport companies; Distance; Relations between freight transport and industrialisation; Level of industrialisation; Economic growth.
Li et al. (2013)	China	Freight	Emission factor; Market concentration; Road freight market share; Industrialisation level; Fuel intensity; Economic growth.
Mraihi and Harizi (2014)	Tunisia	Freight	Emission intensity; Energy intensity; Transport intensity.
Gambhir et al. (2015)	China	Road Transport	Share of vehicle types; Energy intensity of vehicle types; Emission intensity of vehicle types.
Talbi (2017)	Tunisia	Road Transport	Energy intensity; Economic development level; Urbanisation; Motorisation, Energy consumption.

These studies can be categorised into three groups based on their research targets, i.e., road transport, passenger transport, and freight transport. The first group of studies focus on the entire road transport sector. In these cases, the most commonly used influencing indicators are energy intensity, carbon intensity, and population and economic growth. Although these studies provide some useful insights, the inherent characteristics and relevant factors of passenger transport and freight transport can be different. For example, energy structures are different as freight transport often relies more heavily on diesel than petrol. In addition, as shown in Table 2-6, population is an important factor that affects passenger transport but does not heavily affect freight transport. Failing to choose the relevant factors for passenger and freight transport separately may result biased decomposition results (Wang et al., 2012c).

As such, a number of studies have been initiated to separate passenger and freight transport. For example, Kwon (2005) was one of the first to investigate road passenger transport separately, and considered the effects of population, transport distance per capita, and emissions intensity. Papagiannaki and Diakoulaki (2009) compared the decomposition results of passenger car emissions in Denmark and Greece based on six factors, namely population, vehicle ownership per capita, travelling distance, car fuel type, engine size, and engine technology. For freight transport, Wang et al. (2012c) examined the emissions characteristics of road freight transport in China and decomposed the emissions into nine relevant factors including carbon intensity, vehicle load, distance, industrialisation level, and economic growth. Similarly, Li et al. (2013) investigated the emissions of China's freight transport sector and analysed the contributions of a series of factors including emission factors, market concentration, road freight market share, industrialisation level, fuel intensity, and economic growth. Based on these studies, factors related to passenger and freight transport are quite different and should, therefore, be investigated separately. Consequently, emission factors, transport structure, energy structure, energy intensity, passenger transport intensity, and population are examined in relation to passenger transport emissions in this study. To enable comparison, the same factors are selected for freight transport with the exceptions of passenger transport intensity and population, which are replaced with freight transport intensity and GDP.

2.4.2 Decomposition analysis methods

Index decomposition analysis (IDA) and structural decomposition analysis (SDA) are the most widely used methods in decomposition analysis (Ma et al., 2019). Table 2-7 summarises their application conditions, and advantages and disadvantages. Generally, the IDA method is more widely adopted than the SDA method (Mousavi et al., 2017). In addition, because the IDA method is usually used to analyse energy consumption or energy-related emissions changes in a specific sector, it was considered more suitable for this study.

Table 2-7: Advantages and disadvantages of the Index decomposition analysis (IDA) and structural decomposition analysis (SDA) methods

Method	Application conditions	Advantages	Disadvantages
Index decomposition analysis (IDA)	Usually used to examine the driving factors of energy/energy-related emissions changes in a specific sector (e.g., the transport sector)[1,2,4].	1) High flexibility in formulation and application[2]. 2) A large number of factors can be easily handled with the logarithmic mean Divisia index (LMDI) method[2]. 3) Relatively low data requirement[1,3]. Both data with a high or low degree of sector disaggregation can be used[2].	1) In SDA terminology, it cannot deal with indirect effects[2]. 2) Application is limited in one-stage decomposition models[2].
Structural decomposition analysis (SDA)	Often employed by those comfortable with using input–output analysis[2,4]. Primarily used to analyse the energy/emissions changes in the whole economy[1,2,4].	1) Both direct and indirect effect is captured[2]. 2) Can include two-stage decomposition models[2].	1) Relatively high data requirement[3]. 2) Application relies on the availability of input-output tables, limiting the flexibility[2].

References: [1] Huang et al., 2019; [2] Su and Ang, 2012; [3] Wang et al., 2017; [4] Wu et al., 2019).

Several IDA approaches are available, commonly based on the Divisia index and Laspeyres index. For example, the LMDI and arithmetic mean Divisia index (AMDI) methods are associated with the Divisia index, and the Fisher ideal index, Shapley/Sun, and Marshall-Edgeworth methods are linked to Laspeyres index. Considering their theoretical foundations, adaptability (e.g., data demand and sources), user-friendliness, and result-interpretation issues, Ang (2004) conducted a comprehensive comparison on these approaches, pointing out that the main difference between the two indices is that the Laspeyres index focusses on percentage change where the Divisia index is based on logarithmic change. Due to the symmetry and additivity of logarithmic changes, the Divisia index is considered more scientific than the Laspeyres index (Ang, 2004; Cole and Altman, 2017). In addition, compared to the AMDI method, the LMDI is recommended for general use by Ang (2004), mainly because it is easy to implement and understand, and gives perfect decomposition results without residual terms.

2.5 Chapter Summary

This chapter reviewed published studied related to each of the research objectives stated in Section 1.3.

First, a critical review was conducted on LCA studies on roads. Two general themes were identified, namely the application of LCA to roads and the development of LCA modelling. Among all the identified application themes, P-LCA is the most commonly adopted approach. In addition, most of the current applications have a project-oriented goal, indicating limited implication for road agency decision-making and policymaking. Future LCA studies could pay more attention to network-level analysis. Previous studies were also found to be inconsistent in terms of the selection of FUs; their lack of consideration of the M&R, use, and EOL phases; high uncertainty due to limited reporting of data sources; sensitivity and uncertainty analyses; and the lack of a standardised way of conducting impact assessment. Future studies could examine the M&R and use phases more, and further standardise and tailor LCA methods to better align them with the characteristics of roads.

The review scope was then narrowed to the M&R and use phases to provide further context for Objective 2. The sources of emissions in these phases were reviewed. Material extraction and production, on-site equipment use, and traffic delays are included in the M&R phase, and the RR effect is considered in the use phase, in this research. In addition, existing available hybrid LCA methods were identified and suitable ones for the M&R phase and the use phase of roads were examined, respectively. The PXC method was selected for evaluating emissions from material extraction and production as well as on-site equipment use. The tiered hybrid method was selected for modelling traffic delays and RR effect.

The indicators commonly considered when evaluating a network-level pavement maintenance plan were also reviewed. Road conditions, economic, environmental, and social aspects were examined as well as the methods for combining different indicators into a single index. Based on this review, IRI, agency costs (for materials, equipment use, and labour), GHG emissions (from materials production, equipment use, traffic delay, and the RR effect), and road-user costs (including travel delay cost and VOCs) were selected for this study. In addition, the multi-attribute decision making approach was selected to combine the four attributes in Objective 3.

Finally, factors influencing changes in emissions from the road transport sector and mainstream decomposition analysis methods were reviewed. This showed that passenger transport and freight transport should be treated separately in decomposition analyses. Emission factors, transport structure, energy structure, energy intensity, passenger transport intensity, and population were selected for passenger transport emissions; and emission factors, transport structure, energy structure, energy intensity, freight transport intensity, and GDP were selected for the analysis of freight transport emissions. In addition, based on scientific foundation and ease of use, the LMDI method was selected for Objective 4.

Chapter 3. Methodology

This chapter outlines the methodology of this research. The underpinning philosophy is introduced in Section 3.1 followed by the research design in Section 3.2. Section 3.3 gives a description on the review method adopted for Objective 1 (the critical review) as presented in Section 2.1. The methods for Objective 2 (hybrid LCA method), Objective 3 (multi-attribute decision-making approach), and Objective 4 (decomposition analysis method) are explained in Sections 3.4, 3.5, and 3.6 respectively. Finally, Section 3.7 summarises this chapter.

3.1 Research Philosophy

'Paradigms' are the roots of research (Killam, 2013), derived from the Greek word meaning pattern. According to Guba and Lincoln (1994, p107), paradigms are "*basic belief systems based on ontological, epistemological, and methodological assumptions*". The paradigm of a researcher reflects his/her worldview and guides how things are understood or undertaken. In other words, different types of research are guided by different belief systems or paradigms. Therefore, knowing the underpinning philosophical beliefs is essential for research. Ontology, epistemology, methodology, and axiology together make a research paradigm (Wilson, 2001). Normally these elements are interdependent under a paradigm.

Ontology is a theory of being or existence, dealing with the nature of reality (Aliyu et al., 2015). The Merriam-Webster dictionary (2020) defines ontology as a branch of metaphysics that deals with the nature of being and their relations. A researcher's ontology is what he/she believes is real or true (Wilson, 2001). Two typical contrasting types of ontology are realism and relativism. While realists believe there is only one reality that can be discovered and objectively measured, relativists hold the opinion that reality cannot be found but is instead constructed by people's experiences, so that multiple realities exist and are equally true (Killam, 2013).

Epistemology is the theory of knowledge and is concerned with the relationships between researchers and the researched (Aliyu et al., 2015). Under this framework, a pair of contrasting epistemological positions of researchers such as objectivism vs. subjectivism are formed. Normally, these epistemological beliefs are determined by the ontology of the researchers (Killam, 2013). For example, based on the ontology of realism, a realist believes that the "truth" about the world exists independently that can only be found and measured in an objective manner. However, to a relativist, the "truth" can vary from different people's experiences and contexts. Constructing the meaning or reality through social interaction is more important than searching for the "truth".

Methodology is the way of discovering knowledge about the world systematically (Killam, 2013). Generally, methodology is driven by ontology and epistemology. Depending on the objective and subjective perspectives of researchers, quantitative and qualitative methodologies are adopted (Aliyu et al., 2015), with the main differences being the ways data are collected and analysed. Realists who believe in objectivity usually prefer quantitative inquiry through measurable methods such as experiment and questionnaires. In contrast, relativists, who construct subjective knowledge of the world, often favour qualitative methods such as in-depth interview to understand peoples' experiences. As both methods have weaknesses compensated by the strengths of the other, researchers including Steckler et al. (1992) and Kelle and Erzberger (2004) advocate integrating these two methodologies.

Axiology mainly considers ethical issues (Wilson, 2001). According to the Merriam-Webster dictionary (2020), axiology is the theory of the nature, types, and standards of value and value judgments, especially in morality. Table 3-1 summarises comparisons between the four dominant paradigms of positivism, post-positivism, critical theory, and constructivism based on Killam (2013) and Guba and Lincoln (1994). Positivism is the most traditional paradigm. As the thinking of scientists changes, alternative paradigms emerge (Koschmann, 1996; Kuhn, 1970).

Constructivism is a contrasting paradigm to positivism, and post-positivism and critical theory lie somewhere in-between. While post-positivism is similar to positivism, critical theory is closer to constructivism. It should also be noted that these paradigms are still developing. In addition, different paradigms do not necessarily work in isolation but may work together (Killam, 2013).

This research focuses on the evaluation of GHG emissions of road infrastructure and identification of influencing factors for GHG emissions of the transport sector. First, the emissions from the use and M&R of road infrastructure exist objectively and are unlikely to be constructed or influenced by the researcher. Similarly, factors influencing GHG emissions of the transport sector are also objective and can hardly be influenced by people's experience or values. In addition, the emissions/factors can be objectively measured but are impossible to be perfectly assessed. Therefore, the post-positivism paradigm is suitable for this research.

Table 3-1: Comparisons between four dominant paradigms

Paradigms	Ontology	Epistemology	Methodology	Axiology
Positivism	Realism (One reality exists; objective, static, context-free and measurable)	The reality and the researcher are independent; The "truth" can be known and objectively measured.	Quantitative, usually with large or random samples to avoid bias (deductive in nature); Experimental and manipulative (e.g., experiment, questionnaire, survey); Proves hypotheses.	Values the integrity and honesty of researchers.
Post-positivism	Critical realism (One reality exists; cannot be perfectly understood but approached)	The researchers can influence the researched; Values objectivity and controls the influence of researchers; Welcome to being proven wrong.	Both quantitative and qualitative (favours quantitative ones); Falsifies hypotheses to get the closest possible to the "truth".	Values honesty and objectivity in data collection and reporting; Respects limitations.

Paradigms	Ontology	Epistemology	Methodology	Axiology
Critical theory	Historical realism (Multiple realities exist; can be shaped by different values and can be found)	The researchers can influence the researched and such influences are considered in the research; Embraces subjectivity and interactions between researchers and participants.	Qualitative; Based on dialogues; Dialectical in nature.	Values human rights and social justice; Aims to liberate the oppressed group and follows ethical codes of conduct to protect the participants.
Constructivism	Relativism (The reality is constructed by individual experiences and contexts; subjective, contextual and dynamic)	Knowledge is contextual and is co-constructed by the researcher and participants; People construct their own realities based on their experiences; these realities may conflict but are equally correct; Realities change over time.	Qualitative with typically small samples (inductive in nature); In-depth interview, observation and focus group are common methods.	Alike that of critical theory; Values the experiences of people and the trustworthy of participants.

3.2 Research Design

Based on the paradigm of post-positivism, this study embraces both quantitative and qualitative methodologies, favouring quantitative inquiry to approach the “truth”. The methods adopted are, therefore, quantitative. Figure 3-1 presents the overall research design. A critical review method is adopted for the literature review (Objective 1) as presented in Chapter 2. A structured hybrid LCA approach is developed for evaluating the GHG emissions of the M&R and use phases of roads (Objective 2). To integrate sustainability in road agency decision-making, a multi-attribute decision-making framework is proposed for evaluating and selecting the optimal network-level pavement maintenance plan (Objective 3). In addition, an IDA method (i.e., LMDI) is used to analyse the driving factors of changes in CO_2 emissions from the Australian road transport sector (Objective 4). Each method is elaborated in the following sections.

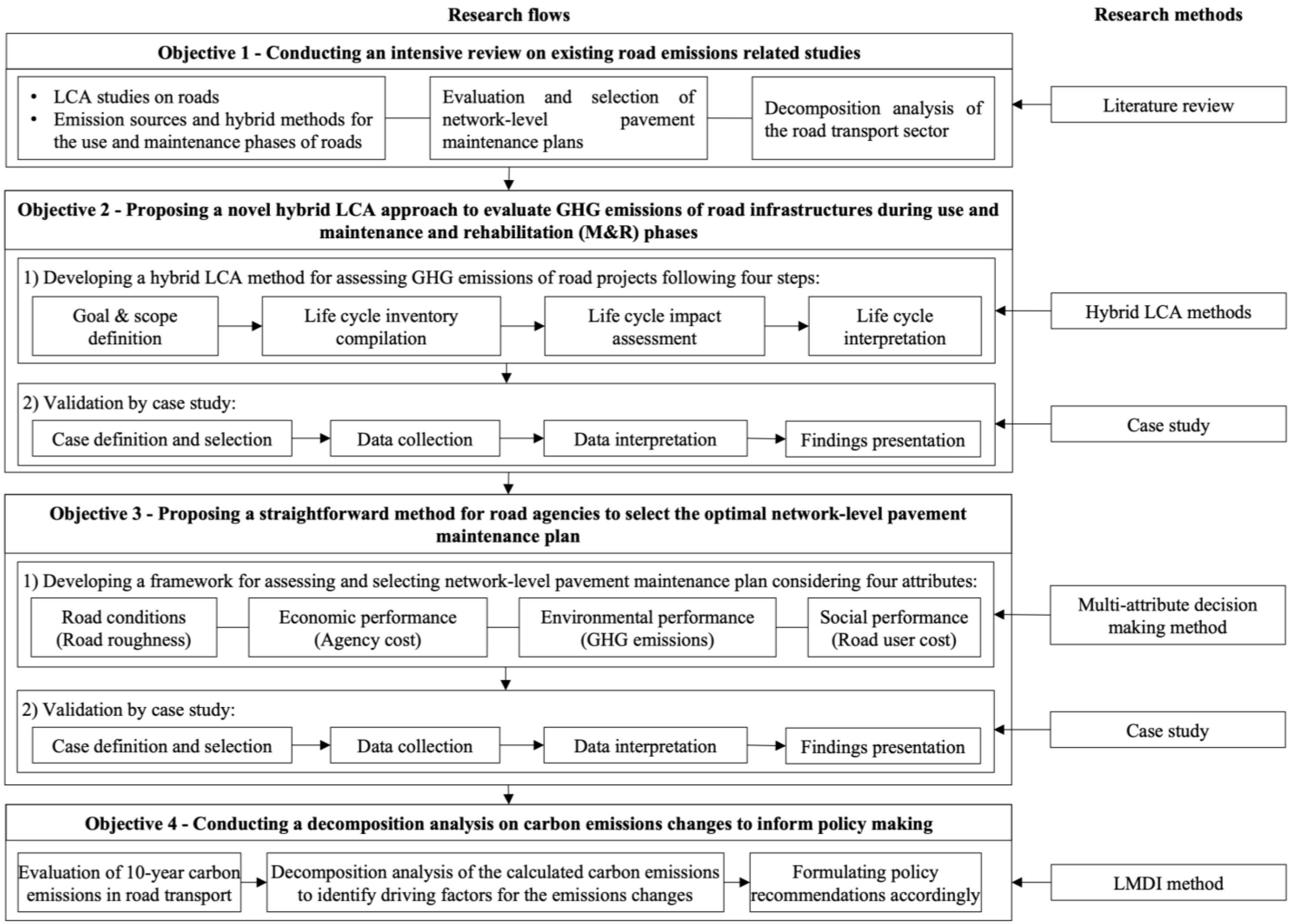

Figure 3-1: Research design (MRWA – Main Roads Western Australia)

3.3 Method for Literature Review (Objective 1)

A six-step approach based on Thomé et al. (2016) was adopted to conduct a systematic review of the literature related to LCA. A similar review process is also used by Wan et al. (2018). The first step was to define the review scope, which was to investigate the development and implementation of the LCA approach in road projects. Therefore, all review activities were centred on this aim.

The second step involved the identification of relevant articles through searching techniques, including the selection of databases and keywords. The Web of Science database was selected as the primary source because of its coverage and quality (Li et al., 2017). The searching terms ("life cycle assessment" OR "LCA") AND ("road" OR "pavement") were used to identify articles containing these terms in their title, abstract, or keywords sections. Only peer-reviewed journal papers and reviews were selected based on quality considerations (Li et al., 2019). Other publication types, such as conference papers, theses, and letters were excluded.

Steps three and four concerned data collection and quality evaluation. Following the article search, 597 potentially relevant articles were identified, among which 220 are directly related to road or pavement LCA. It should be noted that roads are usually classified into three types of facilities, namely earthwork zones, bridges, and tunnels (Park et al., 2016). Most studies are limited to the earthwork zones of paved roads. To ensure that the research aim was consistent, 21 studies on unpaved roads, embankments, trenches, roundabout intersections, bridges, and tunnels were excluded from the review. A similar screening process was adopted by Inyim et al. (2016) and Wan et al. (2018). As a result, a total of 199 peer-reviewed journal papers were retrieved.

The last two steps of the review process are data analysis and interpretation. Content analysis was selected as the method of data analysis as is recommended for analysing textual data (Erlingsson and Brysiewicz, 2017). Table 3-2 presents the codes for the content analysis including year, author, journal, location, goal of study, FU, system boundary, life cycle assessment method, data sources, impact category, major findings, and future needs. These codes were also aligned with the four-step LCA. For example, the FU and system boundary were related to the goal and scope definition.

Table 3-2: Content analysis codes adopted for the literature review

Code	Description of the codes in this review
Year	Year of publication
Author	Authors of the publication
Publication venue	The journal where the paper is published
Location	The location where the research was conducted
Goal of study	The intended aim and objectives for carrying out the study
Functional unit (FU)	The reference unit for the assessment
System boundary	The phases and unit processes
Life cycle assessment method	The method for conducting the LCA
Data sources	The data sources
Impact category	The environmental concerns to which the LCI analysis results are assigned
Major findings	Main results that are related to the goal of the study
Future needs	Limitations or future directions identified by the authors of the publication

The review of literature related to maintenance decision making and emissions decomposition analysis was conducted following similar steps and approaches. Differences mainly lie in the selection of keywords and data collection steps. For example, ("road" OR "pavement") AND "maintenance" AND ("selection" OR "optim*" OR "decision" OR "evaluat*") are used to derive literature for road maintenance decision making. ("transport" OR "passenger" OR "freight") AND "decomposition analysis" are used to obtain studies related to transport emissions decomposition analysis. As literature review for these two topics in this research does not have a systematic nature, only the most relevant and relatively highly cited articles are collected for further review and analysis.

3.4 A Hybrid LCA Approach for Road Use and Maintenance Assessment (Objective 2)

The proposed hybrid LCA approach follows the four steps defined in ISO 14044 (2006) and ISO 14067 (2018), namely 1) defining goal and scope, 2) compiling LCI, 3) assessing life cycle impact, and 4) conducting life cycle interpretation.

3.4.1 Goal and scope definition

3.4.1.1 Functional unit (FU)

Conventional FUs such as kilometre, lane-kilometre and lane-mile are inappropriate as standard FUs for roads (Inyim et al., 2016). The road function should be fully reflected by region, FU, lane width, shoulder width, thickness, roadway type, type and number of pavement, and analysed period (AzariJafari et al., 2016). In addition, it should be noted that pavement roughness changes as roads deteriorate and receive M&R, meaning that the performance and functioning of roads evolve during the use and M&R phases. Therefore, FUs that can clearly specify the temporally evolving function of a road are recommended (Batouli and Mostafavi, 2017; Inyim et al., 2016).

As such, here, FUs were defined by integrating traditional FUs, design parameters, and serviceability. The traditional FU component provides a reference to which the evaluation results can be normalised and acts as a comparable basis across different studies; design parameters and serviceability were included to clearly specify the functions of roads. Serviceability is represented by the IRI, which is a consistent measurement of road roughness developed by the World Bank in 1984 and is well-recognised throughout the world (Múčka and Design, 2017; Sayers, 1984). The relationships between the IRI and the serviceability of roads are demonstrated by Al-Omari (1994), as has the transferability of the IRI throughout the world (Du et al., 2014). Table 3-3 presents an example of the adopted FU indicators.

Table 3-3: Examples of the indicators of road functional units (FUs)

Components	**Indicators**	**Example values**
Traditional FU	E.g., Lane-kilometre, lane-mile, square metre, cubic metre	Lane-kilometre
Design parameters	Region	Western Australia
	Roadway classification	Medium-standard single carriageway
	Annual average daily traffic (AADT) (base year: 2015)	2,270
	Traffic composition	16.7% heavy trucks, 83.3% vehicles
	Traffic growth rate	0.02
	Speed limit	110 km/h
	Pavement type	Granular
	Lane width	13.62
	Lane number	4
	Shoulder width	-
	Layer & thickness	150 mm
	Analysis period	10 yr.
Serviceability	IRI_1	2.495
	IRI_2	2.595
	IRI_3	2.699
	IRI_4	2.807
	IRI_5	2.919
	IRI_6	3.036
	IRI_7	3.157
	IRI_8	3.284
	IRI_9	3.415
	IRI_{10}	3.552

Note: IRI_i refers to the IRI of the i^{th} year.

3.4.1.2 System boundary

The use and M&R phases of roads were considered in this study, while the construction and EOL phases fall outside of the research scope (Figure 3-2). The construction phase is not included in this study because Australian road agencies are preferring road M&R rather than new construction. The number of newly constructed roads in Australia is limited at the time of the study. For one thing, plenty of LCA models for the construction phase have been successfully developed in previous studies. For another, the evaluation of the construction is of little value due to a lack of new construction project. Moreover, the EOL phase is excluded because roads are usually not disposed but rehabilitated to restore their normal function when they reach low serviceability. As this research primarily aims to develop a hybrid LCA model specifically for the use and M&R phases of road infrastructure instead of providing a full life cycle GHG emissions inventory, the exclusion of the construction and EOL phases is consistent with the research scope.

The M&R phase consists of on-site equipment operation, embodied emissions from material production, and traffic delays caused by work zone disruption. In the use phase, emissions that are directly related to the pavement should be considered including those caused by RR, albedo, carbonation of the concrete pavement, and road lighting (Loijos et al., 2013). Among these effects, RR, which is the most investigated and can be modelled with well-established models, was included in this study. As most of the roads in Australia are paved with granular or asphalt materials while concrete is rarely used, the effect of carbonation was not considered. Albedo and lighting were also excluded because their impacts are relatively small compared to RR (Santero and Horvath, 2009)

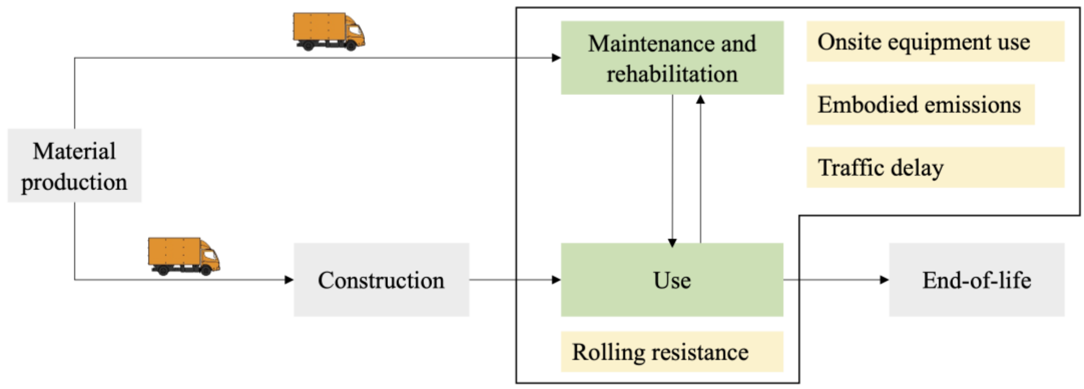

Figure 3-2: System boundary definitions for this study

(Reference: Loijos et al., 2013)

3.4.2 Life cycle inventory (LCI)

Among the four hybrid LCA methods, the PXC method and the tiered approach were selected for the use and M&R phases. PXC has a complete EIO-based analysis framework and a relatively standardised way of application. It was, therefore, adopted to calculate carbon emissions generated by on-site M&R work and its embodied carbon emissions. Fuel consumption due to traffic delays and RR, however, are difficult to fit within an economic sector (Crawford et al., 2018). Therefore, a strategy of conducting the process calculation first and then completing the upstream emissions with IO data using the tiered approach was adopted.

3.4.2.1 LCI for the M&R phase

The PXC method proposed by Treloar et al. (2004) was adopted for evaluating emissions from on-site equipment operations and embodied emissions, which includes the following four steps:

1) Building an EIO-LCA model for roads using Eqs. (1) and (2) (Treloar et al., 2004):

$$\boldsymbol{X} - D\boldsymbol{X} = \boldsymbol{F} \tag{1}$$

$$\boldsymbol{E} = R\boldsymbol{X} = R(I - D)^{-1}\boldsymbol{F} \tag{2}$$

where vector $\boldsymbol{X}$ is total monetary output of each economic sector; matrix D refers to the direct requirement coefficients matrix, which is often published by the national statistics bureau; vector $\boldsymbol{F}$ is the final monetary demand of each economic sector; vector $\boldsymbol{E}$ is the total emissions of different kind; matrix R is emissions caused by every unit of output of each economic sector; and matrix I is a unit matrix. The associated data demand and data sources are demonstrated in Table 3-4.

Table 3-4: Data demand for the EIO-LCA model

Component	Data demand	Data sources
D	Direct requirement coefficients matrix (2015-2016)	(ABS, 2018)
R	GHG inventory by economic sector (2015)	(Australian Government, 2019)
	Output of each economic sector (2015-2016)	(IBISWorld, 2019)
$\boldsymbol{F}$	Cost for each M&R strategy	Main Road Western Australia (MRWA)

It should be noted that the most recent direct requirement coefficients matrix (2015–2016) was used in this study. In addition, because the GHG inventory is derived from the Australian-New Zealand Standard Industrial Classification (ANZSIC) and the IO table follows the input-output industrial classification, which is disaggregated based on ANZSIC, the coefficients matrix was aggregated to the 36 sectors in the GHG inventory following the method proposed in Su et al. (2010).

2) Extracting the most important paths based on the EIO model using an algorithm adopted by Treloar et al. (2004). This aims to identify nodes with the highest emissions in the entire supply chain. The power series expansion is used to present each sector in the supply chain by exclusive nodes, as shown in Eq. (3) (Treloar et al., 2004):

$$(I - D)^{-1} = \sum_{k=0}^{\infty} D^k \tag{3}$$

where k is a series of integers ranging from zero to positive infinity, with each representing a phase. For example, k = 0 refers to on-site equipment operation; k = 1 refers to the closest upstream phase, which involves a number of different economic sectors, such as the manufacturing of cement, manufacturing of petroleum, and so on; k = 2 represents the closest upstream phase of the manufacturing activities; and so forth. Generally, with the increase in the value of k, the emissions in the corresponding phase decrease. Figure 3-3 provides a simple demonstration of this structure, where red nodes represent the most carbon-intensive sectors (some less important nodes are not presented for clarity and simplicity). Through a preliminary analysis, the construction sector, cement, lime, plaster and concrete product sector, iron and steel manufacturing sector, basic chemical and chemical, polymer and rubber product manufacturing sector, and petroleum and coal product manufacturing sector were identified as the most carbon-intensive sectors. Therefore, emissions from these sectors were substituted with more accurate case-specific data derived in the following step.

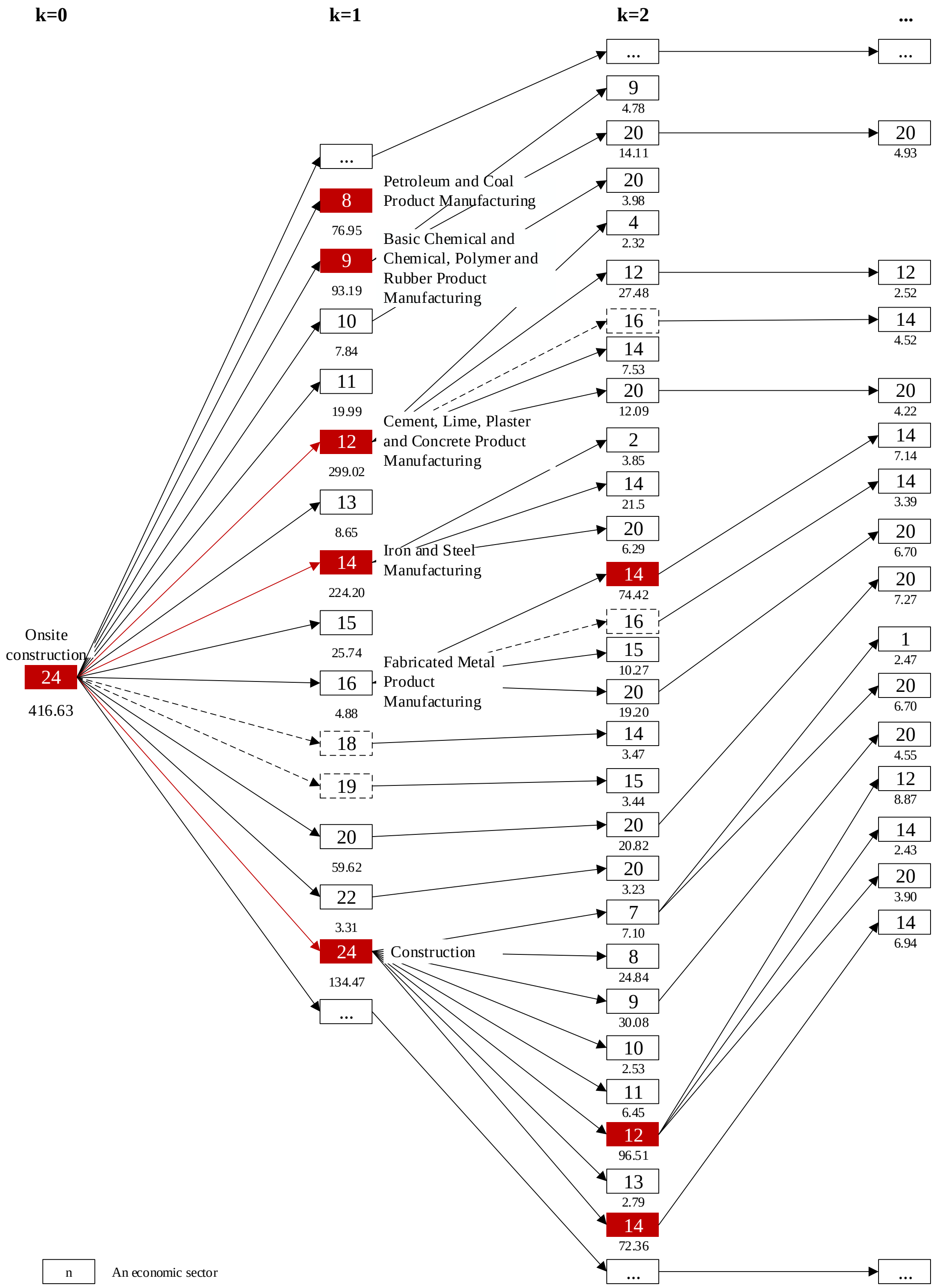

Figure 3-3: Simple demonstration of the important emission path extraction results (Note: red nodes represent the most carbon-intensive sectors and some less important nodes are not presented for clarity and simplicity)

3) Deriving case specific LCA data using a process-based method for the identified nodes on the paths. Primary data for material usage for each M&R strategy

were obtained from MRWA. Equipment fuel usage data were extracted from the published literature and authorised reports. In addition, emission factors for material production and fuel combustion were derived from TAGG (2013), ensuring that they were specific to Australia.

4) Modifying the derived EIO model by replacing the EIO value of the identified nodes with corresponding case specific data.

To evaluate traffic delays caused by on-site works, the tiered hybrid method was used. During a traffic delay, GHG emissions are generated from three sources—vehicles queueing in line, passing through the work zone at a lower speed, and taking detours (Jiang et al., 2020; Yu and Lu, 2012). Collectively, these resulting emissions are higher than those occurring from normal road use, and such increases are attributed to road maintenance. Therefore Eq. (4) was used to conduct the process-based calculation, as is widely used to estimate the effects of traffic delays (e.g., Chen et al., 2016; Yu and Lu, 2012). The data demand for these calculations is summarised in Table 3-5. The IO data for the upstream phases were derived using Eqs. (1) and (2):

$$Y_{total} = VMT_{queue} \times Y_{queue} + VMT_{workzone} \times Y_{workzone} + VMT_{detour} \times Y_{detour} - VMT_{normal} \times Y_{normal} \quad (4)$$

where Y_i is the unit fuel usage (L/km) or emission factors (t/km); and VMT_i evaluates the distances travelled by vehicles (km), where i represents different scenarios including the total, waiting in queue before entering the work zone, passing through the work zone at a lower speed than normal, taking a detour, and travelling under normal conditions, respectively.

Table 3-5: Data demand for calculating emissions from traffic delays

Component	Data demand	Data (data sources)
VMT_{queue}	Hourly distribution of traffic	Hourly distribution pattern (Regehr et al., 2015)
	Work zone capacity	Calculated following Margiotta and Washburn (2017)
	Effective spacing between vehicles	Calculated following Chitturi and Benekohal (2010)
Y_{queue}	Average queue speed	Assumption: 8 km/h
	Fuel efficiency at queue speed	0.160 L/km (Oak Ridge National Laboratory, 2019)
$VMT_{workzone}$	AADT & traffic composition	Varied for different road segments (MRWA)
	Work zone length	Unit length 1 km
$Y_{workzone}$	Work zone speed	National highway: 80km/h, secondary highway: 60 km/h, local road: 40 km/h (Department of Infrastructure, 2015)
	Fuel efficiency at work zone speed	Obtained for different speed from Oak Ridge National Laboratory (2019)
VMT_{detour}	No. of vehicles that detour	Detour vehicles: 10% (Santos et al., 2015b)
	Detour length	2.4 km (Chen et al., 2016)
Y_{detour}	Average detour speed	60 km/h (Santos et al., 2015b)
	Fuel efficiency at the detour speed	0.076 L/km (Oak Ridge National Laboratory, 2019)
VMT_{normal}	AADT & traffic composition	Varied for different road segments (MRWA)
	Work zone length	Unit length 1 km
Y_{normal}	Normal speed	Varied for different road segments (MRWA)
	Fuel efficiency at normal speed	Varied for different road segments (MRWA)

3.4.2.2 LCI for the use phase

Carbon emissions generated from the impact of RR were considered for the use phase. RR is caused by the complex interactions between the road pavement and vehicle tires (Santos et al., 2015b), and is affected by the characteristics of the pavement, of which macrotexture (represented by mean profile depth, MPD) and roughness (represented by IRI) have the most significant impacts (Trupia et al., 2017). Only Highway Development and Management Model - version 4 (HDM-4) and the model developed by the Swedish National Road and Transport Research Institute (VTI) are available to model both MPD and IRI (Trupia et al., 2017). In addition, the HDM-4 model requires calibration for specific countries before it can be used, which was not possible for Australia. Therefore, the VTI model was adopted, which has been successfully used by Santos et al. (2015a) and Bryce et al. (2014). The fuel use of a single car or heavy truck due to RR can be calculated using Eqs. (5) and (6), respectively (Hammarström et al., 2012):

$$F_{cj} = 0.103\ (1.208 + 0.000479 * IRI_j * v_c + 0.0393 * MPD_j)^{1.163} * {v_c}^{1.056} \quad (5)$$

$$F_{tj} = 0.246\ (1.451 + 0.00172 * IRI_j * v_t + 0.111 * MPD_j)^{1.027} * {v_t}^{0.960} \quad (6)$$

where F_{cj} (F_{tj}) is the fuel use of a car (truck) in the jth year, L/h; IRI_j (MPD_j) is the IRI (MPD) of the pavement in the jth year; and v_c (v_t) is the moving speed of the car (truck), m/s. Fuel use can then be used to calculate carbon emissions during the use phase by multiplying corresponding emission factors and deriving IO data for the upstream phases using Eqs. (1) and (2). The IRI data were provided by MRWA for each year while only a static MPD value was available for each road segment. In addition, the emission factors used for the calculation were collected from TAGG (2013) to ensure they were specific to Australia.

3.4.3 Life cycle impact assessment (LCIA)

GWP was used to assess global warming impact (Levasseur et al., 2010). The mechanism for calculating the GWP of a GHG is illustrated by Yu et al. (2018). Based on the GWP, GHGs can be converted to CO_2-e by multiplying their mass by their corresponding GWP. For example, the GWP values for CO_2, CH_4, and N_2O are 1, 25, and 298, respectively. GHG inventory and emission factors in Australia are all provided in the form of CO_2-e following the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines and the 2019 amendment. This includes common GHGs such as CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride (Australian Government, 2019; TAGG, 2013). Therefore, LCI results were calculated as CO_2-e, and GWP derived in the LCIA corresponds to the LCI results.

3.4.4 Life cycle interpretation

Interpretations were made on the basis of the overarching goal and scope of the study as well as the results of LCI and LCIA. A contribution analysis was conducted to identify significant GWP contributors during the use and M&R phases. The spatial distribution of GWP was also visualised to identify the most carbon-intensive road segments across the entire road network. Finally, a sensitivity analysis was implemented to determine the extent to which the results of the proposed methods were influenced by the choice of emission factor data (Guinée and Lindeijer, 2002; ISO, 2006).

3.4.5 Case study

Case study is a research method that is commonly used to conduct in-depth investigation on complex issues in real-life context (Crowe et al., 2011). It originated in medical research, and its application has been expanded into a wide research area of psychology, education, environmental management, and engineering etc. (Duan et al., 2017; Jaspal, 2019; Klaassen, 2018; Shabi et al., 2017). Generally, a case can be a person (e.g., a patient in health service research), a community (e.g., in poverty research), and a project (e.g., in engineering research) (Ali and Hatta, 2014; Crowe et al., 2011; France-Mensah and O'Brien, 2018). In engineering research, no matter it is civil engineering, system engineering, or environmental engineering, the case study method is extensively used to demonstrate the effectiveness of a proposed analytical model or solution in real-life projects. For example, Yu and Lu (2012) and Zheng et al. (2019) illustrated their proposed LCA methods for pavements with case studies, arguing that case studies are critical for promoting the practical implementation of the methods. Shabi et al. (2017) also applied a case study to demonstrate their developed decision support model after justifying the rigours of the case study method. Therefore, the case study method was considered reliant and used to demonstrate the usefulness of the proposed hybrid LCA model in this research.Four steps were followed to conduct the case study (Crowe et al., 2011). The first step was to define and select a representative case to demonstrate the proposed approach. Then data were collected for the case using a range of techniques, such as literature review and database searching, followed by data interpretation and analysis. The last step was to report the findings. Detailed information for the case study is presented in Chapter 4.

3.5 Multi-attribute Decision-Making Approach for Selecting Optimal Maintenance Plans (Objective 3)

The framework proposed for evaluating network-level pavement maintenance plans consists of four attributes, namely road condition, economic performance, environmental performance, and social performance (Figure 3-4). The selection of criteria was based on France-Mensah and O’Brien (2019), which is one of the few studies to include environmental impacts and road-user costs when developing a road management plan. Modifications have been made to ensure completeness and accuracy.

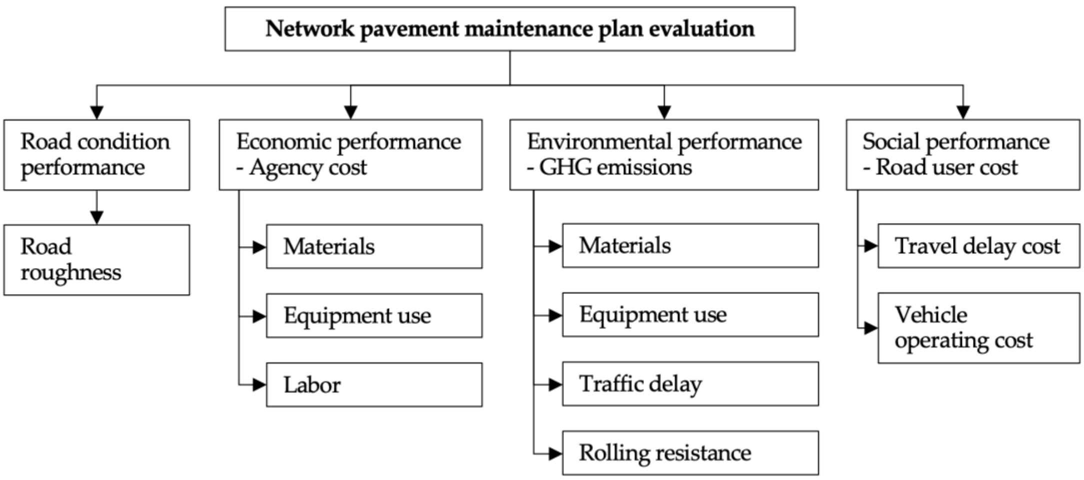

Figure 3-4: Proposed framework for evaluating network-level pavement maintenance plans

France-Mensah and O’Brien (2019) included distress and roughness to assess road condition; however, their distress score was developed for the Texas Department of Transportation and cannot be easily applied in other countries or jurisdictions (France-

Mensah and O'Brien, 2019). Considering its international acceptance and widespread use, here, road condition was considered based on the IRI as a measure of road roughness. Environmental performance was evaluated through a LCA of GHG emissions from materials, equipment use, traffic delays, and RR (France-Mensah and O'Brien, 2019). GHG emissions are targeted because of two main considerations. First, many countries (e.g., Australia, America, and China) have committed to reduce GHG emissions (Jiang et al., 2020; The White House, 2015); considering the large contribution of road transport to GHG emissions, it is imperative to incorporate GHG emissions in assessments of road maintenance plans (Climate Council, 2017). Second, GHG emissions inventories are provided by many countries, making such data more accessible than other environmental impacts. Similar to France-Mensah and O'Brien (2019), road-user costs including travel delay costs and VOCs are calculated to evaluate social performance. Due to the scarcity of models and data for crash costs and the uncertain relationships between maintenance treatments and accident rates, crash costs were not included (Gao and Zhang, 2013; Giustozzi et al., 2012; Santos et al., 2017a). It should be noted that economic aspects were not included as one of the objectives by France-Mensah and O'Brien (2019). As the maintenance of the pavement network is an on-going task, here, economic performance was evaluated based on life cycle agency costs including materials, equipment, and labour use (Beatty, 2002). In addition, a multi-attribute decision-making approach adopted by Giustozzi et al. (2012) was used to combine the four attributes of the evaluation. Finally, the proposed framework was validated using a case study.

3.5.1 Road condition

Road condition was measured using the IRI, where a smaller IRI value indicates a lower degree of roughness and a better-condition pavement. Thus, the road condition of a network is calculated using Eq. (7):

$$RC_t = \frac{\sum_{p=1}^{P} IRI_{pt} \times l_{pt}}{\sum_{p=1}^{P} l_{pt}} \tag{7}$$

where p is a single pavement segment of the studied road network and P indicates the number of pavement segments that form the network; t is a single year of a studied time period (the analysis period) where $t = 1$ indicates the first year of analysis; IRI_{pt}

and l_{pt} represent the IRI and length of pavement segment p in the t^{th} year, respectively; and RC_t is the pavement condition of the network in the t^{th} year represented by the weighted average IRI of the entire network.

3.5.2 Agency costs

Agency costs usually include the direct costs of materials, equipment use, and labour. Agency costs (C_e) for network-level pavement maintenance is calculated using Eq. (8):

$$\mathrm{C}_e = \sum_{t=1}^{T} \sum_{p=1}^{P} (c_{mpt} + c_{ept} + c_{lpt}) x_{pt} \quad (8)$$

where T is the analysis period; c_{mpt}, c_{ept}, and c_{lpt} represent the maintenance costs of materials, equipment use, and labour for pavement segment p in the t^{th} year, respectively. c_{mpt}, c_{ept}, and c_{lpt} are calculated by multiplying the unit cost of the corresponding maintenance strategy by the treated area of the pavement being maintained; x_{pt} is a binary variable, where 1 indicates that a maintenance strategy is allocated for pavement segment p in the t^{th} year and 0 indicates no action taken. As a network-level pavement maintenance plan for a 10-year period (2017–2026) was considered in this study, T = 10. The plan indicates whether or not pavement segment p receives a maintenance treatment in the t^{th} year. For example, if the first pavement segment receives a rehabilitation in 2018, then $x_{1,2} = 1$ and $x_{1,t}\ (t = 1,3,4,5,6,7,8,9,10) = 0$; and $c_{m1,2}$, $c_{e1,2}$, and $c_{l1,2}$ represent the rehabilitation costs of materials, equipment use, and labour for this segment, respectively. Therefore, agency costs for the considered pavement segment are represented as $c_{m1,2} + c_{e1,2} + c_{l1,2}$. The details of sources and structure of the data applied in this analysis are presented in Section 3.6.

A present worth analysis approach was adopted, which discounts the yearly cost to an equivalent cost that occurs at the beginning of the analysis period, with results presented as net present value (NPV). In addition, an equivalent uniform annual cost method was adopted to obtain equivalent annual costs based on a net annual value (NAV). A discount rate of 4% was adopted following previous studies (Giustozzi et al., 2012) and discussion with local road agencies.

3.5.3 Greenhouse gas emissions

The proposed hybrid LCA approach was used to evaluate GHG emissions from the road network. The FU is the whole road network and the maintenance and use phases were considered as the system boundary. Specifically, embodied emissions from materials extraction and production, on-site equipment operation, and traffic delays due to maintenance work were included in the maintenance phase. The use phase considered the rolling resistance effect given its relatively high impact and well-established evaluation methods (Santero and Horvath, 2009). The analysis period was 10 years, matching the agency cost analysis. In the proposed method, the GHG emissions of a road network (E_c) are calculated by summing the network emissions from materials and equipment use (E_{me}), traffic delays during maintenance (E_{td}), and RR (E_{rr}), as shown in Eq. (9a) (France-Mensah and O'Brien, 2019):

$$E_c = E_{me} + E_{td} + E_{rr} \tag{9a}$$

The network GHG emissions from materials and equipment are calculated by summing the emissions from each road segment based on Eq. (9b):

$$E_{me} = \sum_{t=1}^{T} \sum_{p=1}^{P} (e_{mept}) x_{pt} \tag{9b}$$

where e_{mept} represents the GHG emissions from materials and equipment use of a pavement segment p in the t^{th} year. Here, the GHG emissions from materials and equipment use of road segments were calculated through the PXC hybrid LCA method explained in Section 3.4 (Jiang et al., 2020). An EIO-LCA model was first built and case-specific data were subsequently used to substitute the most important nodes with the highest emissions in the EIO-LCA model (Treloar et al., 2004).

In the case of emissions from traffic delays and RR, fuel use cannot be easily fitted into an economic sector. Therefore, the PXC method is not applicable and, instead, a tiered hybrid LCA method was adopted as explained in Section 3.4 (Jiang et al., 2020). The first step involved obtaining process-based data (i.e., direct fuel combustion) and then EIO data were derived for all other upstream processes, such as raw material extraction and fuel production (Wang et al., 2012a). The network GHG emissions from traffic delay and RR were calculated using Eqs. (9c) and (9d), respectively:

$$E_{td} = \sum_{t=1}^{T} \sum_{p=1}^{P} (e_{tdpt}) x_{pt} \tag{9c}$$

$$E_{rr} = \sum_{t=1}^{T} \sum_{p=1}^{P} e_{rrpt} \quad (9d)$$

where e_{tdpt} and e_{rrpt} represent the GHG emissions from the traffic delays and RR of pavement segment p in the t th year, respectively. During traffic delays, GHG emissions are generated from three main sources—vehicles queueing in line, passing through the work zone at a lower speed, and taking detours (Jiang et al., 2020; Yu and Lu, 2012). Together, emissions are higher than vehicle emissions from normal road use, and such an increase is, therefore, attributed to road maintenance. Therefore, e_{tdpt} was calculated using Eq. (9e), which is based on Eq. (4) (Yu and Lu 2012):

$$e_{tdpt} = (e_{queue} + e_{workzone} + e_{detour} - e_{normal})_{pt} \quad (9e)$$

where e_{queue}, $e_{workzone}$, e_{detour}, and e_{normal} are the GHG emissions generated from vehicles queueing in line, travelling through the maintenance work zone at a lower speed, taking a detour, and passing through the work zone at a normal speed, respectively.

The RR effect, on the other hand, measures GHG emissions generated from fuel combustion due to the interaction of vehicle tires and an uneven road pavement. Such interaction can be affected by vehicle speed and pavement features, such as roughness (represented by the IRI) and macrotexture (represented by the MPD). As cars and trucks have different interaction modes, fuel use was calculated separately. The fuel use of a single car or heavy truck due to RR was calculated using Eqs. (5) and (6), respectively, and e_{rrpt} was calculated using Eq. (9f) (Hammarström et al., 2012):

$$e_{rrpt} = \left(\frac{f_{cpt} \times AADT_{pt} \times Perc_{cp} \times ef_c}{v_{cp}} + \frac{f_{trpt} \times AADT_{pt} \times Perc_{trp} \times ef_{tr}}{v_{trp}}\right) \times l_p \times 365 \quad (9f)$$

where f_{cpt} (f_{trpt}) represents the fuel use of a single car (truck) per hour due to its RR on pavement p in the tth year; $AADT_{pt}$ is the AADT of pavement segment p in the t^{th} year; and $Perc_{cp}$ ($Perc_{trp}$) refers to the percentage of cars (trucks) on pavement p; ef_c (ef_{tr}) indicates the emission factor for car (truck) fuel. Gasoline and diesel fuel were considered as typical fuels for cars and trucks, respectively (Oak Ridge National Laboratory, 2020).

Finally, to assess the environmental impact of the emissions, GWP was selected as the characterisation factor. Thus, all GHG emissions including CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride were converted to CO_2-e.

3.5.4 Road-user costs

Travel delay costs (C_{td}) and VOCs (C_{voc}) were considered to calculate road-user costs (C_s), as indicated by Eq. (10a):

$$C_s = C_{td} + C_{voc} \tag{10a}$$

As shown in Eq. (4b), the calculation of travel delay costs was similar to that of traffic delay emissions, thus:

$$C_{td} = \sum_{t=1}^{T} \sum_{p=1}^{P} (c_{queue} + c_{workzone} + c_{detour} - c_{normal})_{pt} x_{pt} \tag{10b}$$

where c_{queue}, $c_{workzone}$, c_{detour}, and c_{normal} are fuel costs generated from vehicles queueing in line, travelling through the maintenance work zone at a lower speed, taking a detour, and passing through the work zone at a normal speed, respectively.

The VOCs consist of fuel costs (C_f), repair and maintenance costs (C_{rm}), and tire wear costs (C_{tw}) (Zaabar and Chatti, 2014), based on Eqs. (10c)–(10e):

$$C_f = \sum_{t=1}^{T} \sum_{p=1}^{P} (c_{normal})_{pt} \times C_{1pt} \times (IRI_{pt} - IRI_0) \tag{10c}$$

$$C_{rm} = \sum_{t=1}^{T} \sum_{p=1}^{P} (c_{rm})_{pt} \times C_{2pt} \times (IRI_{pt} - IRI_0) \tag{10d}$$

$$C_{tw} = \sum_{t=1}^{T} \sum_{p=1}^{P} (c_{tw})_{pt} \times C_{3pt} \times (IRI_{pt} - IRI_0) \tag{10e}$$

where C_{npt} $(n = 1, 2, 3)$ is a coefficient representing the change of fuel costs ($n = 1$), repair and maintenance costs ($n = 2$), and tire wear costs ($n = 3$) per 1 m/km change in the IRI respectively, as adapted from Zaabar and Chatti (2014); IRI_0 is the initial value of the IRI before maintenance; and $(c_{rm})_{pt}$ and $(c_{tw})_{pt}$ are repair and maintenance costs and tire wear costs for pavement segment p in t^{th} year, respectively. The details of the data and data sources used in these calculations are presented in Section 3.5.6. As with the agency costs, the social costs were also discounted to the NPV and NAV based on a rate of 4%.

3.5.5 Multi-attribute decision-making approach

Multi-attribute decision-making involves making decisions among a set of finite and usually conflicting alternatives (Triantaphyllou and Baig, 2005). Three steps are needed in a multi-attribute decision-making approach. First, weights for each attribute are assigned based on their relative importance; a higher weighting indicates higher importance, and weights can vary according to the preferences of the decision-makers. Second, to enable comparison between the alternative plans, their respective attribute values are normalised or rescaled, usually within the range of 0 to 1, with 1 representing the highest value. Finally, all attributes are combined into a single index to inform decision-making. Various methods are available for this, such as the WSM and the analytic hierarchy process method. It is difficult, if not impossible, to determine which method provides the "correct" answer, but the WSM method is the most widely adopted approach, possibly because it is relatively user-friendly and easy to apply (Triantaphyllou and Baig, 2005; Yang, 2020). Therefore, in this study, the following three steps were followed:

1) Assign weights initially for road condition, agency costs, GHG emissions, and road-user costs;

2) Normalise the attribute values of alternative maintenance plans to the range 0 to 1. The highest value of each attribute is rescaled to 1 and the values of other alternatives are rescaled proportionally following Eq. (11a) (Giustozzi et al., 2012); and

3) Combine the normalised values of the four attributes into a single value for each alternative maintenance plan using the WSM method based on Eqs. (11b) and (11c) (Triantaphyllou and Baig, 2005):

$$x_{ij} = \frac{a_{ij}}{a_{max,j}} \times 1 \tag{11a}$$

$$P_i = \sum_{j=1}^{n} a_{ij} \times w_j \tag{11b}$$

with

$$\sum_{j=1}^{n} w_j = 1,\ w_j > 0 \tag{11c}$$

where i indicates an alternative maintenance plan for the pavement network; j denotes an attribute where n is the total number of attributes (n = 4 in this study); a_{ij} represents the performance of alternative plan i in terms of attribute j, where $a_{max,j}$ is the highest value among all alternatives for attribute j; P_i is the WSM value for maintenance plan i; and w_j refers to the nonnegative weight of attribute j. Equal weights were adopted as an example to illustrate the application of the proposed framework. As such, w_j = 0.25 for all four attributes. As different road agencies have their own preferred importance ranking of the four attributes, 1,000 sets of weights were randomly generated for the four attributes to cover a wide range of possibilities based on the following steps (Yang, 2020). First, four values of u_j were generated following a normal distribution N (0,1) assuming that most decision-makers do not have extreme preferences. Then, these four values were normalised following Eq. (11d) so that Eq. (11c) was satisfied. Finally, the first two steps were repeated 1,000 times. This approach, adopting the WSM with random weights, has been shown to work well (Yang, 2020).

$$w_j = \frac{u_j}{\sum_{j=1}^{4} u_j} \tag{11d}$$

The resulting weights for road condition and economic, environmental, and social aspects range 0.0008–0.7790, 0.0002–0.8040, 0.0002–0.8605, and 0.0005–0.8898, respectively. These ranges are considered to cover most of the preferences of decision-makers, including some extreme situations, such as when environmental aspects are given higher significance due to aggressive emissions reduction targets.

3.5.6 Case study

A case study was conducted to demonstrate the effectiveness of the proposed framework. Reasons for the selection of this method and its implementation are similar to those explained in Section 3.4.5. Detailed information for the case study adopted for the demonstration of the framework is presented in Chapter 5.

3.6 Methods for Carbon Emissions Evaluation and Decomposition (Objective 4)

3.6.1 Evaluation of CO_2 emissions in road transport

The CO_2 emissions from road transport were calculated using two main sources of data, namely energy consumption and CO_2 emissions coefficients. Energy consumption data for the U.S. were collected from the Transportation Energy Data Book series. The latest edition was Edition 38 which includes the energy sources and consumption of the transport sector in 2017 (Oak Ridge National Laboratory, 2020). Here, the CO_2 emissions from road transport between 2008 and 2017 were used to ensure data consistency because of the change of method for evaluating energy use by the Federal Highway Administration. The Transportation Energy Data Book publishes transport energy by mode (including light vehicles, buses, and medium/heavy trucks) and energy type (including road transport related petrol, diesel, liquefied petroleum gas, natural gas, and electricity). The energy consumption data for Australia were retrieved from the Australian Bureau of Statistics, published every other year. To keep in-line with the U.S., the analysis for Australia was from 2009 to 2017.

In addition, the CO_2 emissions coefficients published by the U.S. were retrieved from the U.S. Energy Information Administration (2016b). For the CO_2 emissions coefficients for electricity generation, the State Electricity Profiles of the U.S. were referred to U.S. Energy Information Administration (2019). The CO_2 emissions coefficients for the Australian road transport sector were obtained from Transport and Infrastructure Council (2016).

As petrol, diesel fuel, liquefied petroleum gas (LPG), natural gas, and electricity were included as energy courses, the CO_2 emissions from the road transport sector were calculated by Eq. (12):

$$CO_{2,road} = \sum_i CO_{2,i} = \sum_i E_i \times CC_i \tag{12}$$

where E_i represents the energy use from energy source i; and CC_i refers to the CO_2 emissions coefficients of energy source i.

3.6.2 LMDI decomposition approach

The LMDI method was adopted to analyse the factors influencing changes in CO_2 emissions from the road transport sector in the U.S. and Australia. It should be noted that passenger transport and freight transport are reported differently because they are affected by different influencing factors. As such, two separate decomposition models were developed for passenger transport, i.e., light vehicles (cars, light trucks, and motorcycles) and buses, and freight transport (medium/heavy trucks).

Eq. (13) was used for the decomposition analysis of passenger transport:

$$CO_{2,P} = \sum_{ij}\left(CO_{2,P}\right)_{ij} = \sum_{ij}\frac{\left(CO_{2,P}\right)_{ij}}{E_{P,ij}} \times \frac{E_{P,ij}}{E_{P,i}} \times \frac{E_{P,i}}{E_P} \times \frac{E_P}{V} \times \frac{V}{P} \times P = \sum_{ij} EF_{P,ij} \times TS_{P,ij} \times ES_{P,i} \times EI_P \times PI \times P \quad (13)$$

where $CO_{2,P}$ represents the CO_2 emissions from passenger transport; $E_{P,ij}$ represents the energy use of source *i* in mode *j* of passenger transport; $E_{P,i}$ denotes the energy use of source *i* for passenger transport; E_P refers to the total energy use of passenger transport; V is the passenger transport service (measured by million passenger miles/km); P is population; EF_P represents the emission factor; TS_P refers to the transport structure, i.e., the share of transport mode *j* in the passenger transport sector; ES_P refers to the energy structure, i.e., the share of energy source *i* in the passenger transport sector; EI_P represents the energy intensity of the passenger transport sector; and PI is the passenger transport intensity (measured by transport distance per capita).

Changes in the CO_2 emissions from the passenger transport sector were, therefore, decomposed into six factors (EF_P, TS_P, ES_P, EI_P, PI, and P) using Eqs. (14)–(20):

$$\Delta CO_{2,P} = \Delta CO_{2,EF_P} + \Delta CO_{2,TS_P} + \Delta CO_{2,ES_P} + \Delta CO_{2,EI_P} + \Delta CO_{2,PI} + \Delta CO_{2,P} \quad (14)$$

$$\Delta CO_{2,EF_P} = \sum_{ij} L\left(CO_{2,ij}^T, CO_{2,ij}^0\right) ln\frac{EF_{P,ij}^T}{EF_{P,ij}^0} = \sum_{ij}\frac{CO_{2,ij}^T - CO_{2,ij}^0}{\ln CO_{2,ij}^T - \ln CO_{2,ij}^0}\, ln\frac{EF_{P,ij}^T}{EF_{P,ij}^0} \quad (15)$$

$$\Delta CO_{2,TS_P} = \sum_{ij} L\left(CO_{2,ij}^T, CO_{2,ij}^0\right) ln\frac{TS_{P,ij}^T}{TS_{P,ij}^0} = \sum_{ij}\frac{CO_{2,ij}^T - CO_{2,ij}^0}{\ln CO_{2,ij}^T - \ln CO_{2,ij}^0}\, ln\frac{TS_{P,ij}^T}{TS_{P,ij}^0} \quad (16)$$

$$\Delta CO_{2,ES_P} = \sum_{ij} L\left(CO_{2,ij}^T, CO_{2,ij}^0\right) ln\frac{ES_{P,i}^T}{ES_{P,i}^0} = \sum_{ij}\frac{CO_{2,ij}^T - CO_{2,ij}^0}{\ln CO_{2,ij}^T - \ln CO_{2,ij}^0}\, ln\frac{ES_{P,i}^T}{ES_{P,i}^0} \quad (17)$$

$$\Delta CO_{2,EI_P} = \sum_{ij} L\left(CO_{2,ij}^T, CO_{2,ij}^0\right) ln\frac{{EI_P}^T}{{EI_P}^0} = \sum_{ij} \frac{CO_{2,ij}^T - CO_{2,ij}^0}{\ln CO_{2,ij}^T - \ln CO_{2,ij}^0} ln\frac{{EI_P}^T}{{EI_P}^0} \quad (18)$$

$$\Delta CO_{2,PI} = \sum_{ij} L\left(CO_{2,ij}^T, CO_{2,ij}^0\right) ln\frac{PI^T}{PI^0} = \sum_{ij} \frac{CO_{2,ij}^T - CO_{2,ij}^0}{\ln CO_{2,ij}^T - \ln CO_{2,ij}^0} ln\frac{PI^T}{PI^0} \quad (19)$$

$$\Delta CO_{2,P} = \sum_{ij} L\left(CO_{2,ij}^T, CO_{2,ij}^0\right) ln\frac{P^T}{P^0} = \sum_{ij} \frac{CO_{2,ij}^T - CO_{2,ij}^0}{\ln CO_{2,ij}^T - \ln CO_{2,ij}^0} ln\frac{P^T}{P^0} \quad (20)$$

The decomposition model is also developed for the freight transport, as shown in Eq. (21).

$$CO_{2,F} = \sum_{ij}\left(CO_{2,F}\right)_{ij} = \sum_{ij} \frac{(CO_{2,F})_{ij}}{E_{F,ij}} \times \frac{E_{F,ij}}{E_{F,i}} \times \frac{E_{F,i}}{E_F} \times \frac{E_F}{F} \times \frac{F}{G} \times G = \sum_{ij} EF_{F,ij} \times TS_{F,ij} \times ES_{F,i} \times EI_F \times FI \times G \quad (21)$$

where $CO_{2,F}$ represents the CO_2 emissions from freight transport; $E_{F,ij}$ represents the energy use of source *i* in mode *j* of freight transport; $E_{F,i}$ denotes the energy use of source *i* in this sector; E_F is the total energy use in freight transport; F refers to the total freight transport service (measured by million tonne miles/km); G is the national GDP; EF_F represents the emission factor; TS_F refers to the transport structure; ES_F represents the energy structure; EI_F represents energy intensity; and FI is the freight transport intensity, i.e., the freight transport distance per GDP. This calculation is similar to Eqs. (3)–(10). It should be noted that in the U.S., energy use for medium and heavy trucks are not separately counted, and so TS was only considered for the Australian freight transport sector.

Data related to transport activities including passenger transport and freight transport were collected from the Organisation for Economic Co-operation and Development (OECD) database (OECD, 2019a, b). The population and GDP data for the U.S. and Australia were retrieved from The World Bank (2020a, 2020b) respectively.

3.7 Chapter Summary

This chapter presented the research philosophy and research design of this study. The methods adopted for each research objective were also explained, specifically 1) the six-step method adopted for the critical literature review (Objective 1); 2) the hybrid LCA approach proposed for the estimation of GHG emissions from the use and M&R

phases of roads (Objective 2), which combines the PXC and tiered methods; 3) the conceptual framework developed to integrate sustainability indicators into traditional assessment network-level pavement maintenance plans (Objective 3), which considers road condition and economic, environmental, and social sustainability; and 4) the LMDI decomposition analysis adopted to analyse the factors influencing changes in CO_2 emissions in Australia and the U.S. (Objective 4). Justification for the selection of these different methods and for the data collection and analysis were also provided.

Chapter 4. Developing a Hybrid LCA Approach to Estimate Carbon Emissions from the Use and M&R Phases of Road Infrastructure (Objective 2)

The use and M&R phases of road infrastructure are important carbon emissions sources; however, their environmental impacts are rarely assessed in existing LCA studies. In addition, as Australian road agencies currently prefer road M&R over new construction, a structured LCA model is needed to accurately estimate the environmental impacts of the use and M&R phases to support decision-making. This formed the focus of Objective 2. The proposed approach was explained in Section 3.4, and this chapter presents the description and results of the case study for the proposed hybrid LCA approach for the M&R and use phases of a road network in WA. Section 4.1 gives a description of the case. Sections 4.2, 4.3, 4.4, and 4.5 present the four steps of a typical LCA study, namely, goal and scope definition, LCI, LCIA, and life cycle interpretation, respectively, and Section 4.6 summarises this chapter.

4.1 Case description

A road network in WA was taken as a case to demonstrate the proposed hybrid LCA approach. The road network consists of 17,764 road segments including medium-standard single carriageways (37.5%), heavy traffic roads in metropolitan areas (18.7%), high-standard single carriageways (16.2%), basic-standard single carriageways (14.7%), and freeways (12.9%). Among these road segments, most (> 70%) have granular pavements and less than 30% are paved with asphalt; very few (< 0.1%) are paved with concrete. As indicated in Table 4-1 and Table 4-2, the AADT in the network ranges from 41 to 91,390, and the percentage of heavy trucks ranges from 0% to 72.6%. As the road network includes roads of various classifications and characteristics, it was deemed a useful representative case study to demonstrate the implementation of the proposed approach.

Table 4-1: Annual average daily traffic (AADT) of the 17,764 road segments comprising the case study road network in WA

AADT	No. of road segments
41–100	422
100–500	5,602
500–1,000	3,745
1,000–5,000	2,624
5,000–10,000	1,393
10,000–50,000	3,794
50,000–91,390	184
Total	**17,764**

Table 4-2: Percentage of heavy trucks for the 17,764 road segments of the case study network in WA

Percentage of heavy trucks	No. of road segments
0–10	3,053
10–20	4,527
20–30	4,255
30–40	2,546
40–50	1,419
50–72.6	1,964
Total	**17,764**

4.2 Goal and Scope Definition

As the design parameters for the road segments differ and every road segment has its own serviceability (IRI) and deterioration features, FUs should be defined separately. The FU for a typical road segment was provided in Table 3-3. Because all the road segments are in normal use and only receive M&R rather than new construction, the layer and thickness specifically refer to the M&R work and not the entire road structure. In addition, due to data limitations, the analysis period was defined as 10 years, specifically 2017–2026, which is considered sufficient for demonstrating of the proposed approach (Hasan and You, 2015).

4.3 Life Cycle Inventory (LCI)

4.3.1 LCI for the M&R phase

The eight considered M&R strategies for the roads are presented in Table 4-3, among which GrOL and ASRS are rehabilitation strategies and others only require regular maintenance work. Based on the specific condition of a road segment, a most suitable strategy is triggered at a specific year within the next 10 years. The M&R program for each road segment is provided by MRWA. Table 4-3 presents the EIO results for each strategy, which were calculated based on the unit cost. Table 4-4 demonstrates the derivation of case-specific data, and Table 4-5 shows the unit carbon emissions for each M&R strategy by substituting specific nodes in the EIO model from the case specific data. The rehabilitation strategies (ASRS and GroL) yield the highest unit carbon emissions followed by the ASIM and RipSeal treatments. CS, which only requires operation on the surface of roads, has the lowest unit carbon emissions.

Table 4-3: Eight M&R strategies and their carbon emissions based on the EIO approach

M&R program	**Description (Wu et al., 2017)**	**Cost[1] (AUD/m^2)**	**EIO carbon emissions (kg/m^2)**
ASDG	Dense graded asphalt replacement (asphalt mixing plant, paver, and compactor) (30 mm)	52.07	27.746
ASIM	Intersection mix asphalt replacement (asphalt mixing plant, paver, and compactor) (40 mm)	60.00	31.971
ASOG	Open graded asphalt replacement (asphalt mixing plant, paver, and compactor) (30 mm)	48.00	25.577
ASRS	Full depth asphalt (major rehabilitation - replacing the top 150 mm and 5% of road to full depth. The rehabilitation takes place every 50 years)	138.00	73.534
CS	Surface Dressing: spraying a layer of bitumen on the road surface and laying one or more layers of aggregate	5.99	3.192
Slurry	Cold mixed surface treatments, including application of 3–20 mm in-situ mixture of aggregate, cement/lime, polymer modified bitumen emulsion, adhesive, and water	12.00	6.394
RipSeal	50 mm gravel replacement with cement stabilisation and seal	47.00	25.044
GrOL	Major rehabilitation replacing 150 mm of aggregates with cement stabilisation and seal	63.00	33.570

Note: [1] The unit cost varies for road segments located in different region and the table only list the values for region 1. Similarly, only corresponding carbon emissions is listed.

Table 4-4: Case-specific carbon emissions (CO_2-e) for the eight M&R programs

M&R programs	**Equipment fuel usage**	**Assumed thickness (m)**	**Fuel use (kL/m^2)**	**Fuel emission factors**	**Fuel emissions (kg/m^2)**	**Material use**				**Material emission factors**	**Material emissions (kg/m^2)**
						Bitumen (L/m^2)	**Crushed aggregate (m^3/m^2)**	**Gravel /sand (m^3/m^2)**	**Cement (kg/m^2)**		
ASDG	6.313 L/m^3 (World Bank, 2010)	0.03	0.00019	2.68 t CO_2-e/kL	0.508	3.6	0.03	0	0	Bitumen: 0.63 tCO_2-e/t; Crushed aggregate: 0.005 tCO_2-e/t; Gravel/sand: 0.003 tCO_2-e/t; Cement: 0.82 tCO_2-e/t;	2.56
ASIM	6.313 L/m^3 (World Bank, 2010)	0.04	0.00025	2.68 t CO_2-e/kL	0.677	4.8	0.04	0	0		3.41
ASOG	6.313 L/m^3 (World Bank, 2010)	0.03	0.00019	2.68 t CO_2-e/kL	0.508	3.6	0.03	0	0		2.56
ASRS	4.3 x 10^{-4} KL/m^2 (Diesel) (TAGG, 2013)	Not needed	0.00043	2.68 t CO_2-e/kL	1.152	12	0.1	0	0		8.52
CS	1.00 kg CO_2-e/m^2 (Spray et al., 2014)	Not needed	Not needed	Not needed	1	1.8	0.00143	0	0		1.15

M&R programs	Equipment fuel usage	Assumed thickness (m)	Fuel use (kL/m^2)	Fuel emission factors	Fuel emissions (kg/m^2)	Material use				Material emission factors	Material emissions (kg/m^2)
						Bitumen (L/m^2)	Crushed aggregate (m^3/m^2)	Gravel /sand (m^3/m^2)	Cement (kg/m^2)		
Slurry	2.87 kg CO_2-e/m^2 (Spray et al., 2014)	Not needed	Not needed	Not needed	2.87	1.92	0.02	0	0.064		1.45
RipSeal	0.31 L/m^3 (World Bank, 2010)	0.05	0.00002	2.68 t CO_2-e/kL	0.042	1.8	0.00143	0.05	4.95		5.54
GrOL	0.19 L/m^3 (World Bank, 2010)	0.15	0.00003	2.68 t CO_2-e/kL	0.076	1.8	0.00143	0.15	4.95		6.21

Note: Values of density used for bitumen, crushed aggregate, and gravel are 1 kg/L, 1.92 t/m^3, and 2.24 t/m^3, respectively.

Table 4-5: Unit carbon emissions (CO_2-e) for the eight M&R programs

M&R programs	**Total EIO carbon emissions[1] (kg/m^2)**	**Material emissions (EIO) [1] (kg/m^2)**	**Equipment emissions (EIO) [1] (kg/m^2)**	**Material emissions (case specific) (kg/m^2)**	**Equipment emissions (case specific) (kg/m^2)**	**Final results[1] (kg/m^2)**
ASDG	27.746	4.955	4.254	2.56	0.508	21.601
ASIM	31.971	5.709	4.902	3.41	0.677	25.445
ASOG	25.577	4.567	3.921	2.56	0.508	20.152
ASRS	73.534	13.131	11.274	8.52	1.152	58.802
CS	3.192	0.452	0.489	1.15	1.000	4.399
Slurry	6.394	1.142	0.980	1.45	2.870	8.596
RipSeal	25.044	4.472	3.840	5.54	0.042	22.316
GrOL	33.570	5.995	5.147	6.21	0.076	28.720

Note: [1]Only for region 1. The same calculation was extrapolated to the entire road network.

4.3.2 LCI for the use phase

The LCI for the use phase was compiled using Eqs. (5) and (6). Excluding upstream carbon emissions, the estimated carbon emissions of one car and one truck are 103.471 and 262.801 gCO_2-e/km, respectively. These results are similar to the findings of Riemersma and Mock (2012), who reported the carbon emissions of one car weighing 1,400 kg to be 102.5 gCO_2-e/km. This indicates that the uncertainties arising due to the use of different models when calculating the carbon emissions of RR are relatively low. When upstream emissions are considered, the whole lifecycle carbon emissions due to RR for one car and one truck increase to 413.766 and 978.498 g CO_2-e/km, respectively. Such differences between methods have also been reported by Jiang et al. (2014), indicating that the cut-off error of a process-based approach can be significant.

4.4 Life Cycle Impact Assessment (LCIA)

Table 4-6 presents the temporal distribution of the average GWP of the road network. The use phase has a much higher GWP than the M&R phase during the operation of roads, accounting for an average of 99.2% during the 10-year study period. In addition, the average yearly increase in GWP from 2017 to 2026 is 2.03%, which is almost the same as the traffic growth rate (2%).

Table 4-6: Temporal distribution of the average network GWP (t CO_2-e/km) of the case study road

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Use phase	466.4	475.9	485.5	495.4	505.4	515.7	526.1	536.8	547.7	558.9
M&R phase	1.4	1.4	1.5	1.5	1.6	1.7	1.7	1.6	1.7	30.6
Total	467.8	477.3	487.1	496.9	507.0	517.4	527.9	538.5	549.4	589.5

4.5 Life Cycle Interpretation

Based on the LCIA results, the GWP of the use phase dominates the service life of the studied road network. This may indicate that road agencies should pay more attention to management of the use phase (e.g., AADT, speed limit, IRI, and MPD) than M&R strategy decisions. A further sensitivity analysis also shows that an increase in the AADT by 10% results in a 9.92% increase in GWP, indicating the importance of controlling AADT. Detailed results for the sensitivity analysis are presented in Table 4-7.

Table 4-7: Sensitivity analysis results for the case study road

Year	Scenario 1 (AADT +/-10%)	Scenario 2 (Spd_Lmt +/-10%)	Scenario 3 (IRI +/-10%)	Scenario 4 (MPD +/-10%)
2017	+/- 9.97%	0.61%, -0.64%	+/- 0.35%	+/- 0.48%
2018	+/- 9.97%	0.61%, -0.64%	+/- 0.35%	+/- 0.48%
2019	+/- 9.97%	0.62%, -0.64%	+/- 0.35%	+/- 0.48%
2020	+/- 9.97%	0.62%, -0.64%	+/- 0.36%	+/- 0.48%
2021	+/- 9.97%	0.62%, -0.65%	+/- 0.36%	+/- 0.48%
2022	+/- 9.97%	0.62%, -0.65%	+/- 0.36%	+/- 0.48%
2023	+/- 9.97%	0.63%, -0.65%	+/- 0.36%	+/- 0.48%
2024	+/- 9.97%	0.63%, -0.65%	+/- 0.37%	+/- 0.48%
2025	+/- 9.97%	0.63%, -0.66%	+/- 0.37%	+/- 0.48%
2026	+/- 9.48%	0.60%, -0.63%	+/- 0.35%	+/- 0.45%
Average	+/- 9.92%	+0.62%, -0.64%	+/- 0.36%	+/- 0.48%

ArcMap was used to visualise the spatial pattern of the calculated emissions across the road network in WA year by year. As the distributions in each year are similar, Figure 4-1 presents data for 2019 as a typical year. This map indicates that the heavy traffic roads in metropolitan areas and freeways (with AADTs > 20,000) are consistently the most carbon intensive.

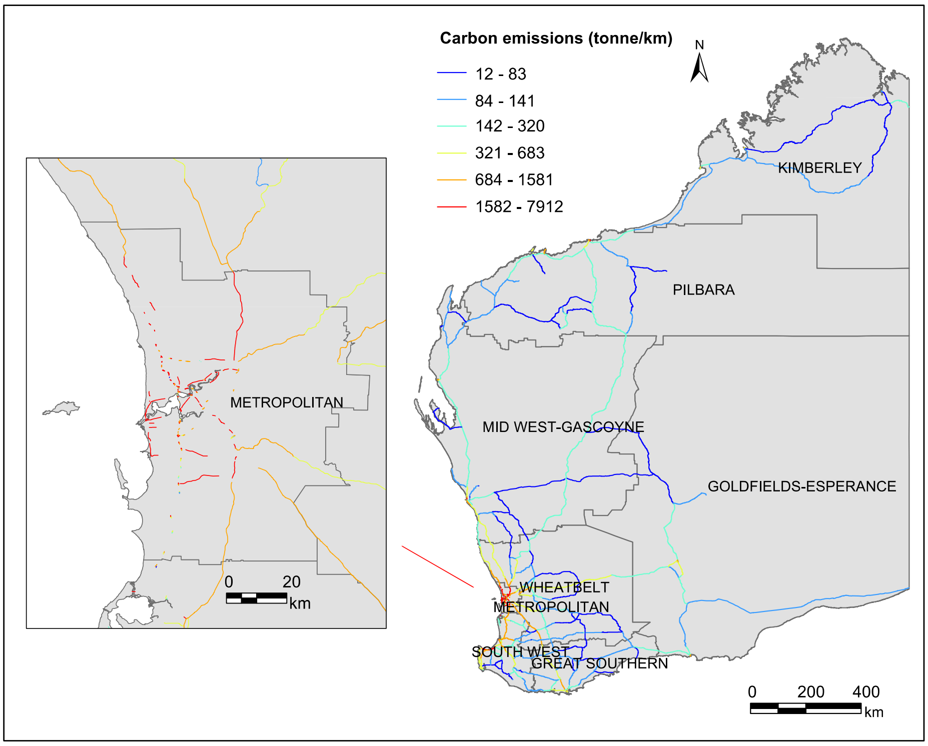

Figure 4-1: Estimated GWP across the case study road network in Western Australia in 2019

As unleaded petrol and diesel are the most frequently used fuel types for cars and trucks in Australia, their emissions factors were applied here (RAC Australia, 2016); however, other types of fuel, such as automotive LPG, are also increasingly used. A sensitivity analysis was, therefore, conducted. Under an extreme case assuming all cars use LPG, GWP varied by -6.02%. Given that variations in results within 10% are not regarded as significant (Huang et al., 2009), these estimates suggest that the impact of using a general emissions factor for different fuel types is insignificant.

4.6 Chapter Summary

This chapter used a case study road network in WA to demonstrate the structured hybrid LCA approach for evaluating the GHG emissions from the use and M&R phases of roads following the four-step LCA proposed in ISO 14044 (2006). The results estimate that from 2017 to 2026, the GWP of the use and M&R phases increased from 467.8 to 589.5 tCO_2-e/km. The use phase has a much higher GWP than the M&R phase during the service life of the road network, accounting for 99.2% of total GWP during the study period. A sensitivity analysis also indicated that these results are most sensitive to changes in AADT. In addition, road segments with heavy traffic volumes in metropolitan areas and freeways with AADTs > 20,000 were identified as the most carbon intensive.

Chapter 5. A Multi-attribute Decision-Making Framework to Evaluate and Select Optimal Network-level Pavement Maintenance Plans (Objective 3)

Based on the literature review, existing research is subject to the following limitations: 1) few indicators beyond agency costs and road conditions are considered, meaning that environmental and social sustainability are often overlooked; 2) single road segments, instead of entire road network, are often investigated, which limits network-level decision-making; and 3) previous multi-attribute methods often rely on pre-determined importance levels for each indicator. However, road agencies may not always have an exact weighting to apply to each attribute, limiting the usability of the developed methods. As the selection of pavement maintenance plans can have long-term influences on the performance of road network, it is imperative that decision-making by road agencies is switched from cost-oriented to sustainability-oriented if sustainable development is be achieved. The evaluation and selection of network-level pavement maintenance plans must, therefore, be amended from a cost-based approach to one focussed on achieving maximum sustainable benefits during road use and M&R phases.

Objective 3 sought to examine how sustainability indicators can be integrated into traditional pavement maintenance evaluations and decision-making frameworks. For this, the hybrid LCA approach proposed in Objective 2 was embodied in the proposed framework, as explained in Section 3.5. This chapter demonstrates the usefulness of the proposed multi-attribute decision-making framework for evaluating and selecting the optimal network-level pavement maintenance plan through case study road network. Sections 5.1 describes the selected case. Sections 5.2, 5.3, 5.4, and 5.5 present the respective results of the four attributes considered in the proposed framework, namely road condition, agency costs, GHG emissions, and road-user costs; Section 5.6

combines the results of the four attributes into a single index using the WSM approach; and Section 5.7 summarises this chapter.

5.1 Case description

The case study road network consists of 16,539 road segments in WA, which extend 17,299.28 km. Most of the road segments (71.9%) have a granular surface and 28.1% have asphalt pavements. Medium standard single carriageways are the most common road classification, accounting for 39.1% followed by heavy traffic roads (generally in metropolitan areas; 18.9%); high standard and basic standard single carriageways account for 16.5% and 14.0%, respectively; and other types including freeways account for 11.5%. Among these road segments, 88.8% have two lanes. The lane width of the entire network ranges from 3.4 to 42.5 m, with an average of 9.2 ± 2.6 m. The average initial IRI of the network is 2.6104 ± 0.7460, ranging from 0.3333 to 8.2200. The AADT of the network in the first year of the analysis period (2017–2026) ranges from 43 to 101,259 with an average of 6,534 vehicles per day. The annual traffic growth rate was assumed to be 2%. In addition, over half of the road segments have limited vehicle speeds to within 110 km/h, and the average percentage of heavy truck use is 25.7%.

Eight M&R strategies were considered for each road segment, as shown in Table 5-1. The definitions of these strategies were obtained from MRWA. Of these, the structural rehabilitation strategy for asphalt pavements (ASRS) and granular overlay (GrOL) are higher-cost rehabilitation strategies but perform better at improving the IRI of pavements. The other strategies require only regular maintenance but the resulting improvements in road condition are relatively limited. One or none of the eight M&R strategies are triggered for each road segment of the studied road network each year, depending on their particular condition and the allocated maintenance budget of the entire network. The following eight network-level maintenance scenarios under different budget are considered by MRWA: 1) AUD 50 million (50M); 2) AUD 60 million (60M); 3) AUD 70 million (70M); 4) AUD 85 million (85M); 5) AUD 95 million (95M); 6) AUD 105 million (105M); 7) AUD 115 million (115M); and 8) AUD 125 million (125M). These values correspond to a rough value related to the yearly routine maintenance budget. The 50M budget scenario is demonstrated as an example on https://ars.els-cdn.com/content/image/1-s2.0-S1361920921002182-mmc1.xlsx, specifying when, where, and what M&R strategy to apply in a road network under a certain budget scenario. The algorithm behind the allocation is explained in (Li, 2018). Typically, rehabilitation strategies are more frequently triggered under a scenario with higher budget. When the maintenance budget is insufficient, non-rehabilitation strategies are triggered until road condition deteriorates to a certain standard.

Table 5-1: Eight maintenance and rehabilitation (M&R) strategies considered in the case study demonstration

M&R program	**Description**
ASDG	Dense graded asphalt replacement (asphalt mixing plant, paver, and compactor) (30 mm)
ASIM	Intersection mix asphalt replacement (asphalt mixing plant, paver, and compactor) (40 mm)
ASOG	Open graded asphalt replacement (asphalt-mixing plant, paver, and compactor) (30 mm)
ASRS	Full-depth asphalt (major rehabilitation - replacing the top 150 mm and 5% of road to full depth. The rehabilitation takes place every 50 years)
CS	Surface dressing: spraying a layer of bitumen on the road surface and laying one or more layers of aggregate
Slurry	Cold-mixed surface treatments including application of a 3–20 mm in-situ mixture of aggregate, cement/lime, polymer modified bitumen emulsion, adhesive, and water
RipSeal	50 mm gravel replacement with cement stabilisation and seal
GrOL	Major rehabilitation replacing 150 mm of aggregates with cement stabilisation and seal

(Reference: Wu et al., 2017).

The eight network-level pavement maintenance plans under the different budget scenarios were provided by MRWA. All other data sources are summarised in Table 5-2.

Table 5-2: Data demands and sources for the four attributes considered in the case study demonstration

Attributes		Data demands	Data sources
Road condition		IRI of each road segment, pavement length	MRWA, predicted by dTIMS V9 of Deighton (Li, 2018)
Economic performance (agency costs)		Unit rate of each M&R strategy, treated area	MRWA (refer to Appendix E for raw data)
Environmental performance (greenhouse gas emissions)	PXC model	Direct requirement coefficients matrix	Australian National Accounts (ABS, 2018)
		Australian greenhouse gas inventory	Australian Government (2019)
		Output of each economic sector	IBISWorld (2019)
		Material and equipment use for each maintenance strategy	MRWA
	Tiered hybrid model	Queue speed	Assumed to be 8 km/h
		Queue length	Calculated through obtained data
		Work zone	Department of Infrastructure (2015)
		Detour speed, detour distance	60 km/h (Santos et al., 2015b), 10 km (Chen et al., 2016)
		Fuel efficiency at a specific speed	Oak Ridge National Laboratory (2019)
		Road and traffic information (e.g., IRI, pavement length, MPD, AADT, traffic composition, and speed limit)	MRWA
		Emissions factors	TAGG (2013)

Attributes		Data demands	Data sources
Social performance (road-user costs)	Travel delay cost	Travel delay time	Calculated through obtained data
		Value of time (value per occupant × occupancy rate)	Cars (\$/veh-hour): (37.46 × 5/7 + 14.99 × 2/7) × 1.245; trucks (\$/veh-hour): 16.81 × 1.0 (Transport and Infrastructure Council, 2016)
	VOC	Fuel price	Car fuel: 1.470 \$/L; truck fuel: 1.596 \$/L (Transport and Infrastructure Council, 2016)
		Parameters for vehicle repair and maintenance	Cars: 6.3 cents/km; trucks: 14.0 cents/km (Transport and Infrastructure Council, 2016)
		Tire wear parameters	Cars: 492 \$/set of tires; trucks: 6,618 \$/set of tires. Assuming each set of tires can last 40,000 km (Transport and Infrastructure Council, 2016)

5.2 Road Condition

Figure 5-1 presents the yearly average IRI of the case study network. All maintenance budget scenarios have the same initial IRI, then, over time, the pavements deteriorate and the IRI increases. The rate of increase varies for different maintenance scenarios, however; the IRI increases much more slowly when maintenance budgets are higher, reflecting that more road segments will benefit from M&R when more funds are available. For example, an average of 6.76% of road segments are maintained under the 50M scenario, increasing to 7.13% in the 125M scenario.

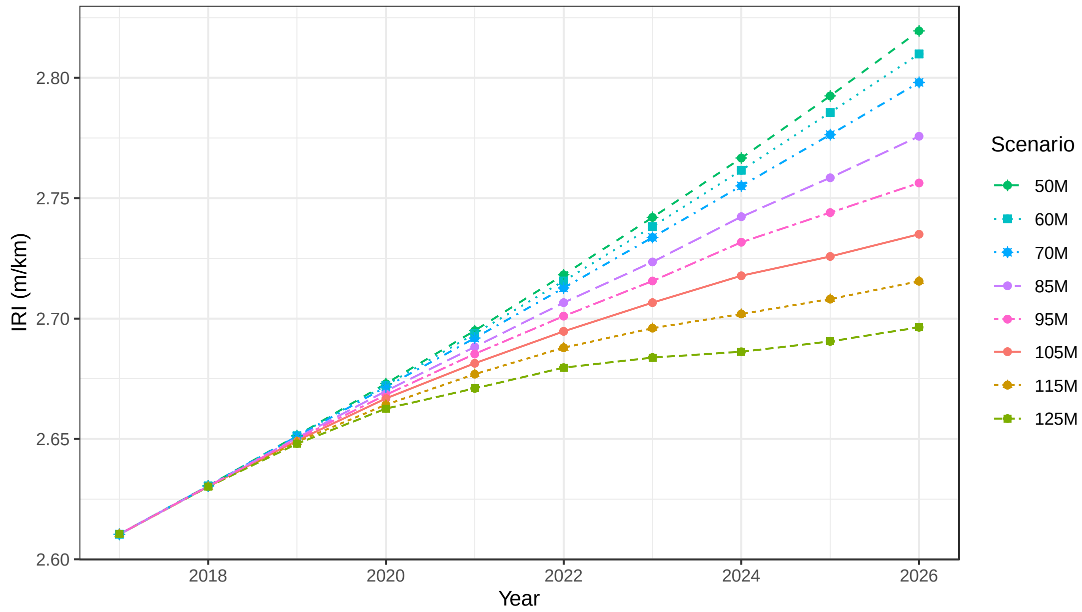

Figure 5-1: Network average international roughness index (IRI) projections based on eight maintenance budget scenarios for the case study network in Western Australia

5.3 Agency Costs

The annual agency costs for each maintenance budget scenario are presented in Table 5-3. The total costs for the network-level M&R during 2017–2026 are equivalent to AUD 946.417–1,036.660 million depending on the budget. Interestingly, the equivalent annual costs of all options are above AUD 115 million. Specifically, in 2026, the agency costs increase sharply under scenarios 50M, 60M, and 70M. The lower the budget, the shaper the increase. This is because of the relatively low annual routine maintenance budget in earlier years, and more rehabilitation work is needed in 2026.

To this end, a further analysis of the percentages of road segments that receive M&R each year was conducted. Under the 50M, 60M, and 70M scenarios, road segments receiving M&R account for an average of 5.2%, 5.8%, and 6.4%, respectively, from 2017 to 2025, and 21%, 15.5%, and 11.3%, respectively, in 2026. Specifically, under these three scenarios, an average of 2.0%, 1.9%, and 2.2% of segments receive rehabilitation work in 2017–2025, while 8.5%, 8.6%, and 9.6% receive rehabilitation in 2026. It should be noted that under the 85M, 95M, and 105M scenarios, the percentages of road segments receiving M&R in 2017–2026 changes very little, while the percentages of segments receiving rehabilitation in 2026 are significantly higher, increasing from 2.3% to 9.3%, 2.6% to 7.7%, and 2.8% to 5.3%, respectively. For the 115M and 125M scenarios, a large amount of maintenance happens every year across the 10-year projection period, without any sharp increase in 2026. The NAV per km for the eight budget scenarios is also shown in Figure 5-2, showing that the 85M scenario results in the lowest agency costs (NAV = AUD 6,745.06/km). Interestingly, the 50M scenario is most expensive in the long run, with an annual cost equivalent to AUD 7,388.22/km.

Table 5-3: Agency costs (AUD million) for the eight network-level pavement maintenance budget scenarios

Scenario	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	NPV	NAV
50M	53.228	52.261	50.929	50.465	48.596	50.750	46.218	45.921	46.537	928.784	1,036.660	127.811
60M	63.777	61.593	59.861	60.291	58.310	60.028	56.144	57.044	54.152	793.472	1,015.898	125.251
70M	73.701	71.596	68.836	71.191	67.383	69.079	67.350	64.551	61.567	651.974	989.188	121.958
85M	89.984	84.499	85.614	81.994	84.830	82.700	81.702	80.108	77.120	428.208	946.417	116.685
95M	100.058	94.065	94.577	93.474	91.296	98.122	93.867	87.886	84.574	324.184	950.270	117.160
105M	109.475	105.712	103.415	101.388	105.275	106.966	100.422	92.855	93.479	244.045	964.470	118.910
115M	119.631	116.607	108.992	113.313	115.090	115.025	106.497	100.317	100.825	190.541	994.121	122.566
125M	129.218	126.042	119.883	123.185	123.338	121.320	105.541	108.146	109.776	134.751	1,016.387	125.311

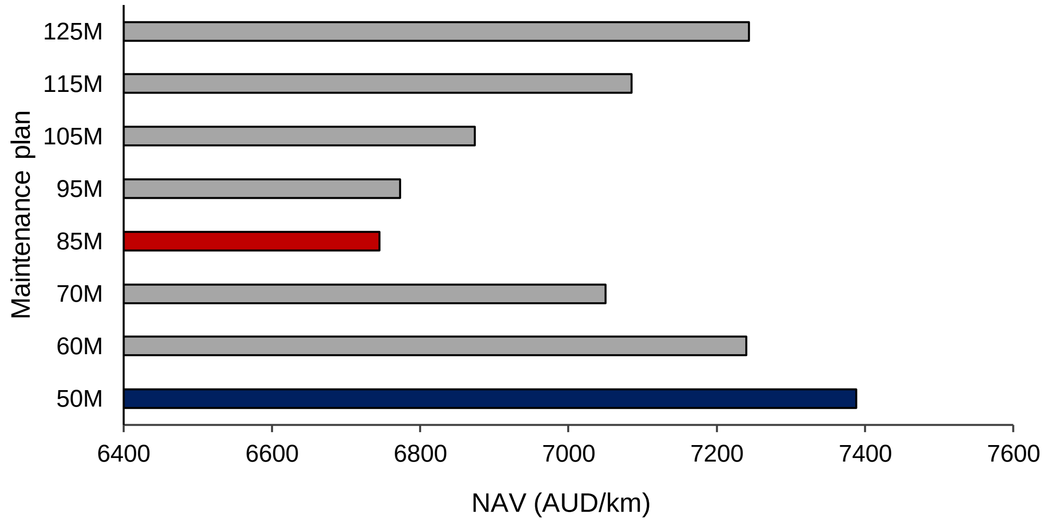

Figure 5-2: Unit agency costs of the eight maintenance budget scenarios for the case study network in Western Australia

Note: red and blue bars represent the lowest and highest values, respectively.

5.4 Greenhouse Gas Emissions

The results of the network emissions calculations under the eight maintenance budget scenarios are presented in Table 5-4. An average of 8.9900 million tCO_2-e emissions are projected per year. The use phase has a dominant role, contributing an average of 99.2% of the total emissions irrespective of the budget scenario. A sensitivity analysis was also conducted to examine the influences of AADT, IRI, MPD, and speed limit on emissions during the use phase. This shows that changes in the AADT explain up to 99.9% of the variations in emissions, significantly outweighing the other factors. In addition, the average GHG emissions from the entire road network increases slightly every year for all maintenance budget scenarios, which likely reflects the assumed annual growth in the AADT.

Compared to the use phase, the projected emissions contributions of the maintenance phase are negligible, especially during the first nine years. During the period 2017–2025, the average emissions contribution from the maintenance phase under scenario 50M is 0.30%, gradually increasing to 0.78% under scenario 125M. In contrast, in 2026, the maintenance phase accounts for an estimated 5.07% of the total GHG emissions under scenario 50M compared to just 0.76% under scenario 125M. This finding is similar to that reported for agency costs. In other words, by 2026, network-level maintenance plans with lower budgets generate higher emissions due to the high number of maintenance activities and high percentage of rehabilitation programs.

Table 5-4: GHG emissions (million tCO_2-e) of the case study network under the eight maintenance budget scenarios

Scenario	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	Average
50M	8.165	8.331	8.500	8.671	8.847	9.030	9.211	9.396	9.588	10.274	9.0013
60M	8.170	8.336	8.505	8.679	8.854	9.037	9.218	9.404	9.590	10.196	8.9989
70M	8.174	8.342	8.512	8.686	8.861	9.043	9.227	9.410	9.594	10.110	8.9960
85M	8.182	8.350	8.524	8.696	8.872	9.053	9.235	9.419	9.603	9.980	8.9914
95M	8.187	8.357	8.530	8.703	8.877	9.062	9.245	9.421	9.604	9.918	8.9904
105M	8.192	8.365	8.538	8.708	8.885	9.068	9.246	9.419	9.606	9.874	8.9900
115M	8.197	8.372	8.543	8.714	8.891	9.069	9.245	9.420	9.609	9.846	8.9906
125M	8.202	8.380	8.549	8.720	8.894	9.071	9.240	9.423	9.612	9.818	8.9909

Figure 5-3 shows the distribution of unit GHG emissions under the eight maintenance plans. Notably, the unit GHG emissions values of scenarios 85M–125M are very similar, varying from 519.68 t CO_2-e/km (105M) to 519.76 t CO_2-e/km (85M). Scenarios 50M, 60M, and 70M have much higher unit GHG emissions, with the 50M scenario being highest at 520.33 t CO_2-e/km. The similarity in the results likely reflects the fact that the network IRI values do not vary much between the different maintenance budget scenarios. The percentage of road segments receiving maintenance treatments is low irrespective of the budget scenario, at an average of approximately 7% each year.

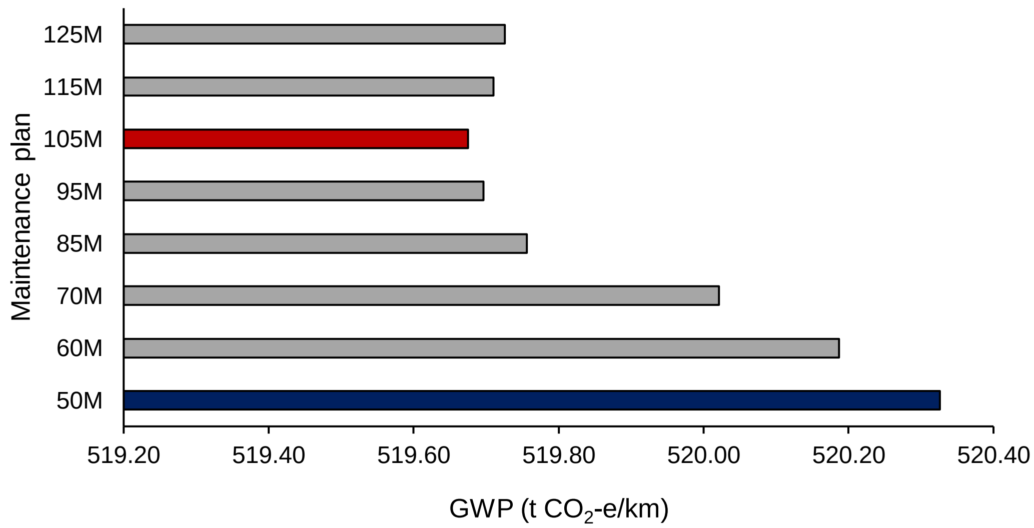

Figure 5-3: Unit GHG emissions of the eight maintenance budget scenarios for the case study network in Western Australia

Note: red and blue bars represent the lowest and highest values, respectively.

5.5 Road-User Costs

Table 5-5 shows the road-user costs for the eight maintenance budget scenarios, which estimate that road users would incur costs of AUD 28.205–28.257 billion across the entire case study network between 2017 and 2026. That is, an equivalent of AUD 3,477.369–3,483.875 million of road-user costs are incurred annually due to travel delays and vehicle operation costs (i.e., fuel use, repair and maintenance of vehicles, and tire wear). This is more than 27-times the estimated agency costs for the same period. Fuel costs are the most significant contributor to the total social costs, accounting for approximately 43.1%; repair and maintenance costs and tire wear costs also contribute approximately 38.7% and 18.2%, respectively. In contrast, travel delay costs contribute less than 0.1% of total social costs due to the limited duration of maintenance works compared to the continuous operative of vehicles in any particular year.

A constant increase in road-user costs between 2017 and 2026 is projected under all maintenance budget scenarios, at a rate between 2.00% and 2.06% (average = 2.03%). As the contribution of travel delay costs is negligible, this could be impacted by the AADT and the IRI, which tend to increase over time. To identify which of the factors is most important, the user cost per vehicle per km travelled was calculated so that only the IRI has an impact. As shown in Table 5-6, each vehicle travelling 1 km costs approximately AUD 89 per year and the highest average annual rate of increase among all the maintenance budget scenarios is 0.13%, which is significantly lower than 2.03%. This indicates that the AADT has a more significant impact on the road-user costs of the entire network. Furthermore, road-user costs (both network NAV and NAV per vehicle per km) slowly decrease as maintenance budgets increase from 50M to 125M, probably because the IRI of pavements is improved under higher budget.

Table 5-5: Road-user costs (AUD Million) of the entire case study network under the eight maintenance budget scenarios

Scenario	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	NPV	NAV
50M	3,072.68	3,135.30	3,199.28	3,264.17	3,331.23	3,399.02	3,469.37	3,541.57	3,615.17	3,692.29	28,257.35	3,483.88
60M	3,072.90	3,135.28	3,199.01	3,263.53	3,330.35	3,398.12	3,468.56	3,540.67	3,614.36	3,690.32	28,251.95	3,483.21
70M	3,073.06	3,135.28	3,198.61	3,263.12	3,329.59	3,397.62	3,467.49	3,539.37	3,613.06	3,688.12	28,245.98	3,482.47
85M	3,073.33	3,135.19	3,197.94	3,262.47	3,328.71	3,396.13	3,465.57	3,537.28	3,610.78	3,684.70	28,235.80	3,481.22
95M	3,073.55	3,135.06	3,197.71	3,261.95	3,328.05	3,395.12	3,464.66	3,536.01	3,609.12	3,682.02	28,229.06	3,480.39
105M	3,073.68	3,135.02	3,197.34	3,261.71	3,327.30	3,394.16	3,463.28	3,534.08	3,606.70	3,679.07	28,220.77	3,479.37
115M	3,073.83	3,134.90	3,197.15	3,261.06	3,326.51	3,393.26	3,461.75	3,532.14	3,604.08	3,676.33	28,212.11	3,478.30
125M	3,073.95	3,134.69	3,196.97	3,260.70	3,325.64	3,391.98	3,460.20	3,530.58	3,602.25	3,674.30	28,204.58	3,477.37

Table 5-6: Annual road-user costs (AUD) per vehicle per km of the eight maintenance budget scenarios

Scenario	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	NAV
50M	85.498	85.581	85.670	85.757	85.853	85.947	86.068	86.189	86.329	86.541	89.344
60M	85.498	85.582	85.670	85.755	85.847	85.935	86.042	86.158	86.288	86.478	89.328
70M	85.499	85.582	85.670	85.752	85.838	85.922	86.020	86.120	86.238	86.398	89.308
85M	85.500	85.583	85.669	85.745	85.819	85.887	85.965	86.047	86.137	86.239	89.267
95M	85.500	85.584	85.667	85.738	85.807	85.858	85.923	85.985	86.044	86.108	89.232
105M	85.500	85.585	85.665	85.730	85.784	85.815	85.850	85.886	85.900	85.922	89.179
115M	85.501	85.586	85.663	85.714	85.757	85.771	85.786	85.775	85.766	85.787	89.129
125M	85.502	85.586	85.661	85.705	85.711	85.713	85.691	85.651	85.639	85.645	89.073

5.6 Multi-attribute Decision-Making

As the 50M scenario has the highest value for each of the four attributes, this was rescaled to have the maximum value of 1. The other scenarios were rescaled following Eq. (5a) and weighted sum values obtained using Eq. (5b). The rescaled and WSM results with equal weights for the eight maintenance budget scenarios are shown in Table 5-7, in which lower values indicate better performance. The rescaled values for road condition and economic, environmental, and social considerations range from 0.9837 to 1, 0.9129 to 1, 0.9987 to 1, and 0.9970 to 1, respectively. These ranges reflect the fact that the variation in economic performance between the eight scenarios is much higher than that of the other attributes. In addition, it can be inferred that those scenarios with high economic performance (i.e., low economic values) are more likely to generate low WSM values.

Table 5-7: Rescaled and WSM results for the eight maintenance budget scenarios

Scenario	Road roughness	Economic costs	Environmental impact	Social costs	Weighted sum
50M	1.0000	1.0000	1.0000	1.0000	1.0000
60M	0.9989	0.9800	0.9997	0.9998	0.9946
70M	0.9975	0.9542	0.9994	0.9996	0.9877
85M	0.9947	0.9129	0.9989	0.9991	0.9764
95M	0.9924	0.9167	0.9988	0.9987	0.9766
105M	0.9896	0.9304	0.9987	0.9981	0.9792
115M	0.9867	0.9590	0.9988	0.9976	0.9855
125M	0.9837	0.9804	0.9988	0.9970	0.9900

To provide a more intuitive comparison of the various maintenance budget scenarios, Figure 5-4 presents the WSM results, in which the 85M scenario is the optimal scenario based on having the lowest WSM value.

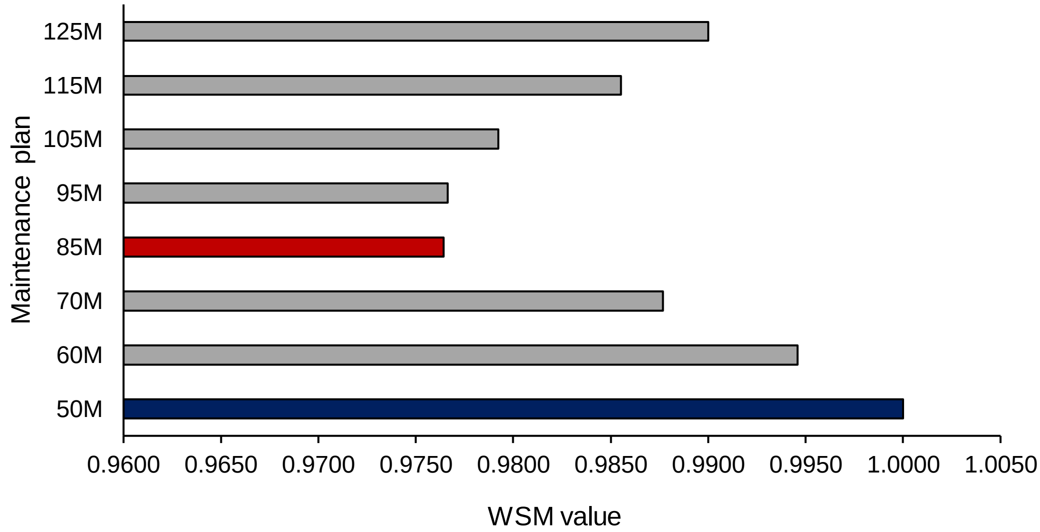

Figure 5-4: WSM results for the eight maintenance budget scenarios for the case study network in Western Australia

Note: red and blue bars represent the lowest and highest values, respectively.

The results for the 1,000 random runs are presented in Figure 5-5. Notably, scenarios 85M, 95M, 125M, and 105M yield relatively low WSM results. Among the 1,000 random runs, the 85M scenario was selected as the optimal option 596 times (59.6%), and the 95M, 125M, and 105M scenarios were optimal in 26.6%, 7.7%, and 6.1% of the runs, respectively. Although the 125M scenario yields relatively high WSM values in the 1,000 runs, this can be the optimal option under certain conditions, such as when the maintenance budget is sufficient and the economic aspects are given a very low weighting (e.g., < 6%).

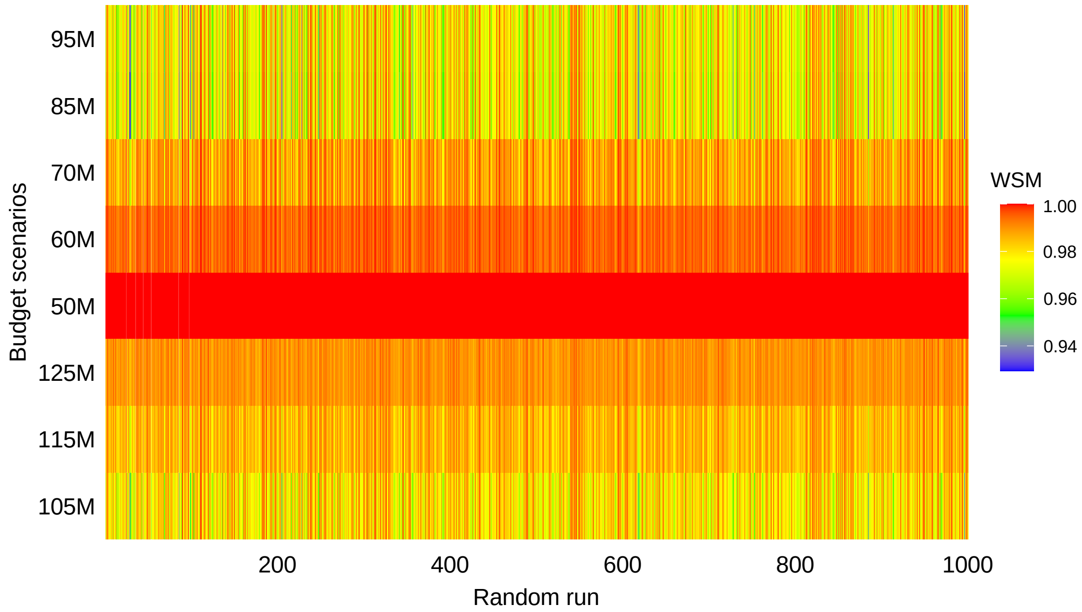

Figure 5-5: WSM results for the 1,000 random runs

Finally, Figure 5-6 shows the relationships between the four potential optimal scenarios and the allocated weights of the four attributes, in which darker circles indicate that a scenario is more frequently selected. Based on this, the optimal results are sensitive to the weights of economic considerations. For example, when the weighting is extremely low (e.g., < 2%), only scenario 125M will be selected, whereas scenario 85M will not be selected until the weighting is higher than 8%. In addition, when economic considerations account for 27% of the overall weight, the 85M scenario is selected more than 99% of the time. Furthermore, when the weighting of road condition is higher than 50%, scenario 85M is unlikely to be selected as the optimal budget scenario.

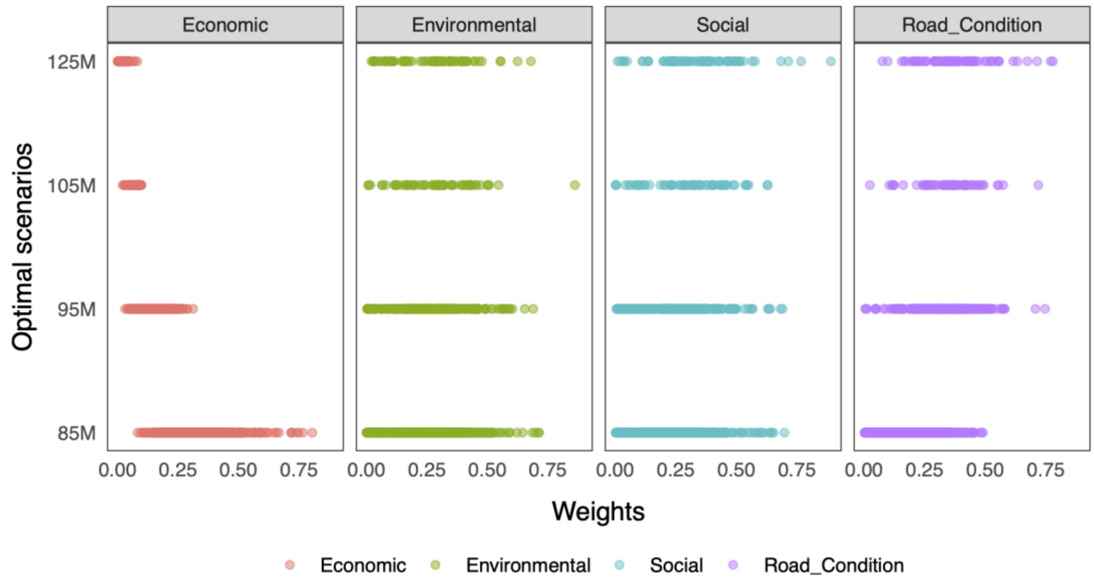

Figure 5-6: Relationships between optimal maintenance scenarios and the weights of the four attributes (darker circles indicate that a scenario is more frequently selected)

5.7 Chapter Summary

This chapter demonstrates the framework developed to help evaluate and select the optimal network-level pavement maintenance plan based on a case study road network in WA. Eight network-level pavement maintenance scenarios with various annual budgets of AUD 50, 60, 70, 85, 95, 105, 115, and 125 million were used for the demonstration. Specifically, the IRI, agency costs, GHG emissions, and road-user costs were evaluated for each scenario. The results show that road conditions and social performance improve as maintenance budgets increase. A similar pattern was not observed for economic nor environmental performance. To combine the four attributes and enable comparability between different network-level pavement maintenance plans, a multi-attribute decision making method was adopted to convert the results to one single index. When equal weighting was given to the four attributes, the 85M scenario was selected as the optimal maintenance plan for the studied network. By assigning different weights for the four attributes, the 85M, 95M, 125M, and 105M scenarios are also identified as potential optimal solutions.

Chapter 6. Evaluation and Decomposition Analysis of Carbon Emissions in the U.S. and Australian Road Transport Sectors (Objective 4)

This chapter presents the results of Objective 4—the evaluation and decomposition analysis of changes in carbon emissions from the Australian road transport sector. CO_2 emissions are exclusively investigated due to data accessibility and their high proportion of GHGs. The U.S. road transport sector was also investigated as a comparison and to provide broadly applicable information that can apply to other countries with similar characteristics. The U.S. is selected because of four reasons. First, the U.S. is one of the leading countries in cutting carbon emissions while still growing its economy (Aden, 2016). Second, the U.S. and Australia share a similar carbon emissions reduction target, both aiming to reduce carbon emissions by 26%-28% relative to 2005 levels, by 2025 and 2030, respectively (Jiang et al., 2020; Shahiduzzaman and Layton, 2015). Third, it has similar characteristics to Australia, such as its federal system of government which may influence policy implementation, developed economy, and the distribution of cities and populations (i.e., densely populated cities in the east and less populated cities in the west), which may affect transport intensity (Ribeiro et al., 2019). In addition, state-level data for the U.S. are easy to access. The results for the evaluation and decomposition analysis of carbon emissions are presented in Sections 6.1 and 6.2 respectively, and Section 6.3 summarises this chapter.

6.1 CO_2 Emissions from the U.S. and Australian Road Transport Sectors

6.1.1 CO_2 emissions from the U.S. road passenger transport sector

Figure 6-1 shows the annual CO_2 emissions from the U.S. road transport sector from 2008 to 2017. The annual CO_2 emissions slightly grow from 1.55 billion tonnes in 2008 to 1.57 billion tonnes in 2017. This is consistent with reports on GHG emissions from the U.S. transport sector including U.S. Environmental Protection Agency (2019). Based on these data, road transport, representing 82% of the transport sector's total emissions (U.S. Environmental Protection Agency, 2020), presents a significant challenge for achieving the U.S. 26–28% emissions reduction target.

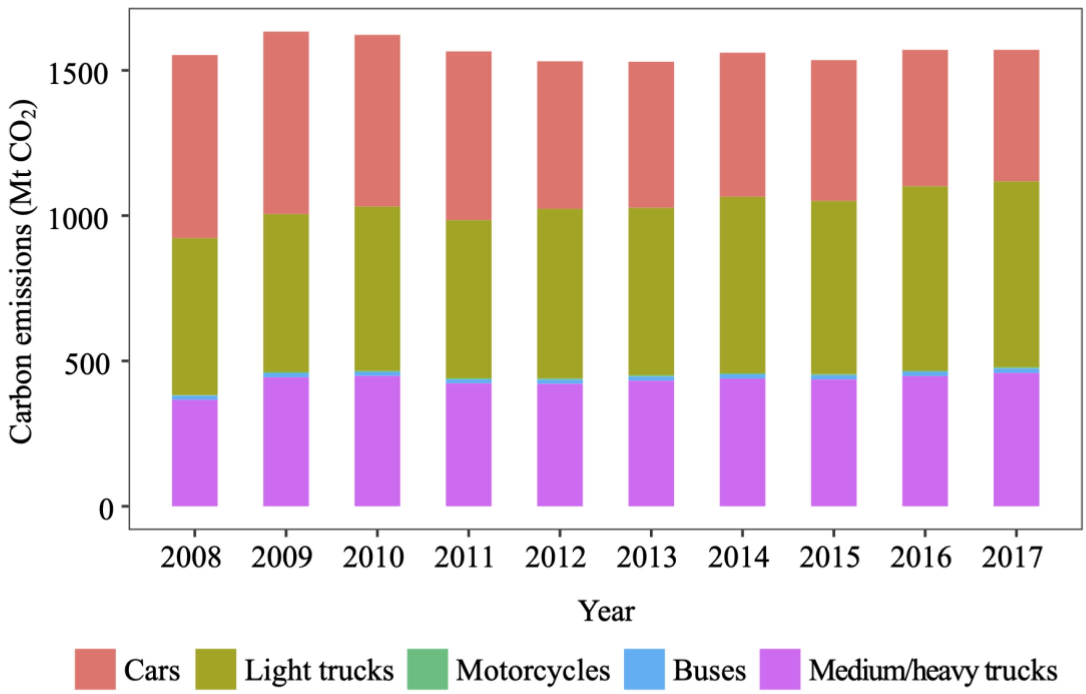

Figure 6-1: CO_2 emissions from the U.S. road transport sector (2008–2017)

Figure 6-1 also highlights the three most important sources of CO_2 emissions, namely cars, light trucks, and medium/heavy trucks. The contribution of light trucks (often used for passenger transport) and medium/heavy trucks (for freight transport) increased gradually over the analysis period, with average contributions of 37.2% and 27.6%, respectively. In contrast, the contribution from cars decreased from 40.6% in 2008 to 28.8% in 2017.

The emissions share of passenger transport (cars, light trucks, motorcycles, and buses) and freight transport in the road transport sector was relatively stable during the study period, at an average of 72.5% and 27.5%, respectively. While the annual CO_2 emissions value from passenger transport slightly decreased, a general increasing trend in freight transport emissions occurred. The annual CO_2 emissions value of medium/heavy trucks increased from 0.37 billion tonnes in 2008 to 0.46 billion tonnes in 2017—a 24.3% increase. It should also be noted that in 2009, there was a sharp increase in carbon emissions from the freight transport sector, and was year with the highest carbon emissions during the 10-year analysis period.

Figure 6-2 shows the annual CO_2 emissions from the U.S. road passenger transport sector from 2008 to 2017, which reduced from 1.19 billion tonnes to 1.11 billion tonnes—a 6.7% decrease. The two most important sources of CO_2 emissions were cars and light trucks. The contribution from cars decreased every year from 53.08% in 2008 to 40.71% in 2017, while the contribution from light trucks increased from 45.53% in 2008 to 57.52% in 2017. The contribution from motorcycles and buses was negligible. In addition, a general increase trend was identified for light trucks, motorcycles, and buses. Thus, the overall decrease in CO_2 emissions from this sector is fully attributed to reductions in emissions from cars, which accounted for a decrease of 0.18 billion tonnes of CO_2 over the analysis period.

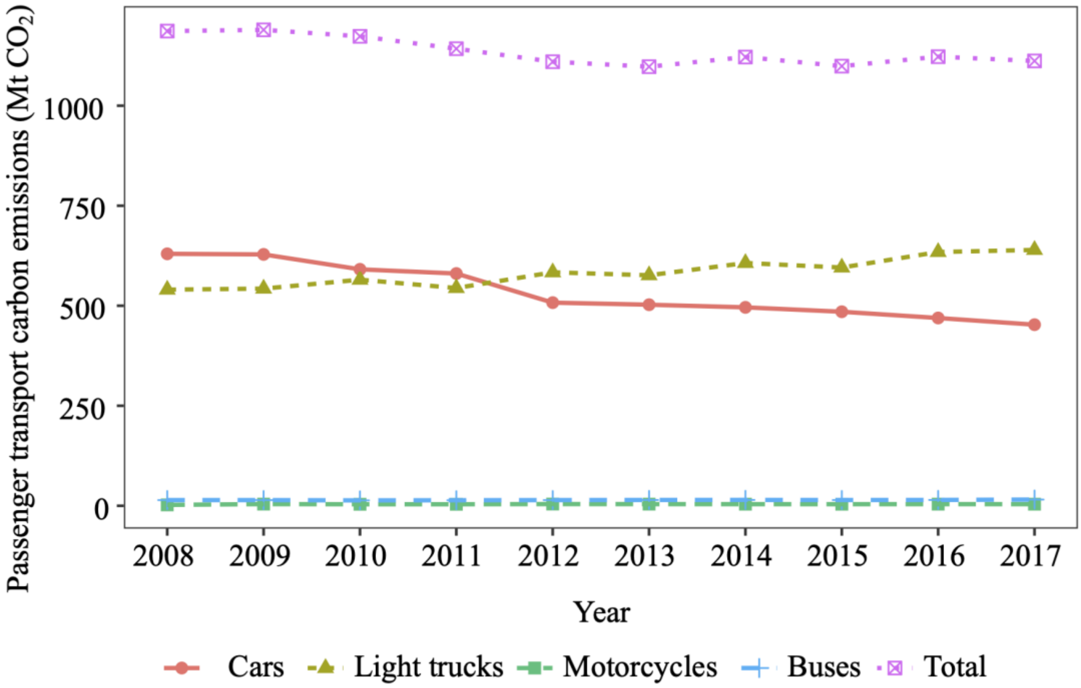

Figure 6-2: CO_2 emissions from the U.S. road passenger transport sector (2008–2017)

6.1.2 CO_2 emissions from the Australian road transport sector

The CO_2 emissions from the Australian road transport sector from 2009 to 2017 are shown in Figure 6-3, increasing from 74.46 million tonnes in 2009 to 83.58 million tonnes in 2017. These data agrees with the Australian Bureau of Infrastructure, Transport, and Regional Economics (AU BITRE, 2019), which reports GHG emissions from the Australian road transport sector. Notably, this sector contributes more than half of the overall transport emissions in Australia (Climate Council, 2017), implying a significant detrimental effect on achieving the national reduction target.

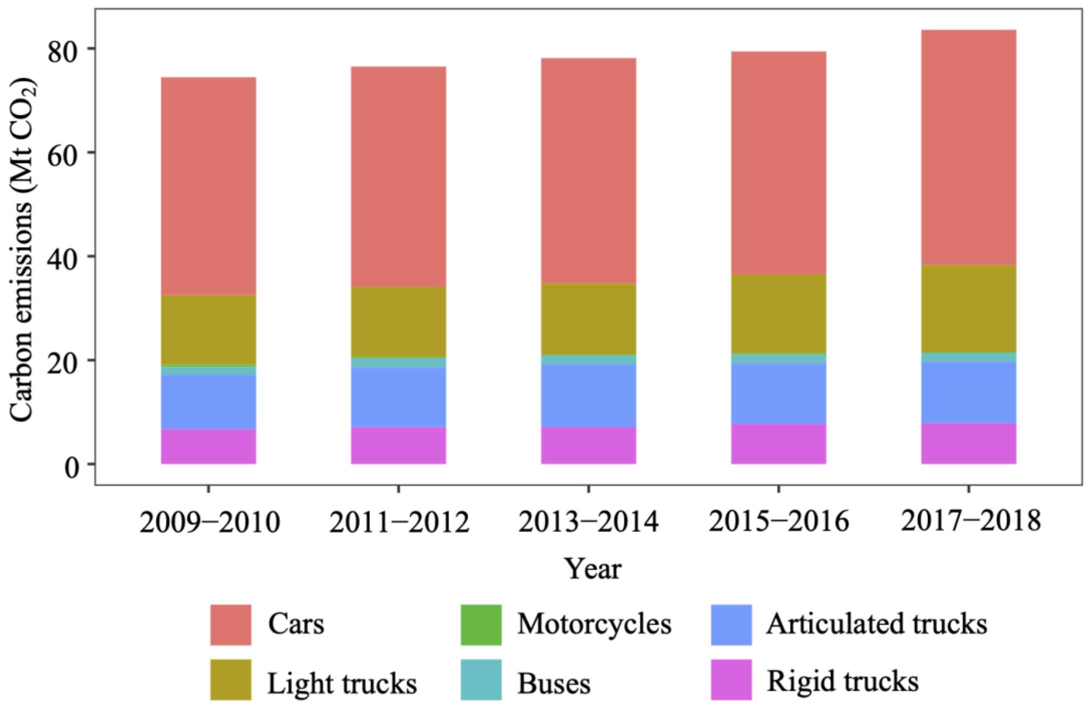

Figure 6-3: CO_2 emissions from the Australian road transport sector (2009–2017)

Figure 6-3 also shows that the most significant source of CO_2 emissions was cars, with a relatively stable share of the total emissions of approximately 55%. Light trucks (for passenger transport), and articulated trucks and rigid trucks (for freight transport), were also important contributors of emissions, averaging 18.4%, 14.7%, and 9.3% over the analysis period, respectively. As a whole, the freight transport sector (articulated and rigid trucks) contributed 24.0% of the total road transport sector emissions, which is similar to the U.S. However, unlike the U.S. where CO_2 emissions from cars decreased significantly over the analysis period, a general increase was observed in all the four of the main CO_2 emissions contributors in Australia.

Figure 6-4 presents the CO_2 emissions from the Australian road passenger transport sector in two-year intervals between 2009 and 2017, which increased from 57.26 to 63.89 million tonnes. Comparatively, this equates to approximately 5% of the equivalent emissions in the U.S.

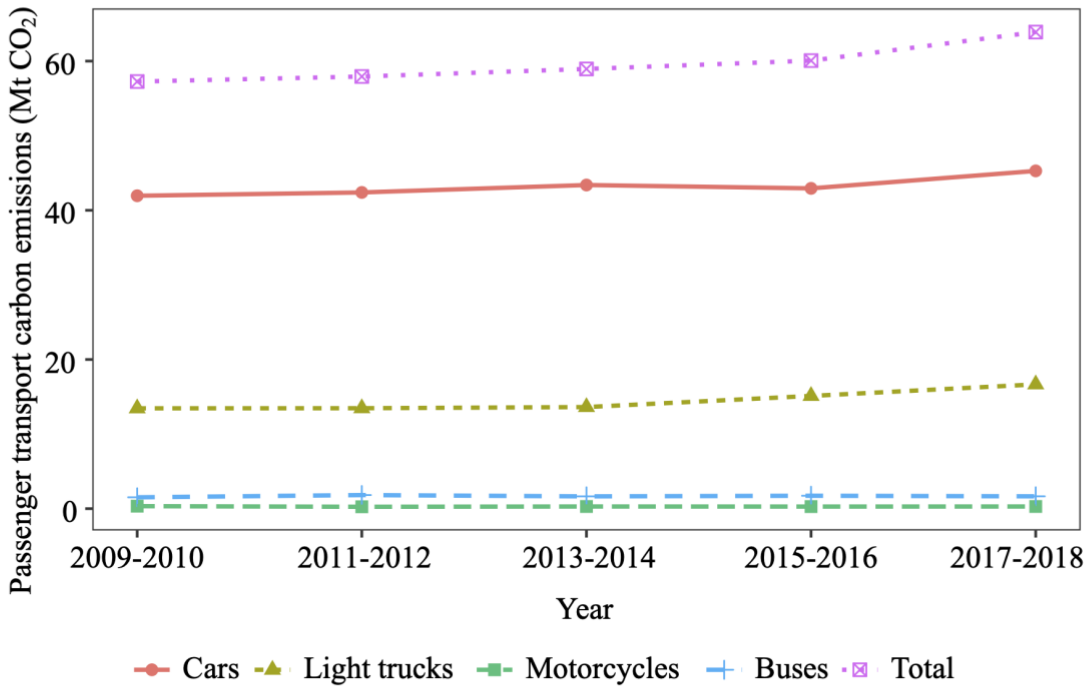

Figure 6-4: CO_2 emissions from the Australian road passenger transport sector (2009–2017)

Similar to the U.S., cars and light trucks contributed the most to passenger transport CO_2 emissions in Australia during the analysis period, and the contributions from motorcycles and buses were relatively small. However, in contrast to the U.S., cars contributed > 70% of total emissions in Australia. In addition, different from the U.S., the share from cars and light trucks remained relatively stable in Australia at approximately 73% and 24%, respectively. These results likely reflect the number of passenger vehicles in operation of the U.S. and Australia, which have a similar structure (Australian Bureau of Statistics, 2020; Oak Ridge National Laboratory, 2020).

6.2 LMDI Decomposition Analysis Results of the U.S. and Australian Road Transport Sectors

6.2.1 U.S. road passenger transport sector

As shown in Table 6-1, the aggregated change in CO_2 emissions from the U.S. road passenger transport sector from 2008 to 2017 was -75.80 million tonnes. Energy intensity was a key driver of this change, causing a change of -203.06 million tonnes of CO_2. This indicates that reducing energy intensity may be the most effective strategy to reduce CO_2 emissions over the analysis period. Passenger transport intensity and population also contributed 52.30 and 75.89 million tonnes of CO_2 emissions, respectively. The contributions from the emission factors, transport structure, and energy structure were limited.

Table 6-1: Decomposition of the U.S. road passenger transport sector (2008–2017)

Year	CO_2 emissions changes (million tonnes)						
	EF	TS	ES	EI	PI	P	Total
2008–2009	0.00	0.52	-0.03	-20.21	13.16	10.01	3.46
2009–2010	0.00	5.33	0.13	-17.72	-7.35	9.46	-10.16
2010–2011	0.00	-0.80	0.02	-27.66	-11.14	8.22	-31.34
2011–2012	0.00	2.97	0.16	-44.23	2.90	8.31	-29.89
2012–2013	0.00	0.03	-0.01	-21.13	0.45	7.84	-12.82
2013–2014	0.00	-1.43	-0.15	7.75	8.43	8.31	22.91
2014–2015	0.00	-0.17	-0.02	-50.59	18.91	8.35	-23.52
2015–2016	0.00	-4.24	-0.15	-3.44	19.40	8.19	19.75
2016–2017	0.00	-2.87	-0.24	-25.83	7.55	7.21	-14.18
Total (2008–2017)	0.02	-0.65	-0.29	-203.06	52.30	75.89	-75.80

Note: EF–emission factor; TS–transport structure; ES–energy structure; EI–energy intensity; PI–passenger transport intensity; P–population.

Figure 6-5 presents the contribution of the six factors (as outlined in Section 3.6.2) to the changes in CO_2 emissions each year. Energy intensity had a notable and consistent effect on the calculated reductions in CO_2 emissions. Passenger transport intensity and population were also important factors; the effect of population was consistently positive, whereas no consistent pattern was observed in the case of contributions from passenger transport intensity.

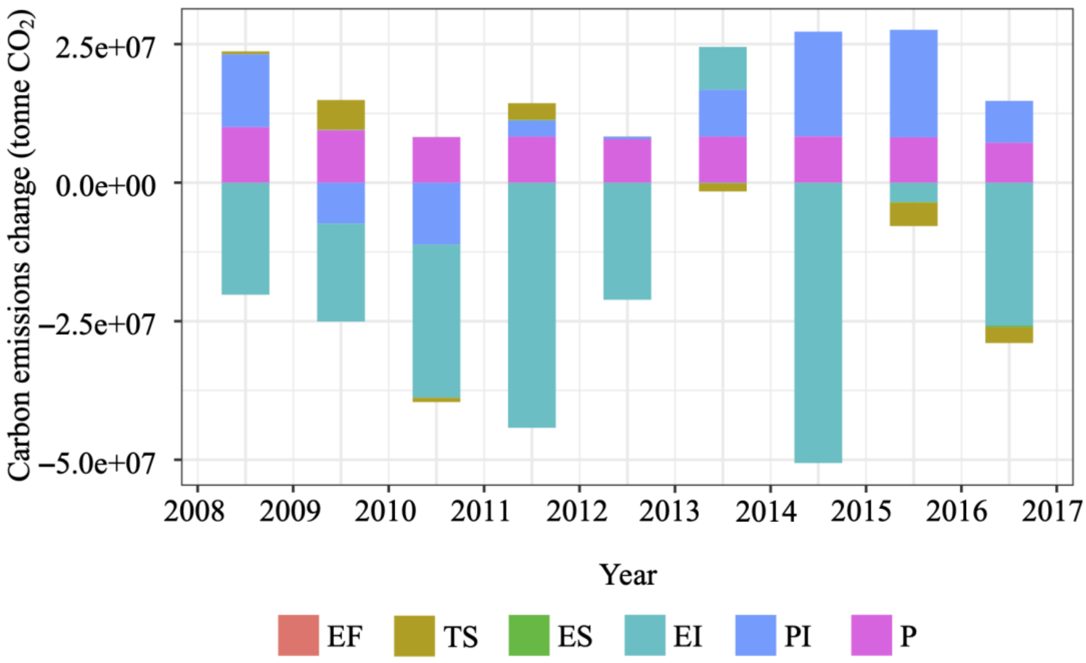

Figure 6-5: Decomposition results for CO_2 emissions from road passenger transport in the U.S. (2008–2017)

Note: EF–emission factor; TS–transport structure; ES–energy structure; EI–energy intensity; PI–passenger transport intensity; P–population.

- Positive factors

Population and passenger transport intensity are the two main factors positively contributing to the changes in CO_2 emissions. The population in the U.S. increased steadily from 304.09 million in 2008 to 324.99 million in 2017 at an average annual rate of 0.76%. This increase in population corresponded to the emission of 75.89 million tonnes of CO_2 during the 10-years analysis period.

Passenger transport intensity denotes the km/miles travelled per capita, and contributed 52.30 million tonnes of CO_2 emissions between 2008 and 2017. Generally, passenger transport intensity increases as populations become richer (U.S. Energy Information Administration, 2016a); as shown in Figure 6-6, the passenger transport intensity in the U.S. generally increased alongside per capita income. Furthermore, the sharp decrease in emissions between 2009 and 2011 likely reflects the impact of the 2008 recession, with per capita income reaching its lowest in 2011 (Department of Numbers, 2020).

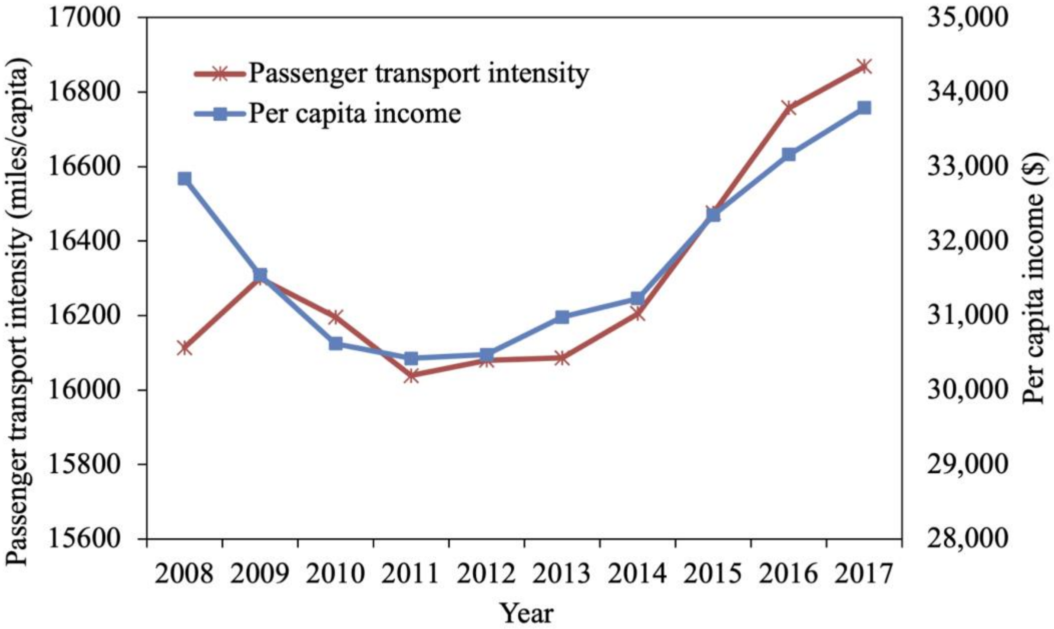

Figure 6-6: Passenger transport intensity and per capita income of the U.S. from 2008 to 2017

- Negative factors

Energy intensity contributed -203.06 million tonnes of CO_2 emissions to the U.S. road passenger transport sector from 2008 to 2017. Energy intensity is the energy use for transporting a passenger by 1 km/mile and can be used to evaluate the fuel economy of road transport, i.e., the lower the energy intensity, the higher the fuel economy. As shown in Figure 6-7, a general decrease in the energy intensity of the U.S. road passenger transport sector occurred during the analysis period, which was mainly driven by a reduction in the energy intensity of petrol. This decrease was related to both a decrease in petrol use and an increase of vehicle miles travelled (VMT), reflecting a significant improvement in the fuel economy. The use of petrol in the road passenger transport sector decreased from 16,009.1 trillion Btu in 2008 to 14,863.2 trillion Btu in 2017—a 7.2% reduction (Oak Ridge National Laboratory, 2020). This indicates that the emissions reduction programs adopted by the U.S. Environmental Protection Agency (EPA) have made positive steps towards achieving the national reduction targets, including establishing GHG regulations for cars and light trucks, encouraging the use of renewable fuels, labelling of vehicles, and sponsoring the development of alternative vehicle technologies (U.S. EPA, 2020). However, the VMT in the U.S. increased by 11.9% from 4,900,171 to 5,482,190 million passenger-miles during the same period (OECD, 2019b). This increase offsets the effect of the regulatory and technological measures, and caused 128.19 million tonnes of CO_2 emissions. These results indicate that significant potential exists for CO_2 emissions reductions if passenger can be encouraged to adjust their behaviours to reduce VMT.

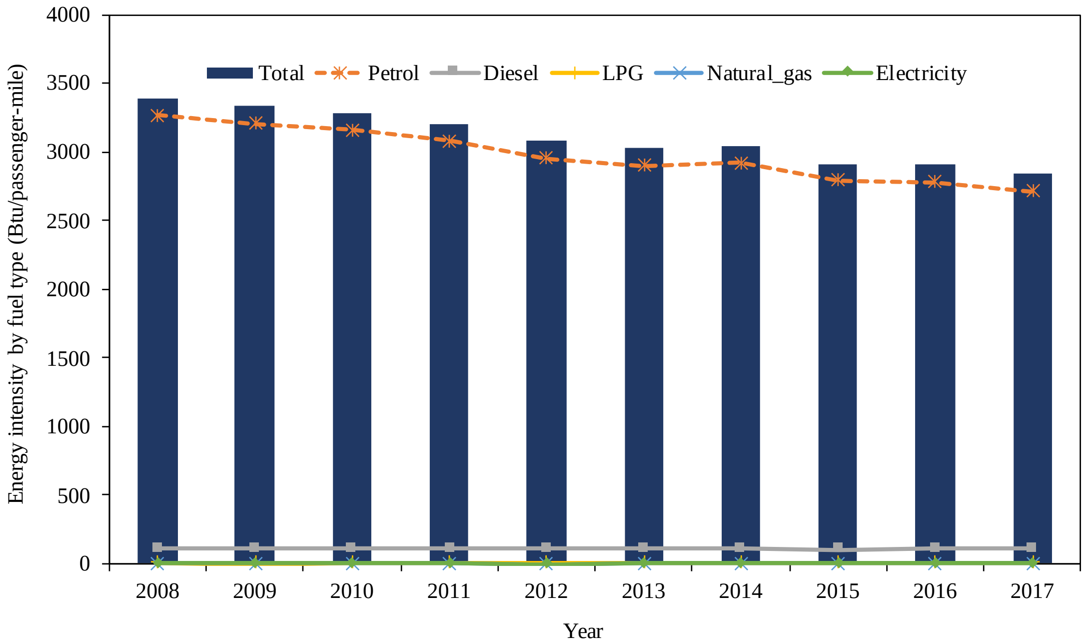

Figure 6-7: Energy intensity in the U.S. from 2008 to 2017

6.2.2 Australian road passenger transport sector

Table 6-2 presents the decomposition results of CO_2 emissions from the Australian road passenger transport sector, which increased by 6.64 million tonnes relative to 2009. Population, energy structure, and transport structure contributed 7.53, 1.80, and 0.01 million tonnes of CO_2, respectively. In contrast, energy intensity and passenger transport intensity contributed -1.64 and -1.06 million tonnes to the total change, respectively. Therefore, similar to the U.S., reducing energy intensity has been the most effective strategy for reducing CO_2 emissions during the analysis period.

Table 6-2: Decomposition of changes in CO_2 emissions from the Australian road passenger transport sector

Year	CO_2 emissions changes (million tonnes)						
	EF	TS	ES	EI	PI	P	Total
2009–2011	0.00	-0.04	0.72	-0.85	-0.65	1.88	1.05
2011–2013	0.00	0.08	0.51	-0.66	-0.47	1.93	1.38
2013–2015	0.00	0.02	0.55	-1.84	0.70	1.80	1.21
2015–2017	0.00	-0.04	0.02	1.71	-0.64	1.93	2.98
Total (2009–2017)	0.00	0.01	1.80	-1.64	-1.06	7.53	6.64

Note: EF–emission factor; TS–transport structure; ES–energy structure; EI–energy intensity; PI–passenger transport intensity; P–population.

Figure 6-8 shows the relative contributions of the six influencing factors on CO_2 emissions changes between 2009 and 2017. Population and energy intensity had the greatest influence, while energy structure and passenger transport intensity were also important. While population and energy structure contributed positively and consistently to emissions over the analysis period, energy intensity and passenger transport intensity made negative but inconsistent contributions.

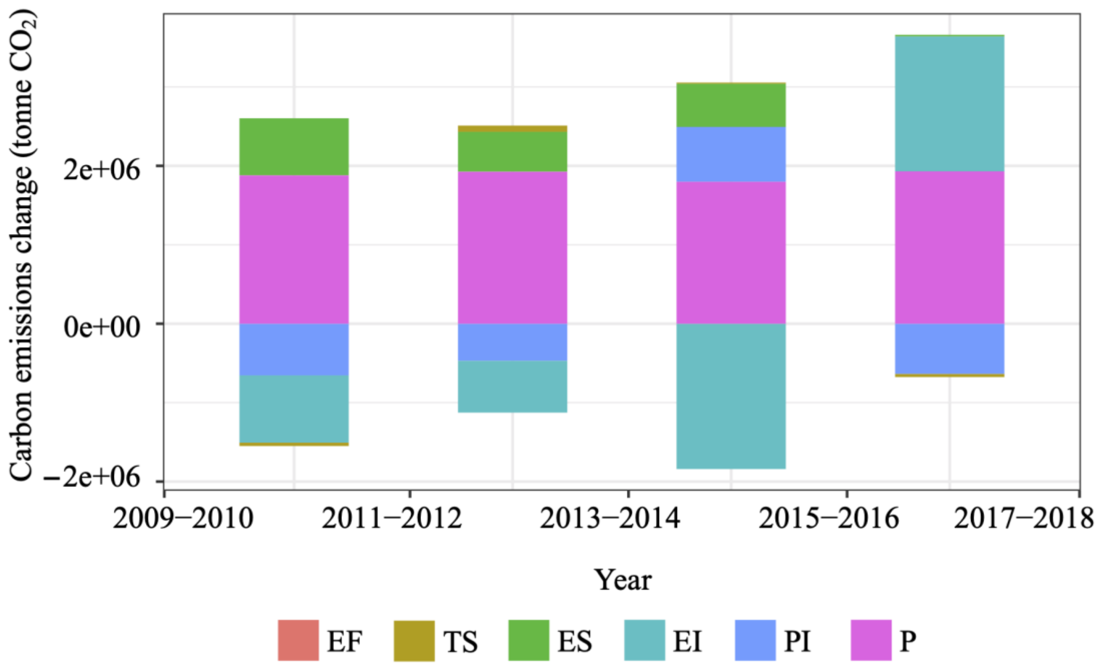

Figure 6-8: Decomposition results for CO_2 emissions from road passenger transport in Australia (2009–2017)

Note: EF–emission factor; TS–transport structure; ES–energy structure; EI–energy intensity; PI–passenger transport intensity; P–population.

- Positive factors

Population had a consistent and positive effect on CO_2 emissions during the analysis period, which increased from 22.03 million in 2009 to 24.98 million in 2017 at an average annual rate of 3.19%. The aggregated contribution of population expansion in Australia was 7.53 million tonnes of CO_2 emissions.

Figure 6-9 demonstrates the energy structure of the Australian road passenger transport sector, which had a consistently positive impact on emissions during the analysis period (approximately 1.80 million tonnes). Such an effect is mainly attributed to the large increase in the use of diesel, which offset the decrease in the use of petrol, LPG and/or compressed natural gas (CNG). Diesel use increased by 76.4% between 2009 and 2017, which is partly attributed to a 56.9% increase in registered diesel-powered vehicles for passenger transport and an 11.4% growth in VMT during this period. In comparison, the use of liquid natural gas and electricity in the Australian passenger transport sector was negligible. For example, compared to Norway which has almost 25% of the electric cars in the market, the share of electric cars in Australia is only 0.08% (Climate Council, 2017). The availability of relatively "clean coal" in Australia may make the generation of electricity less carbon-intensive than in other countries (Shahiduzzaman and Layton, 2015). When using renewable energy for electricity generation, emissions can be reduced to 6 gCO_2/km, offering large capacity for emissions reduction (Climate Council, 2017).

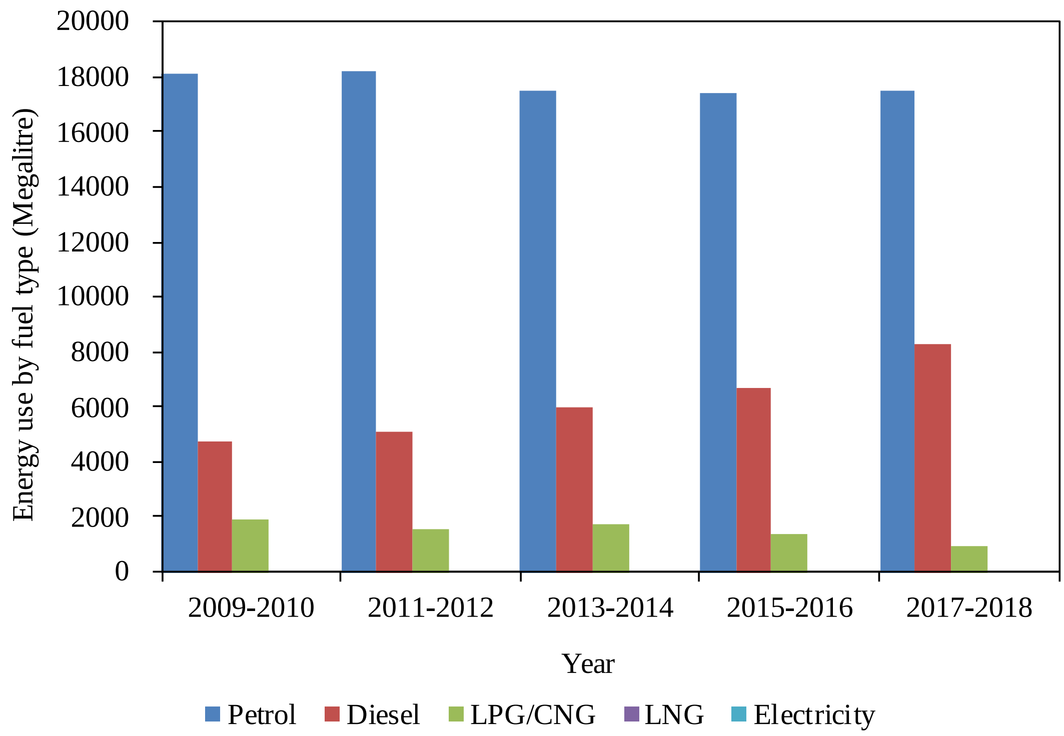

Figure 6-9: Energy structure of the Australian road passenger transport sector (2009–2017)

Note: LPG–liquefied petroleum gas; CNG–compressed natural gas; LNG–liquid natural gas.

- Negative factors

Energy intensity and passenger transport intensity contributed negatively to the overall changes in CO_2 emissions in Australia between 2009 and 2017 (Figure 6-10). The energy intensity of petrol and LPG/CNG decreased, indicating that the fuel economy has improved over this period. Due to the limited legislation for reducing transport emissions in Australia, this improvement can be largely attributed to vehicle imports from countries that have mandated vehicle emissions standards (Climate Change Authority, 2014). During the same period, the energy intensity of diesel increased, also possibly due to the increased use of diesel-powered vehicles. Due to the dominance of petrol use in passenger transport, the aggregated effect of energy intensity was -1.64 million tonnes of CO_2 emissions.

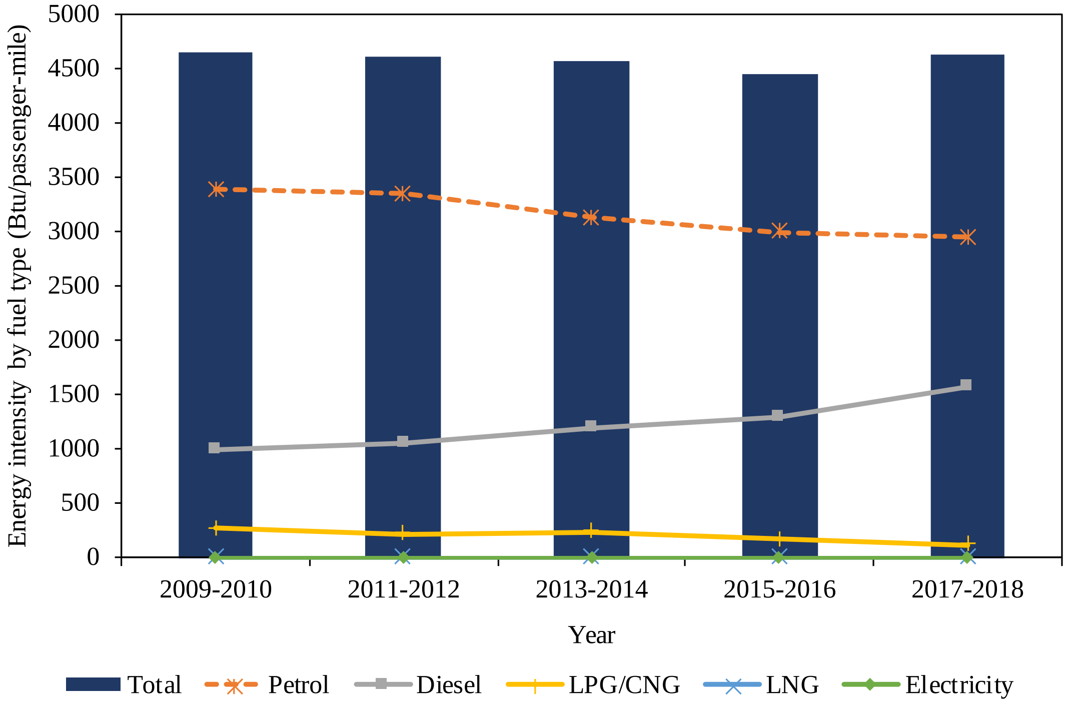

Figure 6-10: Energy intensity of the Australian road passenger transport sector (2009–2017)

Note: LPG–liquefied petroleum gas; CNG–compressed natural gas; LNG–liquid natural gas.

Furthermore, the road passenger transport intensity in Australia decreased by 2% from 7,946.90 to 7,807.36 miles per capita between 2009 and 2017. This may be attributed to the rise in population size and the preference for air transport, as evidenced by its increasing share in passenger transport (AU BITRE, 2019). This resulted in a contribution of -1.06 million tonnes of CO_2 emissions during the analysis period.

6.2.3 U.S. road freight transport sector

As presented in Table 6-3, the CO_2 emissions of the U.S. road freight transport sector increased by 92.41 million tonnes between 2008 and 2017. The most significant contributing factors were GDP and energy intensity, contributing 115.40 and 53.90 million tonnes, respectively. In contrast, freight transport intensity was a major driver of CO_2 emissions reductions. This indicates that reducing freight transport intensity would be the most effective emissions reduction strategy. In comparison, the influence of the emission factor and energy structure was negligible.

Table 6-3: Decomposition of CO_2 emissions from the U.S. road freight transport sector (2008–2017)

Year	CO_2 emissions changes (million tonnes)					
	EF	ES	EI	FI	G	Total
2008–2009	0.00	0.00	40.05	46.24	-7.44	78.86
2009–2010	0.00	0.00	51.55	-62.25	15.16	4.46
2010–2011	0.00	0.00	17.88	-56.97	14.81	-24.28
2011–2012	0.00	0.00	-47.32	28.80	16.94	-1.58
2012–2013	0.00	0.00	-28.75	24.52	14.64	10.41
2013–2014	0.00	0.00	16.61	-27.53	17.65	6.73
2014–2015	0.00	0.00	-8.65	-9.99	16.04	-2.60
2015–2016	0.00	0.00	-4.47	4.36	10.86	10.75
2016–2017	0.00	0.00	17.01	-24.08	16.74	9.68
Total (2008–2017)	0.00	0.00	53.90	-76.89	115.40	92.41

Note: EF–emission factor; ES–energy structure; EI–energy intensity; FI–freight transport intensity; G–GDP.

It should be noted that in line with Figure 6-1, the sharp increase in CO_2 emissions between 2008 and 2009 was identified. As shown in Figure 6-11, freight transport intensity and energy intensity were the two most significant contributing factors in this increase, corresponding to 46.24 and 40.05 million tonnes of CO_2, respectively. Figure 6-11 also shows that the effect of freight transport intensity and energy intensity on the change in yearly emissions was significantly higher compared to other factors including GDP, especially between 2008 and 2013.

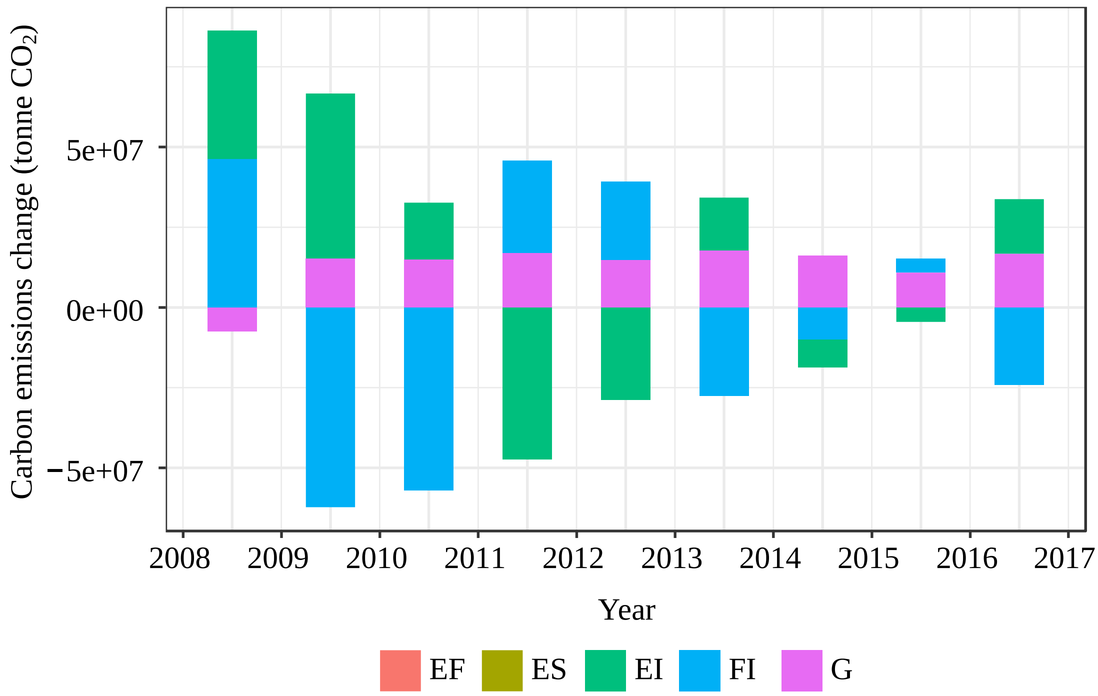

Figure 6-11: Decomposition of CO_2 emissions from road freight transport in the U.S.

Note: EF–emission factor; ES–energy structure; EI–energy intensity; FI–freight transport intensity; G–GDP.

- Positive factors

GDP and energy intensity were two positive factors affecting the CO_2 emissions changes in the U.S. road freight transport sector. GDP reflects the level of economic development of a country, and increased by 24.5% from USD 14,712.84 billion in 2008 to USD 19,485.39 billion in 2017. The cumulative environmental effect of this growth was 115.40 million tonnes of CO_2 emissions.

Figure 6-12 shows the energy intensity of the U.S. freight transport sector, which contributed 53.90 million tonnes of CO_2 emissions between 2008 and 2017. Diesel was the most intensively used type of fuel for every tonne-mile transport of goods. As shown in Figure 6-13, the intensity of diesel fuel during this period was related to the diesel fuel use and freight service of the road freight transport sector. Although the freight service goes down and up sharply between 2009 and 2013, fuel showed a general increasing trend over the entire analysis period. The energy intensity of diesel fluctuated mostly according to the changes in freight service. It also appears that the

SmartWay programme implemented by the U.S. EPA that aims to increase supply chain efficiency has had a limited effect on reducing the energy intensity of the sector.

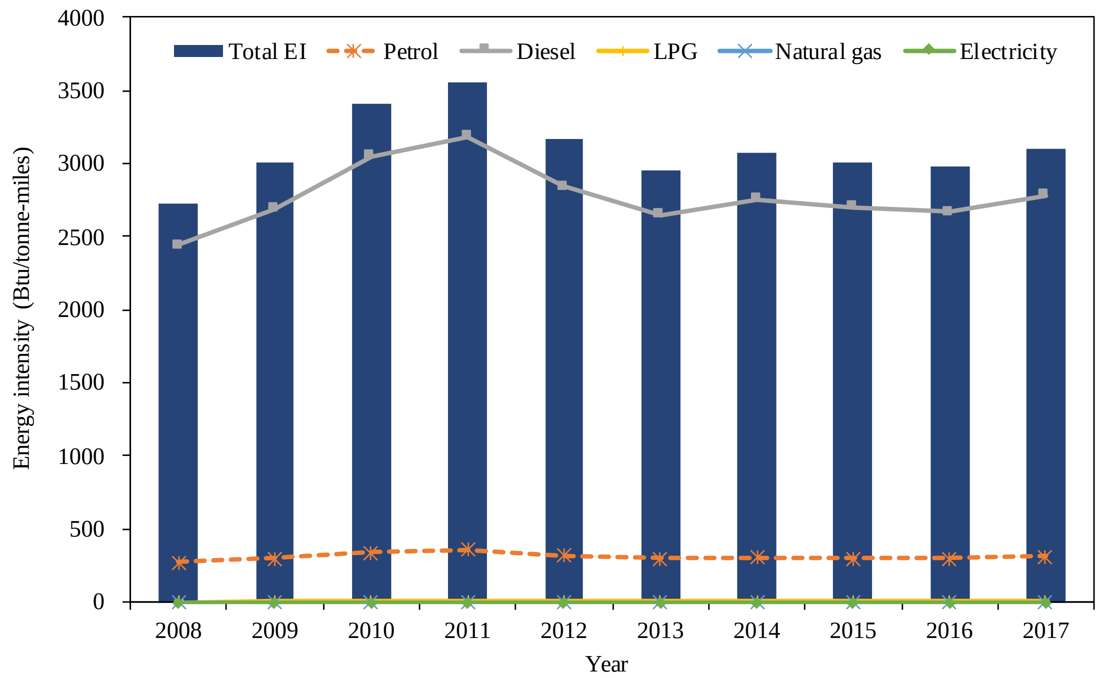

Figure 6-12: Energy intensity (EI) of the U.S. road freight transport sector (2008–2017)

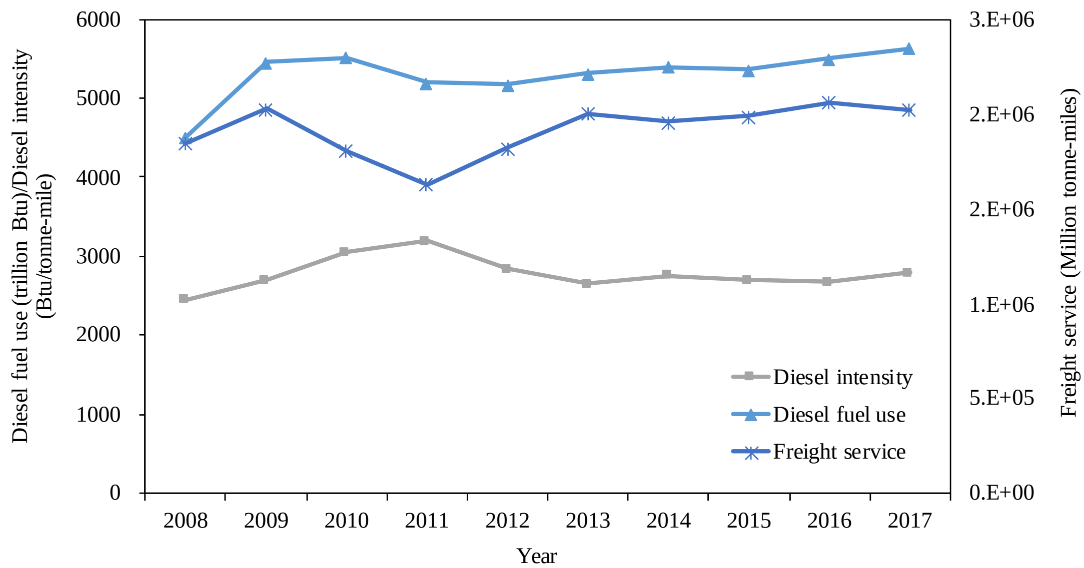

Figure 6-13: Freight service, diesel use, and intensity of the U.S. road freight transport sector (2008–2017)

- Negative factors

Freight transport intensity was another important factor affecting the changes in CO_2 emissions from the U.S. freight transport sector, with an aggregated effect of -76.89 million tonnes of CO_2 emissions during the analysis period. Freight transport intensity indicates the transport demand per dollar of GDP that is created. Figure 6-14 demonstrates that the road freight transport intensity in the U.S. rose and fell during the 10-year analysis period, without a strong correlation with increasing GDP. According to Mraihi and Harizi (2014), freight transport intensity can be impacted by the economic structure of a country because agriculture and industry demand more transport than services. However, Figure 6-14 indicates that the freight transport intensity of roads is more related to other transport modes. In addition, the total freight transport intensity decreased year-on-year. This might be attributed to improved land-use planning and development and/or industry tending to locate close together (Pew Center on Global Climate Change, 2008).

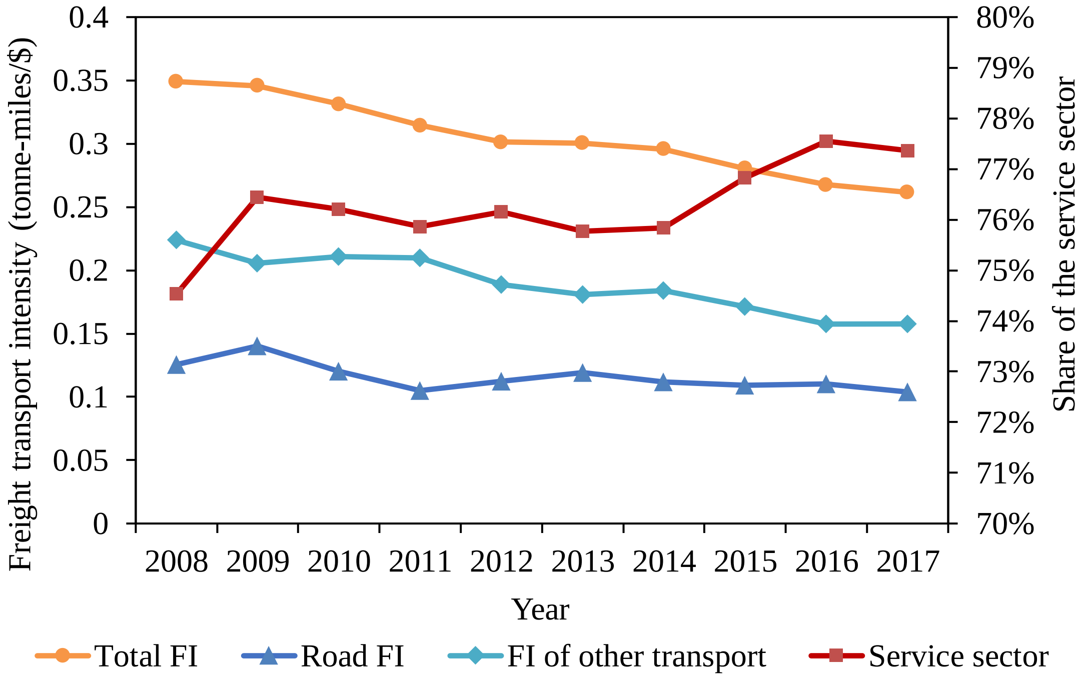

Figure 6-14: Freight transport intensity (FI) of the freight transport sector and share of the service sector in the U.S. (2008–2017)

6.2.4 Australian road freight transport sector

Table 6-4 shows the decomposition results of CO_2 emissions from the Australian road freight transport sector, which increased by 2.58 million tonnes between 2009 and 2017. Most of this change was driven by GDP, which accounted for a 6.61million-tonne increase in CO_2 emissions. The contributions from freight transport intensity, energy intensity, energy structure, and transport structure were -3.86, -0.33, 0.14, and 0.02 million tonnes, respectively. Therefore, as with the U.S., the most effective emissions reduction strategy is reducing the freight transport intensity. The annual contributions of the six considered factors are shown in Figure 6-15. The effect of the emission factor was negligible, and as previously noted, GDP was the most significant contributor followed by freight transport intensity.

Table 6-4: Decomposition of CO_2 emissions from the Australian road freight transport sector (2009–2017)

Year	CO_2 emissions changes (million tonnes)						
	EF	TS	ES	EI	FI	G	Total
2009–2011	0.00	0.00	0.11	0.05	-6.19	7.51	1.48
2011–2013	0.00	-0.01	0.01	0.18	-1.81	2.22	0.59
2013–2015	0.00	0.02	0.02	0.28	2.68	-2.82	0.18
2015–2017	0.00	0.01	0.00	-0.84	1.46	-0.30	0.33
Total (2009–2017)	0.00	0.02	0.14	-0.33	-3.86	6.61	2.58

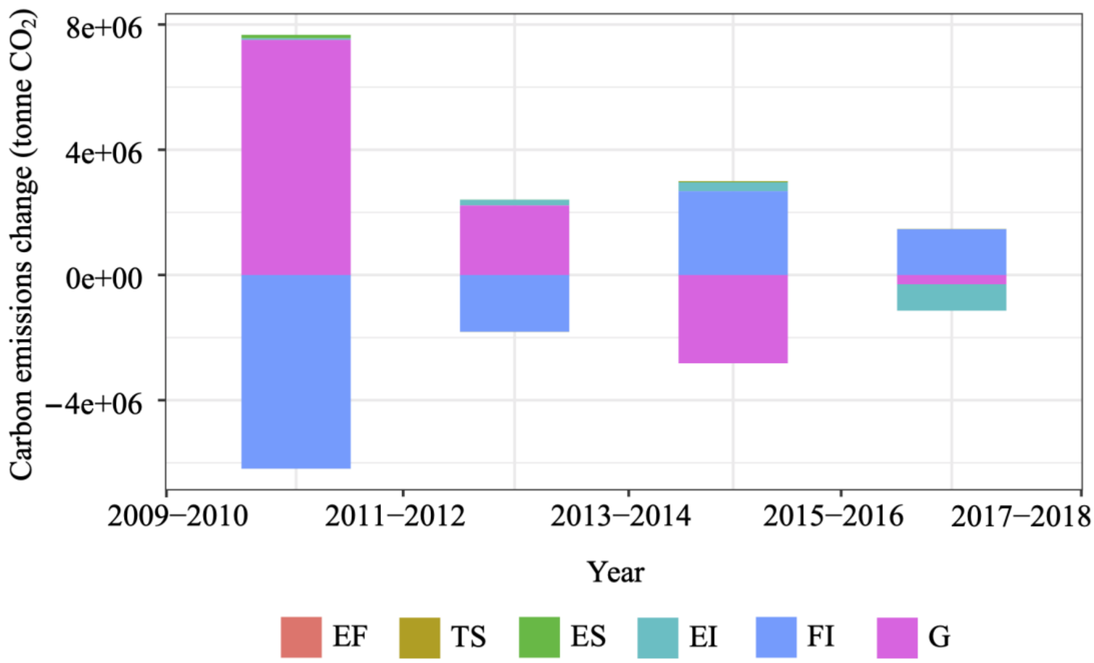

Figure 6-15: Decomposition results for Australia's CO_2 emissions of road freight transport (2009–2017)

Note: EF–emission factor; TS–transport structure; ES–energy structure; EI–energy intensity; FI–freight transport intensity; G–GDP.

As shown in Figure 6-16, GDP in Australia fluctuated vigorously during the analysis period, leading to corresponding oscillations in CO_2 emissions. A notable change occurred between 2009 and 2011, when GDP increased by USD 468.8 billion, leading to 7.51 million tonnes of CO_2 emissions. The overall effect of GDP was an increase of 6.61 million tonnes of CO_2 emissions.

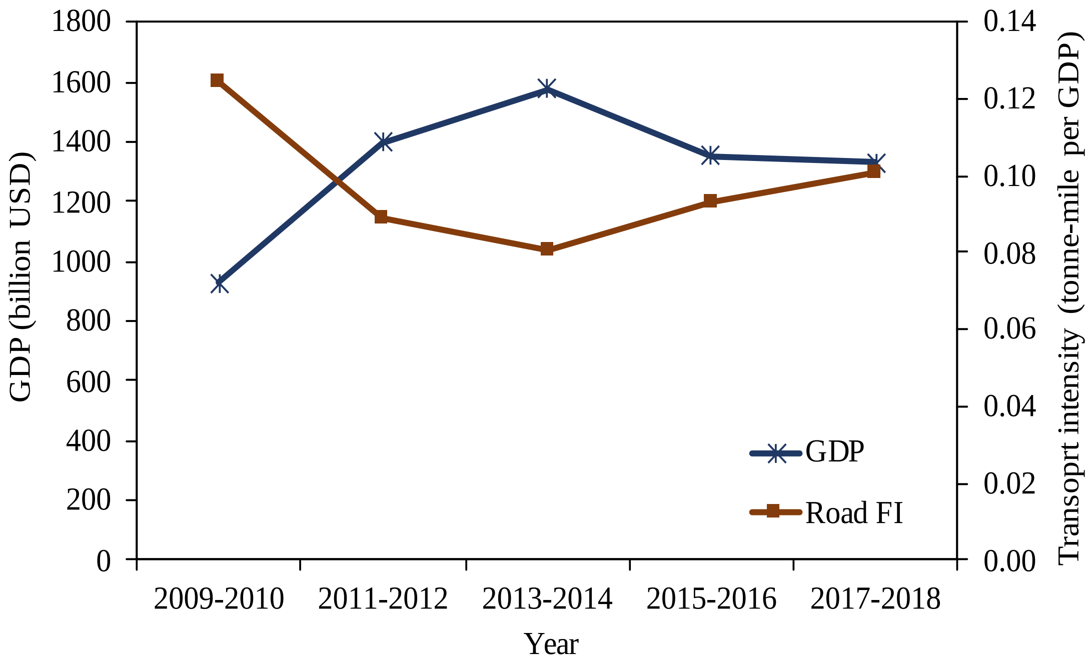

Figure 6-16: GDP and road freight transport intensity (FI) in Australia (2009–2017)

Freight transport intensity contributed -3.86 million tonnes of CO_2 emissions overall, and the sharp decrease between 2009 and 2011 led to a significant decrease in CO_2 emissions, equivalent to -6.19 million tonnes. Figure 6-16 shows that the freight transport intensity showed the opposite trend to GDP, which differs from the U.S. Such a strong correlation may imply that changes in the freight transport intensity were mainly driven by the changing prices of goods.

6.3 Chapter Summary

This chapter presented the results of the evaluation and decomposition analysis of the U.S. (2008–2017) and Australian (2009–2017) road transport sectors from the perspective of passenger transport and freight transport. The key findings include: 1) cars and light trucks (from passenger transport) and medium/heavy trucks (from freight transport) were significant contributors to road transport CO_2 emissions; 2) population had a dominant effect on increases in CO_2 emissions from passenger transport, and the most effective strategy for emissions reduction in the sector has been to reduce energy intensity; and 3) GDP has contributed to the growth of CO_2 emissions from freight transport the most, indicating that reducing freight transport intensity offers an effective means of reducing CO_2 emissions in this sector.

Chapter 7. Discussion

This chapter discusses the results of the research to identify the further implications for academia and decision/policy-makers. Sections 7.1, 7.2, and 7.3 focus on the results for the proposed hybrid LCA method, the multi-attribute decision-making framework, and the road transport emissions decomposition analysis, respectively. Section 7.4 states the overall value of this thesis for greening road construction and the transport sector, and Section 7.5 summarises this chapter.

7.1 Hybrid LCA for Evaluating Road Use and M&R

This study proposes and illustrates a structured hybrid LCA approach under Objective 2 to evaluate the GHG emissions from the use and M&R phases of roads following a four-step LCA. Under this approach, yearly road performance indicators such as IRI are integrated into the definition of FUs as part of the goal and scope definition phase. In this way, the deterioration features and functioning of roads during the use phase can be better captured. This approach is also recommended by Inyim et al. (2016), who encourage the integration of average pavement serviceability rating and potential FUs in future research. Similarly, Batouli and Mostafavi (2017) adjusted annual FUs based on the level of service and performance; however, their applied serviceability index is not available in many countries including Australia. In this study, IRI was used to represent serviceability, which has high transferability throughout the world to maximise applicability.

When compiling the LCI, a hybridisation of the PXC and tiered hybrid LCA methods was proposed, as presented in Figure 7-1. Two main phases are included in the proposed approach, i.e., the M&R and use phases. In each case, emission sources and LCI methods for evaluating the emissions were presented. Emissions sources for the M&R phase include on-site work (equipment operation and embodied emissions) and traffic delays; and emissions from the use phase are mainly associated with RR. It is not possible to calculate emissions from all sources of the use and M&R phases using a single hybrid approach because of its unique characteristics, including: 1) traffic delays and RR cannot be easily assigned to an economic sector, meaning that PXC analysis cannot be easily conducted; and 2) using a tiered approach to model on-site M&R work can cause cut-off errors because of the difficulty in obtaining data for several processes and the omission of "unimportant" processes. Therefore, a hybrid of the two methods was proposed.

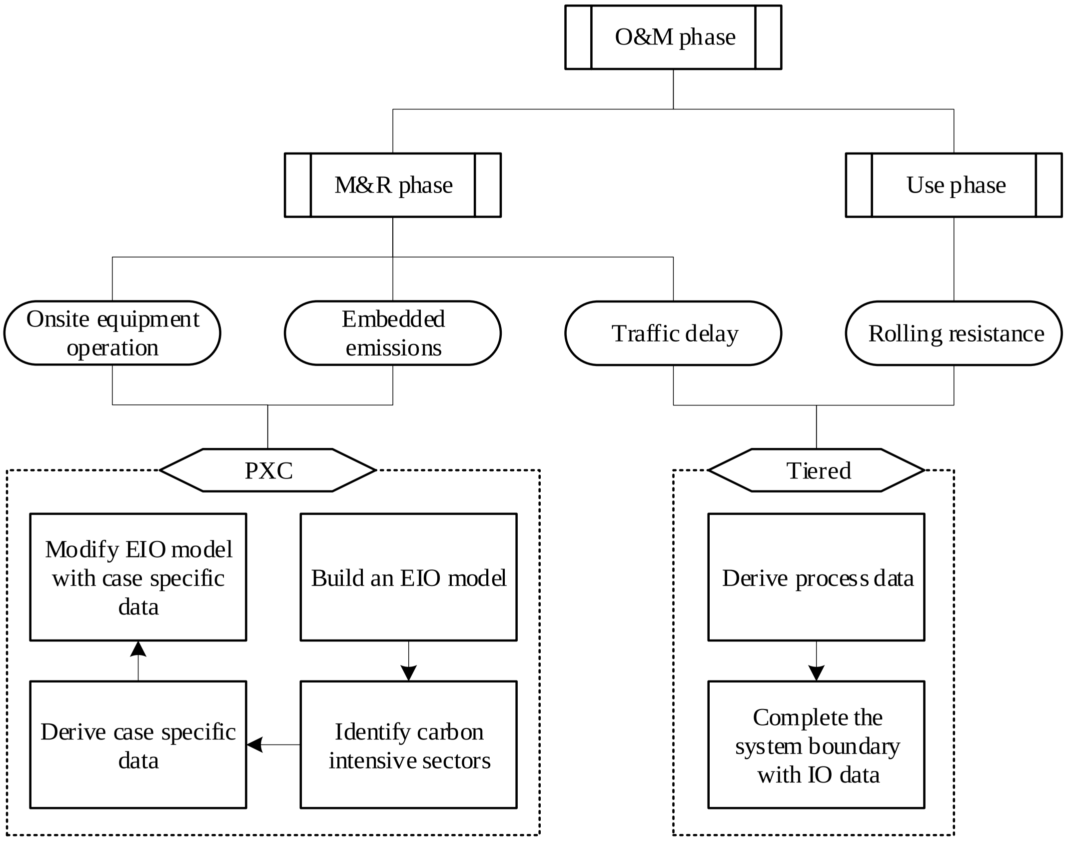

Figure 7-1: Structured hybrid LCA approach for combining PXC and tiered hybrid methods for the use and M&R phases of roads

Note: O&M–operation and maintenance; M&R–maintenance and rehabilitation; PXC–path exchange hybrid LCA method; EIO–environmental input output; IO–input output.

The PXC method is proposed for on-site work as, compared to other hybrid methods, this offers an optimal trade-off between model complexity and accuracy, and provides a standardised four-step calculation process that is relatively easy to follow. Taking this approach, the first step is to establish an EIO model for road M&R, after which the model is expanded to a series of exclusive nodes (sectors) in the entire supply chain using a mathematical algorithm. The aim of this is to identify sectors with the highest volume of emissions, for example, construction (sector 24 in this study) and the manufacturing of certain materials such as petroleum, bitumen, cement, and metal (sectors 8, 9, 12, and 14 in this study). The integration of available case-specific process data, such as on-site equipment operation and the manufacturing of the identified materials, can further improve the accuracy of the results. The final step modifies the EIO model by substituting the EIO values of the identified sectors from the corresponding case-specific data.

Traffic delays and RR are, however, difficult to assign to a specific economic sector when developing an EIO model. Therefore, the tiered hybrid method is recommended. First, this requires relatively fewer data and is less time-intensive than the integrated hybrid method. It also avoids the direct modification of the EIO matrix that is required by the matrix augmentation method, which may lead to high uncertainties in the final results. For the tiered hybrid method, two steps should be followed. First, process data for the emissions from fuel consumption resulting from traffic delays and/or RR are obtained. IO data are then used for upstream phases of the manufacturing of fuels to complete the system boundary. This approach is expected to increase the accuracy of emissions evaluations from traffic delays and RR, which are typically modelled using P-LCA methods. Following the LCI step, LCIA and sensitivity analysis are conducted. The importance of sensitivity analysis is emphasised as this is required by ISO 14044 (2006) and ISO 14067 (2018) to evaluate the uncertainty of LCA results, although this has long been overlooked in existing research (Jiang and Wu, 2019).

The proposed hybrid LCA model can be applied for the evaluation of carbon emissions from the use and M&R phases of roads, which have not been specifically targeted in existing studies. For the maintenance phase, Enache and Stampfer (2015) and Treloar et al. (2004) used the PXC method to calculate on-site work but did not consider the impact of traffic delays. Batouli et al. (2017) and Santos et al. (2017b) included traffic delays by adopting the tiered method for the calculation of on-site work, which generates less accurate results than the PXC method. The proposed method models on-site work and traffic delays using the PXC and tiered methods, respectively, thereby offering a more complete system boundary and achieve higher accuracy. For the use phase, the application of hybrid methods is limited. In addition, the definition of emissions sources in Treloar et al. (2004) has been challenged, and the hybrid method adopted by Batouli et al. (2017) is not reported transparently. Given the unique characteristics of the use phase, the tiered method was adopted in this study to provide a relatively simply means of increasing the accuracy of results obtained from P-LCA.

To illustrate the proposed approach, a case study was conducted, the key findings of which can be summarised as follows. The average GWP of the roads in WA was 467.8 t CO_2-e/km in 2017, predicted to gradually increase to 589.5 t CO_2-e/km by 2026. The use phase is a significant contributor to GWP in the study network, accounting for 99.2% of the total during the ten-year analysis period. This supports the findings of Yu and Lu (2012), who conclude that the use phase is a dominant contributor to GHG emissions for all three of the rehabilitation alternatives they studied. Based on this, the use phase should be prioritised when establishing emissions reduction strategies.

Under the proposed approach, RR is modelled during the use phase and the GWP is impacted by AADT, speed limit, the IRI, and MPD. The estimated average yearly increase in GWP between 2017 and 2026 is 2.03% for the case study network, which is slightly higher than the projected traffic growth rate (2%). This indicates that AADT could have the greatest impact on the GWP. Through a further sensitivity analysis, GWP was shown to be highly sensitive to AADT. This supports the findings of Santos et al. (2015b) and Chen et al. (2016). Loijos et al. (2013) also conducted a sensitivity analysis and concluded that traffic volume accounted for 60% of the variation in their results. In comparison, for the WA case study network, 99.9% of the observed variation was attributed to changes in AADT. This difference likely reflects the selection of the system boundary; Loijos et al. (2013) included all five phases of the life cycle of roads, whereas only the use and M&R phases were considered here. Considering the significant impact of AADT on the obtained results, it is recommended that special attention should be paid to projected increases in AADT.

Compared to the use phase, the M&R phase was estimated to contribute an average of only 1.58 t CO_2-e/km (0.3%) between 2017 and 2025. Interestingly, this value increases sharply to 30.6 t CO_2-e/km by 2026, accounting for 5.2% of the total GWP. One important factor here is that the number of road segments receiving M&R treatments (3,804) in 2026 was four-times higher than the average of the other years. In addition, two rehabilitation programs (ASRS and GroL) are the most carbon-intensive among all the M&R programs. The projected percentage of rehabilitation among the allocated M&R strategies for the road segments in 2026 was 2.5% and 5.42% compared to an average of 1.46% and 0.11% during the period 2017–2025, respectively. This also likely explains the sharp projected increase in GWP by 2026.

Considering the spatial distribution of GWP across the entire case study road network, the heavy traffic roads in metropolitan areas and freeways (with an AADT > 20,000) were identified as the most carbon-intensive road segments; these segments should form the focus of establishing strategies to reduce carbon emissions.

Furthermore, for comparison, separate P-LCA and tiered hybrid LCA methods were also conducted to estimate carbon emissions from the use and M&R phases of the case study road network. The results of these analyses are presented in Figure 7-2. Figure F.1 and F.2 also provide further detailed comparison for on-site work, and traffic delays and the use phase, respectively. Based on these results, P-LCA generates much lower estimates than the two hybrid LCA methods, ranging from 128.6 to 164.4 t CO_2-e/km within the 10-year analysis period. Cut-off errors in the P-LCA method could be a major reason for the low estimates. For on-site work during the M&R phase, the emission factors for materials only cover mine to end-of-production processes (TAGG, 2013), excluding processes such as the transport of the materials to site and subsequent on-site transport. The emission factor for the full life cycle of diesel is reported to cover all processes from raw materials extraction and transport to fuel production and transport to on-site combustion (TAGG, 2013). However, taking diesel as an example, the emission factor for direct combustion on-site is 2.68 tCO_2-e/kL, while the full life cycle emission factor is only slightly higher at 2.887 tCO_2-e/kL. Due to the highly significant contribution of material extraction and production processes (Kang et al., 2014; Kayo et al., 2015), this may indicate an omission of several processes during the pre-consuming phases. This could also explain the difference between the P-LCA and tiered hybrid methods in the estimation of traffic delays and the use phase.

Moreover, it is interesting that the results obtained through the separate tiered method are slightly higher than those derived from the proposed model. The total GWP calculated through the tiered method increases from 468.0 to 608.9 t CO_2-e/km within the 10-year analysis period. More specifically, as the tiered method is used for modelling carbon emissions of traffic delays and the use phase in the proposed model, such differences can be attributed to the ways in which the PXC and tiered methods model on-site work during M&R. A complete tiered method could be subject to cut-off errors. For example, as direct combustion of fuel on-site is modelled with process data, and production of fuel and materials is modelled with IO data, the transport of produced fuel and materials to site is not considered. As the PXC method used in the proposed model has an EIO-based analysis framework, cut-off errors are avoided. In addition, when using the full tiered approach, national average price data for fuel and materials are used to obtain the IO data for upstream production processes, which may generate less accurate results. Based on a sensitivity analysis, a variation of ±10% in material prices leads variations of up to +9.4% and -9.1% in the on-site work emissions calculated using the tiered method. A ±10% variation in the unit cost of each M&R strategy also results in variations of up to +10.2% and -10.1% in the on-site work emissions calculated using the PXC method, respectively. Results are, therefore, sensitive to material prices in the tiered method and M&R costs in PXC method. As road agencies usually have accurate data on M&R costs, using such data in the PXC part of the proposed approach can help achieve more accurate results.

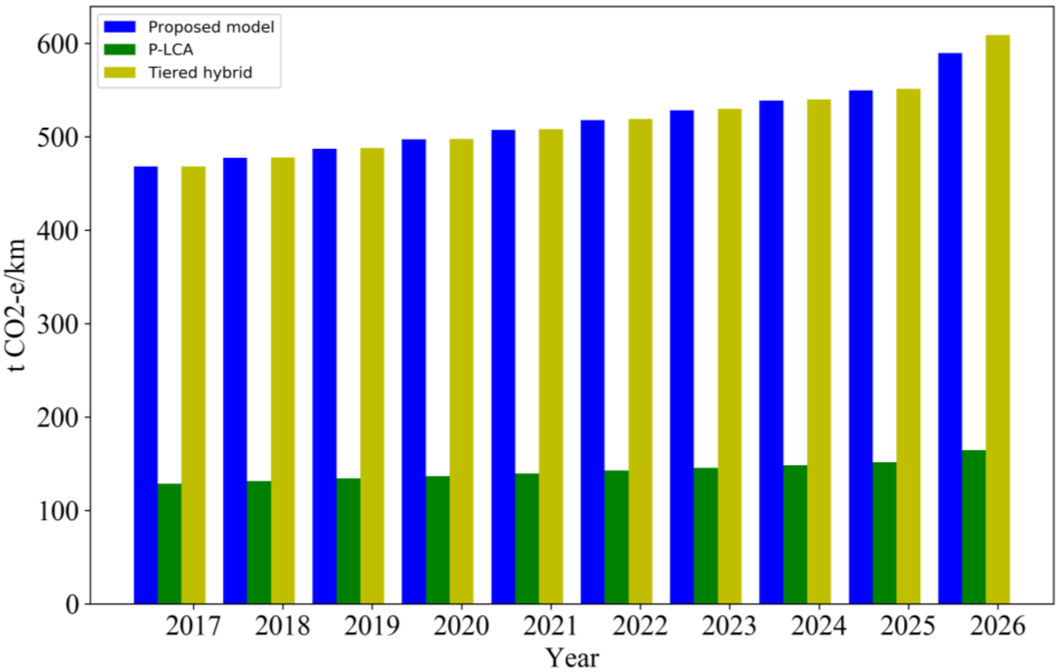

Figure 7-2: Comparison between total GWP generated by the proposed hybrid approach, P-LCA, and tiered hybrid LCA methods for the case study road network in WA

7.2 Multi-attribute Decision-Making in Road Use and M&R

Selecting an optimal network-level pavement maintenance plan is critical for road agencies given limited maintenance funds. Road condition and direct costs are the most frequently considered factors when evaluating a pavement maintenance plan.

However, social sustainability such as road-user costs impacted by maintenance activities and improved road condition are rarely considered. In addition, as GHG emissions reductions have become a target worldwide under the Paris Agreement, environmental sustainability must also be considered in such evaluations. Arif et al. (2016) developed a decision-making framework to support infrastructure maintenance investment decision-making that considers physical condition and socioeconomic performance; however, environmental contributions were not included and the required data are difficult for road agencies to obtain. Batouli et al. (2017) considered road-user cost, but a general unit value was adopted from literature to calculate VOC, which limits application by road agencies in different countries. To address these limitations, a practical framework was developed under Objective 3 for road agencies to accurately evaluate network-level pavement maintenance plans based on road condition and economic, environmental, and social performance.

Under the proposed framework, road condition and the economic performance of network-level pavement maintenance plans are evaluated based on road roughness (the IRI) and agency costs, respectively. Compared to the road condition assessment method adopted by Arif et al. (2016), the IRI is more universally accepted and can be adapted to various countries (Du et al., 2014). To assess environmental impact of proposed maintenance plans, the GWP of GHG emissions are evaluated. In addition, road-user costs are considered to assess social sustainability factors including travel delay cost and VOCs generated through fuel use, vehicle repair and maintenance, and tire wear. The impact of variations in the IRI due to different M&R strategies on road user-cost is also included when assessing social performance. By integrating these environmental and social considerations, the proposed framework provides a more realistic representation of sustainability to satisfy budget constraints and road-use requirements. As such, this framework provides support for road agencies seeking to identify optimal results in line with motivations to take increasing responsibility towards sustainability (PIARC, 2019).

It is important to note that the selection of the aforementioned criteria is based on a study by France-Mensah and O’Brien (2019), with modifications to improve completeness and accuracy. France-Mensah and O’Brien (2019) aimed to maximise road conditions and minimise GHG emissions and road-user costs; however, economic aspects were not considered, whereas life cycle agency costs will always be an important consideration for road agencies given the maintenance of pavement networks is an on-going commitment. In addition, in the France-Mensah and O'Brien (2019) model, averaged emissions and road-user cost data were used, which limit accuracy for network-level calculation. For example, the sources of the applied average data were not reported and, second, traffic delays—especially queueing—are impacted by road capacity and on-road traffic volumes. Therefore, queueing does not occur on every road segment and usually only occurs during peak hours. Thus, using averaged data for all road segments can lead to much higher estimated emissions and traffic delay costs compared to real-life cases. In addition, the RR effect can be affected by both road condition and speed limits, which can widely vary between different road segments, and is not captured by averaged data. As such, the use of averaged data can lead to bias in the decision-making process. The proposed hybrid LCA model for estimating GHG emissions from the maintenance and use phases of roads was developed to address these limitations. Importantly, this approach was shown to have higher accuracy than the P-LCA and tiered hybrid LCA methods when used separately (Section 7.1). Moreover, models and data for all of the attributes considered in this study specifically account for differences between road segments, enabling much more accurate calculations.

As multiple attributes have different unit measures, it is not easy to combine them into a single score. As such, a multi-attribute method was developed to compute a combined index that reflects all four attributes simultaneously, as follows. First, weights are allocated to attributes according to their importance. Assigning equal weights is the simplest while still generating good results (Zhang, 2014). For specific applications, road agencies can re-assess these weighting based on their own organisational requirements. Secondly, quantified performance of the proposed maintenance plans is rescaled to fit the range 0 to 1 to enable comparability. Finally, a combined index is computed for each maintenance plan using a WSM. This approach provides a simple method for road agencies to identify optimal network-level pavement maintenance plans.

The effectiveness of proposed framework was demonstrated using eight network-level pavement maintenance plans with different annual maintenance budget ranging from

AUD 50 to 125 million (plans 50M to 125M, respectively). The results show that when equal weights are allocated for the four attributes, the 85M maintenance plan has the lowest agency cost, with an equivalent value of AUD 6,745.06/km per year within the 10-year analysis period. The 50M plan is most costly, with a NAV of AUD 7,388.22/km. This plan also generates the highest GWP of 520.33 tCO_2-e/km. In contrast, the 105M plan generates the lowest GWP of 519.68 tCO_2-e/km. Furthermore, 1,000 random sets of weights were generated for the four attributes to test whether other potentially optimal plans could be identified under the proposed evaluation framework when different weights were assigned. Based on this, plans 85M, 95M, 125M, and 105M were identified as optimal options in 59.6%, 26.6%, 7.7%, and 6.1% of the tested cases, respectively. Such an analysis approach offers a powerful means of identifying the most optimal maintenance plans when road agencies are unable to assign exact weighting to each attribute but, nevertheless, wish to undertake a preliminary evaluation of different maintenance options. Detailed results are available at https://ars.els-cdn.com/content/image/1-s2.0-S1361920921002182-mmc3.xlsx, with an instruction in which road agencies could select a set of weights to approximate their preference and obtain the corresponding optimal scenario.

Due to the different characteristics of the selected cases (e.g., maintenance strategies, maintenance budgets, length of the network, road width, etc.), it is very difficult to compare network-level results to existing studies/projects even when a similar approach was taken. To ensure the accuracy of results, the data and calculated results for separate road segments were carefully checked and/or compared with existing literature/projects wherever possible before they were aggregated. First, for road conditions, the IRI values for each road segment were provided by Main Roads Western Australia, and are, therefore, assumed to be accurate; as the calculation of an average IRI for the network was relatively direct, it is unlikely that this introduced any degree of uncertainty in the results. Similarly, the results for the calculated network-level agency costs are considered reliable. Second, for the calculation of GHG emissions, both the method and results were validated in a previous study by Jiang et al. (2020), whereby more accurate results are obtained for road agencies than process-based or individual tiered hybrid methods. Detailed results for each emission source were also presented and validated in Sections 4.1 and 7.1.

Currently, research on road-user costs remains limited. Salmon et al. (2020) considered economic, environmental, and social sustainability to develop a framework for road treatment selection without reporting their results for separate attributes. France-Mensah and O'Brien (2019) only reported travel delay costs per AADT per lane-mile, whereas vehicle operating costs and lane widths were not reported. Paik (2018) reported the road-user costs for different maintenance strategies applied to 1 m^2 of road pavement; however, annual aggregated road-user costs were calculated for individual road segments, which makes direct comparison difficult. Therefore, to minimise uncertainties, the results of the road-user cost calculations reported here were checked in comparison to the parameters provided by the Transport and Infrastructure Council (2016). Based on the comparison, the magnitude of the differences was relatively small and, therefore, these uncertainties do affect the implementation of the proposed framework.

To investigate the impact of integrating environmental and social sustainability into the proposed framework, a similar random-weighting process to the 1,000 random runs was implemented for a second time, in which environmental and social sustainability factors were excluded. Based on this, the probability that the 85M plan is selected as the optimal option increases by 9% to 68.6%, and the likelihood of the other three plans (i.e., 95M, 105M, and 125M) being selected decrease to 20.8%, 5.0% and 5.7%, respectively. In addition, Figure 7-3 presents the relationships between the selection of optimal plans and the weights of the other attributes when environmental and social factors are excluded. The results show high sensitivity to the weights of the economic and road condition attributes. Thus, a notable trade-off can be identified; as the weighting of economic considerations increase (or the weighting of road condition decreases), the optimal plan shifts from the 125M to 105M and then to the 95M and 85M plan. On the other hand, when road condition is given a higher weighting, the optimal plan shifts from the 85M to the 125M plan.

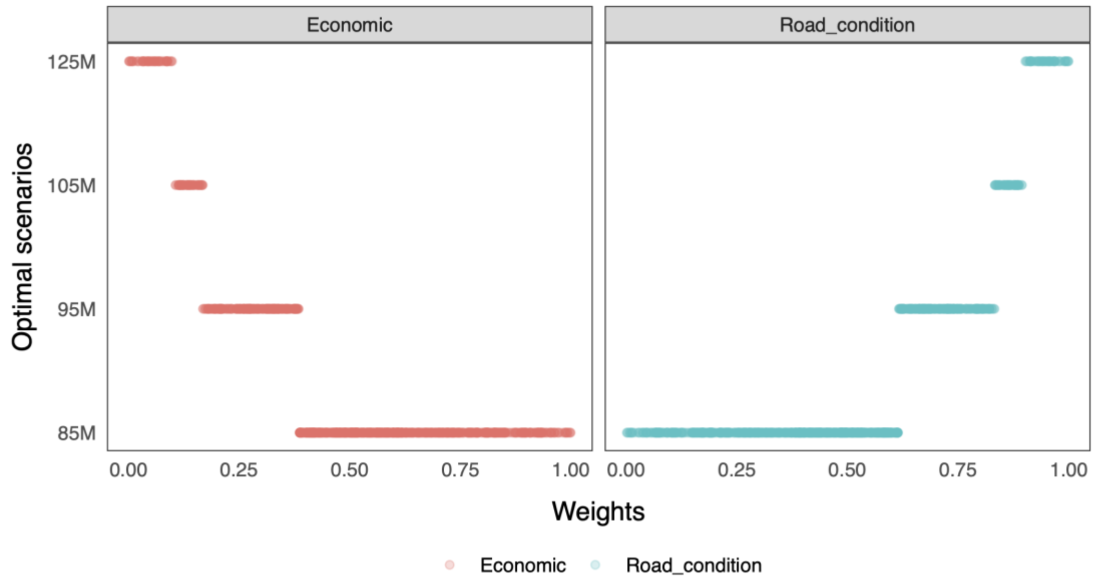

Figure 7-3: Relationships between optimal maintenance plans for the case study WA road network and attributes weighting (traditional method)

Although the applicability of the proposed framework has been demonstrated for a road network in WA, it can also be adopted by road agencies in other countries. Indeed, identifying optimal network-level pavement maintenance plans is a global concern for road agencies given that maintenance funds are often limited and sustainability is becoming an increasingly urgent driver of management decisions. In addition, the data requirements of the proposed framework will typically be easy to fulfil. For example, the index used to represent road condition (i.e., IRI) is a universally adopted index. Furthermore, agency costs and data needed for calculating road-user costs are commonly recorded by road agencies, and data required for environmental assessments, such as direct requirement coefficient matrixes, are regularly published by national government. Finally, many countries have developed national emission databases from which the GHG emission factors can be obtained.

7.3 Developing Strategies for Transport related Carbon Emissions Reduction in Road Use

7.3.1 CO_2 emissions and influencing factors

Based on previous studies examining the CO_2 emissions of the road transport sector, passenger transport generally has higher impacts than freight transport. According to Papagiannaki and Diakoulaki (2009), passenger cars alone contribute approximately half of the emissions from the Greek and Denmark road transport sectors with an upward trend between 1990 and 2005. Kwon (2005) and Hao et al. (2014) also reported that car emissions contribute the largest share of emissions from the road transport sectors of the UK and China, respectively. Based on the results for the U.S. and Australia reported here, passenger transport contributed 70% to the emissions from road transport over the 10-year analysis period. In Australia, where long-distance travel is required, the share of registered diesel cars and light trucks is high and rapidly growing, increasing sharply from 5.0% and 36.4% in 2009 to 11.5% and 59.9% in 2017, respectively (Australian Bureau of Statistics, 2010, 2018). At the same time, the passenger cars and light trucks per capita showed growth of 5.1% and 18.3% between 2009 and 2018, respectively, which was not the case in the U.S. (Sivak, 2017). In addition, much fewer light vehicles are diesel-powered in the U.S. (Matthew Chambers and Rolf Schmitt, 2015), although the considerable mileage travelled by cars and light trucks likely explains the high contribution of passenger transport to CO_2 emissions in the U.S. (Bureau of Transportation Statistics, 2020). Moreover, in both countries, cars and light trucks accounted for over 95% of all passenger transport CO_2 emissions, which explains why light vehicles are often targeted as part of emissions reduction measures (e.g., Climate Change Authority, 2014; Pew Center on Global Climate Change, 2008).

The overall change in CO_2 emissions in the passenger transport sector was -75.80 million tonnes in the U.S. between 2008 and 2017, and 6.64 million tonnes between 2009 and 2017 in Australia. In both countries, energy intensity was the most significant contributing factor driving these reductions. This concurs with several previous studies including Kwon (2005), who reported that improvements in fuel efficiency drive most of the car-related CO_2 emissions reductions in the UK. Millard-Ball and Schipper (2011) also identified energy intensity as a dominant driver for passenger travel-related CO_2 emissions in eight industrialised countries including the U.S. and Australia, which dropped over time. The reduction in energy intensity, especially for petrol, had the largest negative contribution to emissions from the U.S. passenger transport, accounting for -203.06 million tonnes of CO_2; the absolute value of this change is higher than any other positive effect, such as population and passenger transport intensity. In Australia, the influence of energy intensity on changes in CO_2 emissions accounted for -1.64 million tonnes. This indicates that improved energy efficiency is one of the most efficient strategies towards emissions reduction. While the U.S. has launched a series of programmes to reduce energy intensity, such as setting vehicle emissions standards and using renewable fuels, Australia has benefited mostly from importing vehicles from other countries with mandatory vehicle emissions standards (Climate Change Authority, 2014; Dowling, 2020). Furthermore, while the total energy intensity decreased in Australia during the analysis period, the energy intensity of diesel increased. In addition, overall energy intensity is higher in Australia than in the U.S., especially for diesel fuel, suggesting significant potential for emissions reduction through measures aimed at reducing energy intensity in Australia.

In contrast to the influence of changes in energy intensity in reducing emissions, population contributed the most to the increase in CO_2 emissions in this sector. Papagiannaki and Diakoulaki (2009) also observed a positive effect of population on CO_2 emissions in Denmark and Greece. Similarly, Kwon (2005) conducted a decomposition analysis of car emissions in the UK and found that population contributed to the growth in CO_2 emissions. Based on the results reported here, population growth contributed 75.89 and 7.53 million tonnes of CO_2 emissions in the U.S. and Australia, respectively, over the 10-year analysis periods. Notably, the effect of population was stronger than any other factor in Australia.

In previous studies, passenger transport intensity (i.e., VMT per capita) is often identified as the dominant driver of increases in CO_2 emissions from road passenger transport. For example, Kwon (2005) identified per capital car driving distance as the dominant factor in the UK, the growth of which was associated with increasing per capital car trip distance and a decreasing occupancy rate. Passenger transport intensity was also identified as an important contributing factor in this study, although this had a positive effect on emissions in the U.S. but a negative effect in Australia. While the average occupancy rate of the U.S. stayed unchanged during the analysis period (EERE, 2018), the main reason for the increasing passenger transport intensity has been the growth of per capita income. In Australia, the decrease in passenger transport intensity might be attributed to the growing preference of passengers for air transport (AU BITRE, 2019). As such, encouraging people to travel more by mass transit methods, such as rail or air, could be a strategy for reducing emissions from road transport; however, future studies are needed to further investigate the CO_2 efficiency of different transport modes, so that emissions across the entire transport sector are reduced.

The aggregated changes in CO_2 emissions from the freight transport sector were 92.41 million tonnes in the U.S. between 2008 and 2017, and 2.58 million tonnes in Australia between 2009 and 2017. GDP and freight transport intensity were the most significant drivers of increases and decreases in CO_2 emissions from this sector, respectively. This concurs with Li et al. (2013), who identified economic growth as the dominant positive factor and freight transport intensity as the most significant negative factor in emissions from the freight transport sector of China. Domestic economic growth was also recognised by Wang et al. (2012c) as the largest contributor to the growth in carbon emissions from China's freight transport sector. In addition, Mraihi and Harizi (2014) identified freight transport intensity as a positive factor in Tunisia's freight transport emissions, which is the opposite to the findings of this study. This may reflect that developed countries (e.g., the U.S. and Australia) often have a higher share of the service sector in their economic structures than developing countries (e.g., Tunisia), and the service sector relies less heavily on freight transport than agriculture and industry (Central Intelligence Agency, 2017). The effect of such differences could be further investigated in future studies by considering developing countries in more detail.

7.3.2 Policy implications

Comparing the decomposition results of the road passenger and freight transport sectors, the following key findings are highlighted:

- Population and GDP are the dominant factors driving increases in CO_2 emissions from passenger and freight transport, respectively. As the growth of populations and economies is projected to continue, decreasing the emissions intensity will be critical (Australian Government, 2015).

- Energy intensity has the dominant effect on reducing passenger transport CO_2 emissions and also has a significant impact on changes in freight transport CO_2 emissions.

- Passenger and freight transport intensity also have an important influence on changes in CO_2 emissions from passenger and freight transport, respectively.

Based on these findings, several policy recommendations can be made with regard to reducing energy intensity and passenger/freight transport intensity. Measures could be made related to three aspects, namely 1) fuels used for transport, 2) energy intensity of vehicles, and 3) transport distances and intensity.

First, to reduce the energy intensity of fuels used for transport:

- Setting low-carbon fuel standard that encourages both the supply and use of renewable fuels. The U.S. has already set a renewable fuel standard programme to encourage the use of renewable fuels such as ethanol and biodiesel (U.S. EPA, 2020). California also set a low-carbon fuel standard to increase the availability of low-carbon and renewable fuels (California Air Resource Board, 2020). Generally, medium/heavy trucks have lower fuel demand for ethanol than diesel per km travelled, and the combustion of 1 kL of biodiesel generates less GHG emissions than diesel (TAGG, 2013). Therefore, this measure is also recommended for Australia.

- Providing cleaner fuels. Renewable fuels can largely reduce carbon emissions. However, it still takes time for their penetration and share in the market to gradually increase. Therefore, providing cleaner fuels—especially petrol and diesel considering their dominant share in transport—could prove beneficial (Mraihi and Harizi, 2014).

Second, there is a wide range of possible measures to reduce the energy intensity of vehicles:

- Mandating a vehicle emissions standard is highly recommended, as has been implemented by many countries such as the U.S., EU countries, and China (Climate Change Authority, 2014). Although Australia also benefits from such standards by importing vehicles from these countries, the benefits are limited without a national mandate because lower-emission vehicles always go first into markets with higher standards (Climate Change Authority, 2014).

- Another strategy is to sponsor or encourage green vehicle technologies. The Green Racing program sponsored by the U.S. government is one example, which aims to transfer technological innovations in the racing industry, such as fuel-efficient vehicle technologies, to passenger vehicles. Electric vehicles are another promising technology, as most states in the U.S. have reduced carbon emissions from generating electricity from natural gas, wind, and solar energy (Saha, 2020). Renewable energies such as hydro, solar, and wind are also increasingly used in electricity generation in Australia, accounting for 21% of the total electricity generation in 2019 (Australian Government, 2020b). The CO2 emissions from electric vehicles entirely powered with renewable electricity can be reduced to 6 gCO2/km (Climate Council, 2017).

- To promote such technologies, a feebate programme, which rewards energy-efficient and penalise under-complying practice relative to a certain standard, could be established to encourage the manufacturing and selling of electric and hybrid vehicles (Pew Center on Global Climate Change, 2008). The ERF could also be a good source of funding in Australia.

- Moreover, labelling vehicles with fuel-use information can encourage the purchase of fuel-efficient vehicles, which has been adopted in both the U.S. and Australia (Climate Change Authority, 2014).

Finally, the beneficial effects of reducing energy intensity can be easily offset by increased passenger/freight transport distances, as observed in the U.S. As such, several measures could be adopted:

- Intelligent transport systems. This has been adopted by many countries to improve transport efficiency and reduce travelling distances.

- Land-use and development planning that favours locating communities, shopping facilities, businesses, and public transport stations close to each other can effectively reduce driving distances by 20–30% compared to conventional development (Pew Center on Global Climate Change, 2008). Similarly, better locating related industries could help reduce freight transport distances.

- In addition, public signs can be used to encourage alternative transport modes such as walking, cycling, public transport (for passenger transport), and rail (for passenger/freight transport).

For policy implementation, the three levels of government can play different roles; federal government sponsors the research and development of technologies, such as intelligent transport systems, and provides funding including the REF in Australia; State governments decide the allocation of these funds; and local governments are more engaged in practical measures, such as improving land-use planning (Parlow, 2007).

7.4 Greening the Road Construction and Transport Sectors

Sustainable development has been recognised worldwide and net zero emissions is becoming a global trend under the Paris Agreement. Infrastructure provides the basis for economic and social activities including work, education, and everyday life. According to the ISCA (2020), infrastructure is responsible for 70% of Australia's GHG emissions, with a 15% direct impact (e.g., procurement, construction and maintenance work, and decommissioning) and a 55% indirect influence (i.e., end-use). In addition, the design and operation of infrastructure shapes the future due to its on-going use. As roads consume the largest proportion of spending (36%) among all kinds of infrastructure in Australia, greening the road construction and transport industries is critical for a net zero emissions future.

Generally, the greening of an existing industry (e.g., construction, transport, etc.) requires renewal or restructuring of the industry (Trippl et al., 2020). Entrepreneurial discovery is recognised as the first step for such industrial renewal, followed by a structural change of the industry (Foray, 2014). In the road sector, entrepreneurial discovery means that relevant knowledge and activities are spread among a wide-range of stakeholders, such as firms in the supply chain, universities and research and development (R&D) institutions, non-profit organisations, and governments. This can happen through two ways (Kyllingstad and Rypestøl, 2018). First, firms can exploit knowledge exploitation in the pursuit of profits. With more firms seeing the potential profitability and becoming involved, a systematic knowledge-sharing platform and governmental regulations follow to enable knowledge transfer and innovation. The key for the success of this route is that the profitability of greening the industry is well demonstrated to attract the involvement of more firms. Second, and opposite to the first path, is that governments, universities, and other R&D institutions establish innovation opportunities and knowledge-sharing platforms first, which are then utilised by firms. The successful initiation of this route relies heavily on the provision of opportunities that can be identified by firms.

In Australia, the greening of road construction and transport is primarily driven by non-profit organisations. For example, the Climate Change Authority (2014) proposed to mandate light vehicle emissions standards to lower road transport emissions. In addition to mandatory emissions standards, the Climate Council (2017) also recommended increasing the use of public transport and electric vehicles. Moreover, the Infrastructure Sustainability Council of Australia (ISCA) has made various efforts to support sustainability in the infrastructure sector. These includes developing training programmes, providing knowledge-sharing opportunities, and operating the Infrastructure Sustainability (IS) rating scheme (ISCA et al., 2020). It is, therefore, inferred that the second pathway of greening the road sector could be followed to accelerate the greening process in Australia. As such, governments are important actors that can create opportunities and provide directions for firms and industries to follow. However, the Australian government does not always incorporate sustainability in its infrastructure projects. Wider mandating of emissions standards and best practice (i.e., the IS rating scheme) is, therefore, still needed (ISCA, 2019). Indeed, the Australia Infrastructure Audit (2019) has warned of the risks of failure in achieving the national emissions reduction targets without government action.

Different levels of government play different but equally important roles. Generally, federal government is more concerned with international issues and Commonwealth-relevant policies, whereas local governments are more aligned with everyday decisions and actions that directly impact the environment (Thomas, 2010). This thesis specifically conducted research at local and national levels. The expectation is to help governments initiate and develop knowledge of the road sector greening process. Under Objective 2, a hybrid LCA method was proposed for local road agencies to accurately assess GHG emissions from the use and M&R phases of road infrastructure. The accurate evaluation and analysis of the climate change impact of roads is critical to demonstrate the importance of road infrastructure in achieving a net zero emissions future. In addition, by considering sustainability, road agencies could motivate more firms (e.g., local contractors) to adopt sustainable materials and/or M&R techniques.

Objective 3 integrated the proposed method into a framework for road agencies to assess and select optimal network-level pavement maintenance plans. Under this framework, the maintenance plans that maximise the long-term sustainability of road infrastructure can be identified, and such network-level M&R plan decisions directly influence the M&R work of local firms (e.g., contractors and suppliers).

At the national level, the main factors driving changes in emissions from Australia's road sector were revealed and policy recommendations were proposed correspondingly. These results contribute to the knowledge of policy alternatives that are potentially most effective for reducing carbon emissions. As cautious as the Australian government is, this knowledge should provide a solid reference and motivation to take action, initiating and revealing opportunities for greening the road sector (e.g., electric cars).

7.5 Chapter Summary

This chapter discussed the results of the three research objectives of this thesis. For Objective 2, the implementation of the hybrid LCA method developed for the use and M&R phases of roads was presented. In addition, the proposed method was compared to individual P-LCA and tiered hybrid LCA methods. The comparison showed that the proposed method can help road agencies achieve more accurate results. Under Objective 3, the implementation of the proposed framework integrating environmental and social sustainability into the evaluation and selection of optimal network-level pavement maintenance plans was discussed. This showed that the integration of environmental and social sustainability is necessary, as these significantly affect the selection of optimal plans when given higher weighting. In addition, it was suggested that the proposed framework can be applied in many countries. Under Objective 4, the emissions evaluation and decomposition results were discussed in comparison to previous studies. Several policy recommendations were proposed based on these results, which provide a valuable reference for policymakers in the U.S., Australia, and other countries with similar characteristics. Overall, this research was conducted with the aim of promoting the production and dissemination of knowledge on the greening of the road sector, especially among government agencies, so that the greening process can be effectively initiated.

Chapter 8. Conclusions, Implications, and Future Research

This chapter concludes this research. Section 8.1 summarises the main findings following the sequence of Objective 1 to 4; Section 8.2 highlights the theoretical and practical contributions and implications of the work; and the limitations of the research and recommendations for future research are stated in Section 8.3.

8.1 Summary of Key Findings and Recommendations

8.1.1 Research findings and recommendations of Objective 1

Objective 1 - conducts an intensive review on existing studies related to road emissions evaluation and reduction.

8.1.1.1 Research findings

Under Objective 1, a systematic review was conducted on LCA studies on road infrastructure to investigate current developments and their implementation, and identify limitations and future directions in this research field. The main findings of this review can be summarised as follows:

- Two general themes exist in existing studies—the application of LCA in the roads sector and modelling-based development of LCA.
- To date, P-LCA is the most commonly adopted approach.
- Most current applications have a project-oriented goal of study and are inconsistent in their selection of FUs; lack consideration of the M&R, use, and EOL phases; involve a high degree of uncertainty resulting from limited reporting of data sources, and sensitivity and uncertainty analyses; and highlight the lack of a standardised way of conducting impact assessment.

8.1.1.2 Research recommendations

The implications of the inconsistencies identified in existing studies are manifold, including that:

- Project-level studies have limited applicability for policymaking. It is, therefore, recommended that future studies pay more attention to the network-level analysis.

- The non-standardised procedures for conducting LCAs of roads hinders their further development and implementation. Future studies should seek to standardise and tailor LCA methods to align them with the specific characteristics of the roads being considered.
- Existing studies fail to consider the time effect of environmental impact evaluation, causing difficulties in decision-making between alternative road designs intended to function for a long period of time. Road LCAs should, therefore, better consider dynamic changes in environmental impacts arising from GHG emissions.

8.1.2 Research findings of Objective 2

Objective 2 - proposes and illustrates a hybrid LCA approach that can be used by road agencies to estimate GHG emissions specifically for the use and M&R phases of roads.

8.1.2.1 Research findings

Under Objective 2, a structured hybrid LCA approach to evaluate the GHG emissions from the use and M&R phases of roads was proposed following the four steps of LCA proposed in ISO 14044 (2006). Under the proposed approach, a hybridisation of the PXC and tiered hybrid LCA methods is adopted to improve the accuracy of LCA results. Specifically, the PXC method is proposed for evaluating on-site work (materials and on-site equipment use) and the tiered hybrid method is recommended for evaluating traffic delays and RR.

Using a case study of a road network in WA, this proposed approach was demonstrated, yielding the main findings:

- The average GWP of the roads in WA was estimated at 467.8 t CO_2-e/km in 2017 and is projected to gradually increase to 589.5 t CO_2-e/km by 2026.
- The use phase was identified as a significant contributor to the overall GWP, accounting for an average of 99.2% of the total between 2017 and 2026. Compared to the use phase, the M&R phase was calculated to contribute an average of just 1.58 t CO2-e/km (0.3%) during the period 2017–2025, increasing sharply to 30.6 t CO_2-e/km by 2026 and accounting for 5.2% of the total annual GWP.
- Based on a sensitivity analysis, the GWP of the case study network is most sensitive to AADT.

- The spatial distribution of GWP across the whole road network indicates that heavy traffic roads in metropolitan areas and freeways with heavy traffic (AADT > 20,000) are the most carbon intensive.

8.1.2.2 Management recommendations

Based on the findings of Objective 2, the following management recommendations are made:

- Given its dominant role, the use phase should be prioritised when establishing emissions reduction strategies.
- Considering the significant impact of AADT on the results, road agencies seeking to reduce emissions should pay special attention to managing increasing in this variable.
- The most carbon-intensive road segments (i.e., roads in metropolitan areas and/or freeways with AADT > 20,000) should be prioritised when establishing strategies (e.g., M&R strategy) to reduce carbon emissions.

8.1.3 Research findings of Objective 3

Objective 3 – proposes and demonstrates a straightforward method for road agencies to integrate the proposed hybrid LCA approach in evaluating and selecting optimal network-level pavement maintenance plans.

8.1.3.1 Research findings

Under Objective 3, a framework that integrates the proposed hybrid LCA approach was developed to help road agencies select optimal network-level pavement maintenance plans based on pavement condition and economic, environmental, and social sustainability. The IRI, agency costs, GHG emissions, and road-user costs are evaluated under this framework. The specific condition and characteristics of each road segment are considered when modelling of the four attributes to enable more accurate calculations. To combine the four attributes and ensure comparability between different network-level pavement maintenance plans, a multi-attribute decision-making method is then applied to convert the results into a single index.

The proposed framework was demonstrated using eight network-level pavement maintenance plans with annual budgets of AUD 50, 60, 70, 85, 95, 105, 115, and 125 million. Based on this, the following main conclusions can be drawn:

- Road condition and social performance improve as maintenance budgets increase, whereas this pattern is not identified in economic and environmental performance.
- When equal weight is given to the four attributes, the 85M plan was identified as the optimal maintenance plan for the studied network. By assigning different weights to the four attributes, the 85M, 95M, 125M, and 105M plans are also identified as potentially optimal solutions.
- Integrating environmental and social sustainability in the framework is necessary, as these significantly affect the optimal plan selected when given higher weighting.
- The proposed framework provides a straightforward method for road agencies to select optimal network-level pavement maintenance plans, or can be applied to obtain preliminary insights when the precise weighting of each sustainability attribute cannot be accurately obtained.

8.1.3.2 Management recommendations

Based on the findings of Objective 3, it is recommended that road agencies take the environmental and social performance of pavement maintenance plans into consideration when they are allocating maintenance budget. In this way, the maintenance plans that maximise the long-term sustainability of road infrastructure can be performed, and such network-level M&R plan decisions directly influence the M&R work of local firms (e.g., contractors and suppliers) to act more sustainably.

8.1.4 Research findings of Objective 4

Objective 4 – identifies the influencing factors which contribute to the changes in CO_2 emissions from the Australian road transport sector and provide recommendations for policy-making based on comparisons with other countries with similar characteristics such as the U.S.

8.1.4.1 Research findings

Under Objective 4, the energy-related CO_2 emissions of the U.S. and Australian road transport sectors between 2009 and 2017 were evaluated. The calculated CO_2

emissions of these two countries were also decomposed to identify and compare those factors driving change over time. Based on this, the following key findings are highlighted:

- Cars and light trucks (from passenger transport) and medium/heavy trucks (from freight transport) are significant contributors to road transport CO_2 emissions.
- Six factors were considered as contributors to CO_2 emissions from the road passenger transport sector, namely emission factors, transport structure, energy structure, energy intensity, passenger transport intensity, and population. During the analysis period, population was identified as the dominant positive factor while reductions in energy intensity were most effective at reducing CO_2 emissions in both countries. Passenger transport intensity also had significant impacts on the changes in CO_2 emissions.
- Similarly, changes in CO_2 emissions from the freight transport sector were decomposed into emission factors, transport structure, energy structure, energy intensity, freight transport intensity, and GDP. Of these, GDP had the most significant impact on increase in CO_2 emissions during the analysis period. In addition, the decrease in freight transport intensity was effective at reducing CO_2 emissions from freight transport.

8.1.4.2 Policy recommendations

Based on the findings, the following policy recommendations are made:

- For fuels used in transport in Australia, setting low carbon fuel standards to increase the availability of low-carbon and renewable fuels should be adopted, as has been applied in the U.S.
- To reduce the energy intensity of vehicles, mandating a vehicle emissions standard is highly recommended. Sponsoring and encouraging green vehicle technologies, such as electric vehicles, would also prove beneficial. A feebate program or government funding schemes, such as the ERF in Australia, could encourage the manufacturing and selling of electric and hybrid vehicles. Moreover, ensuring fuel-usage information labels are present on vehicles will likely help increase the purchase of fuel-efficient vehicles, as has already been adopted in both the U.S. and Australia.

- With regard to reducing transport distances and intensity, many countries including the U.S. and Australia have begun to adopt intelligent transport systems. By placing communities, shopping facilities, businesses, and public transport sites close to each other, effective land-use and development planning can also shorten driving distances. Similarly, better positioning of related industries can help shorten freight distances.
- In addition, public signage could be used to encourage alternative modes of transport such as walking, cycling, public transport (for passenger transport), and railway (for passenger/freight transport).

8.2 Contributions and Implications

8.2.1 Theoretical contributions

This research aimed to support reductions in GHG emissions from the Australian road transport sector to help achieve the 26–28% reduction target of the Australian government. To achieve this aim, the research was carried out at both the local and national level.

1. **A hybrid LCA method specifically developed for evaluating GHG emissions from the use and M&R phases of roads**

A hybridisation of the PXC and tiered hybrid LCA methods has been proposed for evaluating GHG emissions from the use and M&R phases of roads to increase the accuracy of results. In existing LCA studies on roads, the use and M&R phases are less frequently included compared to other phases such as materials production and construction phases. In addition, the use and M&R phases have mostly been modelled using the P-LCA method, especially the use phase; however, due to cut-off errors, this method may lead to the underestimation of emissions. Whilst some studies have modelled the M&R phase using a hybrid method, traffic delays and the use phase have not been considered. Through a literature review, a PXC method based on an EIO framework was identified as offering a complete system boundary and also avoids issues such as double-counting. Under the proposed approach, the PXC method is used to model GHG emissions from materials and on-site equipment use and, as traffic delays and RR in the use phase are difficult to assign to an economic sector, the tiered hybrid method is recommended. The proposed hybrid approach provides more accurate results than the P-LCA and tiered hybrid methods when used individually.

2. **A framework for integrating environmental and social sustainability into traditional assessments of network-level pavement maintenance plans**

A framework has been proposed to integrate environmental and social sustainability in the evaluation and selection of optimal network-level pavement maintenance plans. In traditional assessment, road condition and economic performance are usually considered by road agencies, whilst environmental and social sustainability can be overlooked. To achieve emissions reductions, LCA results need to be coupled with real-life decision-making. There is also a growing recognition of social performance in road maintenance plan assessment. As such, this research advocates the integration of environmental and social performance into network-level pavement maintenance plan assessments to maximise sustainable benefits. Given that the proposed framework is based on relatively easily available datasets, it can also be adapted to the requirements of different countries.

3. **Contributing to the domain knowledge of identifying the key factors driving changes in CO_2 emissions from the Australian road transport sector**

LCA studies can help local road agencies select more sustainable maintenance plans; however, LCA results can have limited implications for policymakers. The basis for formulating relevant policies to achieve emissions reduction is to accurately estimate emissions and reveal the driving factors underpinning past changes in emissions. For the Australian road sector, these driving factors have remained largely unknown. This research contributes to knowledge by identifying the factors driving CO_2 emissions changes in this sector between 2009 and 2017. In addition, existing studies have often overlooked the specific characteristics of passenger and freight transport, considering the road transport sector as a whole. This practice may lead to inaccurate results. In this research, passenger and freight transport were considered separately. Correspondingly, the respective driving factors for passenger and freight transport emissions have been revealed as a valuable reference for policy-making. By comparing to the U.S., these findings have wider applicability to other countries, especially those with similar socioeconomic characteristics and systems of governance.

8.2.2 Practical implications

The primary motivation of this research was to provide reference evidence and recommendations to help reduce GHG emissions from the Australian road transport sector so as to support the national emissions reduction targets.

As road M&R is increasingly favoured by road agencies over new construction, the lifecycle emissions of different M&R strategies need to be accurately assessed to inform decision-making. As such, a method for road agencies to accurately evaluate emissions from M&R works and the use of roads after M&R treatment is required. Existing guides and tools in Australia (e.g., the Carbon Gauge Calculator tool) often focus on materials production and construction phases, overlooking the use and M&R phases of roads. This research has proposed a hybrid LCA method specifically designed for the use and M&R phases, enabling more accurate GHG emissions evaluation results to inform road agency decision-making. The case study of a road network in WA was used as a step-by-step example of implementation.

Road agencies usually consider agency costs and road condition when selecting network-level pavement maintenance plans. To achieve emissions reductions, it is imperative that environmental impact (i.e., GHG emissions) is also considered in the decision-making framework. By integrating LCA results in maintenance plan evaluations, this research proposes a decision-making framework that can assist road agencies select the most optimal network-level pavement maintenance plan to maximise sustainable benefits, as demonstrated by the WA case study. In addition, the results of 1,000 random model runs provide preliminary insights for road agencies for whom the weightings of sustainability attributes cannot be accurately obtained. This should help reduce infrastructure related GHG emissions from the Australian road sector.

To further reduce the GHG emissions, the policy implications of this research have been elaborated (Section 7.3.2). Referencing the factors driving changes in U.S. road transport related CO_2 emissions and the strategies adopted by other countries, several policy recommendations were proposed for Australian government. These recommendations are primarily related to the energy intensity of fuels used in vehicles, the energy intensity of vehicles, and transport distances and intensity. The proposed measures provide a valuable reference for policymakers seeking to achieve emissions reductions in the Australian road transport sector.

8.3 Limitations and Future Research

This section identifies the limitations of this research. Under Objective 2, the VTI model used in the hybrid LCA model was based on empirical data obtained in Sweden. There is some uncertainty, therefore, when applying the model to other countries including Australia. Although the results show that differences generated by using different models are insignificant, this uncertainty still requires further investigation. In addition, averaged values for the mass of cars and trucks were used in model estimating RR impact; due to the lack of accurate data for each road segment, the impact of vehicle mass is not captured and should be considered in future studies. Furthermore, national GHG emissions inventories and emissions factors were obtained in form of CO_2-e meaning that temporal effects on GWP were not captured in this study.

Under Objective 3, considering applicability and data accessibility, only roughness and GHG emissions were considered for road condition and environmental sustainability, respectively. Therefore, future studies are recommended to include more indicators. Due to the unique characteristics of the selected cases (e.g., the maintenance strategies, maintenance budgets, the selected functional unit, road width, etc.), it is very difficult to compare the results of the case study to existing studies even where a similar approach was adopted. Therefore, the uncertainty in the case study results should be considered if they are to be applied, although this does not affect the implementation of the proposed framework. In addition, the weights of the attributes were generated through random model runs; future research may consider obtaining more accurate weights by other methods, such as a trade-off or an analytic hierarchy process method, to provide agency-specific recommendations.

Under Objective 4, due to limited data on energy consumption in the Australian transport sector, data were collected and analysed every other year, meaning that some important information might have been lost. Results could be improved, therefore, if a more complete dataset was available. In addition, as road transport emissions were not examined by state, the effects of population distribution have not yet been fully captured. Lastly, as this research specifically considered developed countries with similar socioeconomic and governance contexts, further studies are required to investigate the applicability of the knowledge to developing countries to enable wider comparison and support the broader application of this research.

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Appendices

Appendix A. List of publications arising from this thesis

A. Journal papers

1. **Jiang, R.**, Wu, C., Song, Y., & Wu, P. (2020). Estimating carbon emissions from road use, maintenance and rehabilitation through a hybrid life cycle assessment approach–A case study. Journal of Cleaner Production, 277, 123276.
2. **Jiang, R.**, & Wu, P. (2019). Estimation of environmental impacts of roads through life cycle assessment: a critical review and future directions. Transportation Research Part D: Transport and Environment, 77, 148-163.
3. **Jiang, R.**, Wu, P., & Wu, C. Selecting the optimal network-level pavement maintenance plan based on sustainable considerations. (Under review).
4. **Jiang, R.**, Wu, P., & Wu, C. Driving factors behind carbon emissions in the road transport sectors in Australia and the U.S. from 2009 to 2017: a decomposition analysis. (Under review)

B. Conference papers

1. Jiang, R. & Wu, P. (2018). Life Cycle Assessment Methods of Road Infrastructures – Insights from Past Studies. *In* International Conference on Construction Project Management and Construction Engineering (iCCPMCE).

Appendix B. Summary of highly cited LCA studies in roads: goal of study and functional parameters

Citation	Study	Goal of study	Location	Functional unit	Roadway classification	Lane width	Shoulder width	Layers & thickness	Lanes type & number	Analysis period
67	Chiu et al. (2008)	Material evaluation	China (Taiwan)	Length: per lane-kilometre	-	2.65 m	-	5 cm	Asphalt, 1	40 years
58	Treloar et al. (2004)	Road evaluation	Australia	Length: 5 km	Rural roads	-	-	-	Various, -	40 years, 20 years
53	Chowdhury et al. (2010)	Material evaluation	US	Length: 1 km	-	2.5 m	-	600 mm	-, -	-
53	Birgisdottir et al. (2006)	Material evaluation	Denmark	Length: 1 km	Secondary road	3.5 m	2.1 m	0.7 m in total	Asphalt, 2	100 years
53	Birgisdottir et al. (2007)	Material evaluation	Denmark	Length: 1 km	Secondary road	7 m in total	-	0.37 m	Asphalt, -	100 years
52	Wang et al. (2012b)	Alternative design	US	-	Rural road	-	-	-	Both asphalt and concrete, -	-

Citation	Study	Goal of study	Location	Functional unit	Roadway classification	Lane width	Shoulder width	Layers & thickness	Lanes type & number	Analysis period
50	Huang et al. (2009)	Alternative design	UK	Length: 2.6 km	-	3.5 m	-	200 mm base; 60 mm binder course; 40/50 mm layer	Asphalt, 2	-
50	Vidal et al. (2013)	Material evaluation	Spain	Length: 1 km	1,000 vehicles per day (8% heavy vehicles)	13 m	-	0.08 m asphalt layer	Asphalt, 2	40 years
45	Carpenter et al. (2007)	Material evaluation	US	Length: 305 m	Highway	10.4 m	1.5 m	Various	Asphalt, -	-
44	Cass and Mukherjee (2011)	Road evaluation	US	Length: per lane mile	Highway	24 feet	-	-	Concrete, 4	-
39	Yu and Lu (2012)	Alternative design	US	Length: one km overlay system	Highway	3.6 m	1.2 m, 2.7 m	225 mm PCC surface; 250 mm base course	Various, 2*2	40 years
31	Olsson et al. (2006)	Material evaluation	Sweden	Length: 1 km road	-	-	-	-	-, -	-
29	Loijos et al. (2013)	Road evaluation	US	Various	Various	Various	Various	Various	Concrete, various	40 years

Citation	Study	Goal of study	Location	Functional unit	Roadway classification	Lane width	Shoulder width	Layers & thickness	Lanes type & number	Analysis period
29	Jullien et al. (2006)	Material evaluation	France	Area: a 3.8 m × 150 m road section	-	3.8 m	-	0.07 m	Asphalt, -	-
28	Anastasiou et al. (2015)	Material comparison	Greece	Length: 1 km	Urban road (low traffic)	7.3 m in total	-	-	Concrete, 2	40 years
28	Aurangzeb et al. (2014)	Material evaluation	US	Length: a 1.6 km lane	-	-	1.8 m	254 mm binder course; 51 mm surface course	Asphalt, 1	45 years
28	Oliver-Sola et al. (2009)	Alternative design	Spain	Area: 1 m^2 of sidewalk	Urban	-	-	All layers	Concrete, -	45 years
26	Roth and Eklund (2003)	Material evaluation	Sweden	-	-	-	-	-	-, -	-
25	Tatari et al. (2012)	Material comparison	US	Length: 1 km	-	7.2 m (total)	-	Different asphalt surface layer; 10 in. base course layer	Asphalt, 2	30 years
23	Giani et al. (2015)	Material evaluation	Italy	Length: 1 km	Suburban road	15 m (total)	-	25 cm	Asphalt, 2 × 2	30 years

Citation	Study	Goal of study	Location	Functional unit	Roadway classification	Lane width	Shoulder width	Layers & thickness	Lanes type & number	Analysis period
13	Santos et al. (2017b)	Material evaluation	US	Length: 1 km	Highway	3.66 m	-	-	Asphalt, 2	50 years
11	Farina et al. (2017)	Material evaluation	-	Length: 1 m of built pavement layer	-	Depending on the project	-	Depending on the project	Asphalt, -	18 years, 20 years

Notes:

1. '-' = not specified;

2. Highly cited indicates the twenty most-cited papers and two recent highly cited publications with more than 10 citations.

Appendix C. Highly cited LCA studies on roads. LCI method, database and tool, impact categories, and sensitivity and uncertainty analysis are indicated

Study	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Wang et al. (2012b)	Combined models	Stripple (1998); Athena Institute (2006); EcoInvent; USLCI; Cement LCI by PCA	-	Energy use; Greenhouse gas (GHG) emissions	√	√
Birgisdottir et al. (2006)	P-LCA	Standard sources, i.e., Stripple (2001); Environmental Design of Industrial Products database	ROAD-RES model	Leaching of heavy metals and salts from the bottom ash; Resource and energy consumption; Emissions (CO_2, NO_x); Salts used for road salting	×	×
Vidal et al. (2013)	P-LCA	Field study; Ecoinvent; Published literature	SimaPro	All 18 ReCipe midpoint impact categories; 3 ReCipe endpoint damage categories; cumulative energy demand	×	√
Giani et al. (2015)	P-LCA	Key processes: Company survey;	SimaPro 7.3	All 18 ReCipe midpoint impact categories	×	√

Study	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
		Upstream processes: Ecoinvent database; published literature				
Oliver-Sola et al. (2009)	P-LCA	Ecoinvent 1.2 database	EcoConcrete LCA tool	Abiotic depletion potential; Acidification potential; Eutrophication potential; Global warming potential (GWP); Human toxicity potential; Ozone layer depletion potential; Photochemical ozone creation potential	×	√
Chiu et al. (2008)	P-LCA	Eco-indicator 99	-	Energy sources; Resources	×	×
Chowdhury et al. (2010)	P-LCA	Published literature; CMLCA	CMLCA	Acidification potential; Aquatic ecotoxicity potential; Aquatic sediment ecotoxicity potential; Energy consumption; GWP; Human toxicity potential; Terrestrial ecotoxicity potential	×	×
Huang et al. (2009)	P-LCA	Published literature and publications	VISSIM, EnvPro	Acidification; Eco-toxicity; Eutrophication; Global warming;	×	×

Study	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
				Human toxicity; Photo-oxidant formation		
Loijos et al. (2013)	P-LCA	Published literature and LCI databases	-	GWP	√	×
Yu and Lu (2012)	P-LCA	Portland Cement Association; Swedish Environmental Research Institute	-	Energy (Primary and feedstock); GHGs (CO_2, CH_4, N_2O, VOC, NO_x, CO, PM_{10}, SO_x)	√	√
Birgisdottir et al. (2007)	P-LCA	-	ROAD-RES model	Acidification; Ecotoxicity in water/soil; Global warming; Human toxicity via air/water/soil; Nutrient enrichment; Photochemical ozone formation; Stored ecotoxicity to water/soil; Stratospheric ozone depletion	√	×
Olsson et al. (2006)	P-LCA	-	-	Emissions to air (SO_2, NO_x, CO, CO_2, HC, CH_4, VOC, N_2O, and particles) and water (COD, N-tot, Oil, Phenol, As, Cd, Cr, Cu, Ni, Pb, and Zn);	√	×

Study	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
				Resources use (natural aggregates and energy)		
Jullien et al. (2006)	P-LCA	-	-	Odours; PAH; VOCs	×	×
Anastasiou et al. (2015)	P-LCA	-	SimaPro 7.1	GWP_{100}; Resource use	√	×
Farina et al. (2017)	P-LCA	-	SimaPro 7.3	17 ReCiPe midpoint categories; 3 ReCiPe endpoint damage categories	×	×
Cass and Mukherjee (2011)	Hybrid	Site investigation using FieldManager	SimaPro 7, EIO-LCA, e-CALC	CO_2 emissions	×	×
Tatari et al. (2012)	Hybrid	Published literature and reports; National Renewable Energy Laboratory LCI database	-	CH_4, CO, CO_2, N_2O, PM, and SO_2; Cumulative mass; Ecological cumulative exergy consumption; Energy; Industrial cumulative exergy consumption	√	√
Treloar et al. (2004)	Hybrid	Published literature	-	Energy	×	×

Study	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Aurangzeb et al. (2014)	Hybrid	-	-	Energy consumption; GHG emissions (CH_4, CO_2, and N_2O)	×	×
Santos et al. (2017b)	Hybrid	-	EIO-LCA model	Acidification air (AC); Eutrophication air (EU); Human health criteria pollutants (HH); Photochemical smog formation (PSF)	√	√
Roth and Eklund (2003)	-	-	-	-	×	×
Carpenter et al. (2007)	-	-	PaLATE, HYDRUS 2D	CO, CO_2, NO_X, PM_{10}, and SO_2; Energy; Hg, HTP (carcinogenic); HTP (non-carcinogenic); Pb; RCRA HazW Gen; Water	×	×

Notes:

1. '-' = not specified; √ = included; × = not included;

2. Highly cited indicates twenty most-cited papers and two recent highly cited publications with more than 10 citations.

Appendix D. Overview of key findings on the contributions of different life cycle phases

Study	Location	Phases: Material production	Transportation	Construction	Use	M&R	EOL	Analysis Period (years)	Results
Cass and Mukherjee (2011)	US	√	×	√	×	×	×	-	**Materials, equipment, and fuel production**: 90–94% of the CO_2 emissions; Equipment use and transportation = 6–10%
Santos et al. (2015b)	Portugal	√	√	√	√	√	√	40	**Materials and usage phases**: major contribution to overall environmental impacts (low-volume traffic roads: materials phase contributes the most; high-volume traffic roads: usage phase dominates)
Loijos et al. (2013)	US	√	×	√	○	√	√	40	Year one generates the **majority of emissions** (materials production, pavement construction)
Kayo et al. (2015)	Japan	√	√	√	×	×	×	-	**Raw material procurement** = 88%; Material production = 7%; Transportation < 1%; Construction = 4%
Kang et al. (2014)	US	√	√	√	×	×	×	-	The energy consumption and GWP in the **material phase** is remarkably higher than in the construction phase.

Study	Location	Phases						Analysis Period (years)	Results
		Material production	Transportation	Construction	Use	M &R	EOL		
Mendoza et al. (2012)	Spain	√	×	√	×	×	√	> 45	**Construction materials** have the highest environmental impact (48–87%)
Oliver-Sola et al. (2009)	Spain	√	√	√	×	√	○	45	Main contributor: **cement production** (especially clinker)
Weiland and Muench (2010)	US	√	√	√	×	√	×	50	**Material production** (cement, asphalt, HMA, and PCC) dominates all impact categories
Yu and Lu (2012)	US	√	×	√	√	√	√	40	**Materials, congestion, and usage** contribute the most to air emissions and energy consumption
Chen et al. (2016)	US	√	×	√	√	√	√	20, 40	**Material module and usage module** dominate
Choi et al. (2016)	US	√	√	√	×	√	√	50	**Cement manufacturing:** top-contributing sector
Mazumder et al. (2016)	US	√	√	√	√	√	×	50	**Material phase**: 97% of overall human toxicity in water (asphalt)

Study	Location	Phases: Material production	Transportation	Construction	Use	M&R	EOL	Analysis Period (years)	Results
Araujo et al. (2014)	-	√	×	√	√	√	√	20	Energy consumption of the **use phase** is approximately 700-times higher than that of the construction phase

Notes:

1. √ = included; ○ = limited consideration; - = not specified; × = not included;

2. Highly cited indicates twenty most-cited papers and two recent highly cited publications with more than 10 citations.

Appendix E. Unit cost for the eight maintenance strategies for the case study network in Western Australia

Maintenance strategy	Region 1	Region 2	Region 5	Region 6	Region 7	Region 8	Region 11	Region 14
ASDG	52.07	34.39	48.00	55.00	60.46	29.68	54.00	29.98
ASIM	60.00	46.00	60.00	60.00	65.00	60.00	60.00	60.00
ASOG	48.00	56.00	48.00	55.00	43.00	48.00	48.00	48.00
ASRS	138.00	113.61	138.00	150.00	75.00	138.00	138.00	147.77
CS	5.99	5.99	4.43	5.86	14.62	4.07	5.20	4.34
Slurry	12.00	19.25	12.00	14.00	14.00	12.00	12.00	13.49
RipSeal	47.00	45.00	47.00	55.00	58.00	47.00	47.00	50.00
GrOL	63.00	62.42	70.00	70.00	85.00	106.00	75.00	55.04

Appendix F. Comparison between different LCA methods

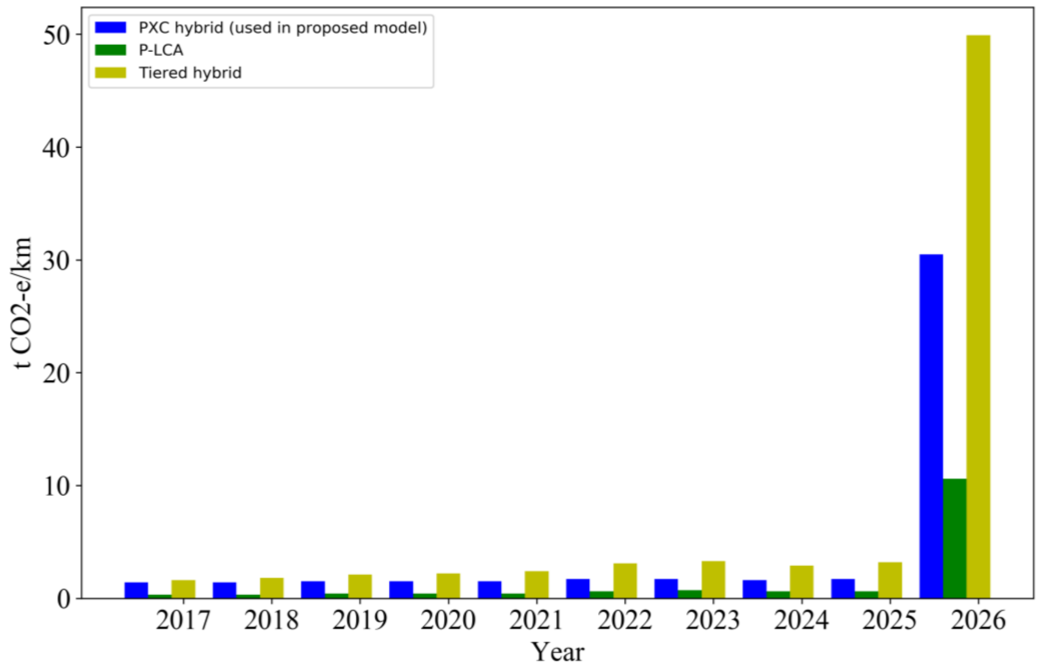

Figure F.1. Comparison of results of the GWP of on-site work generated by PXC, P-LCA, and tiered methods

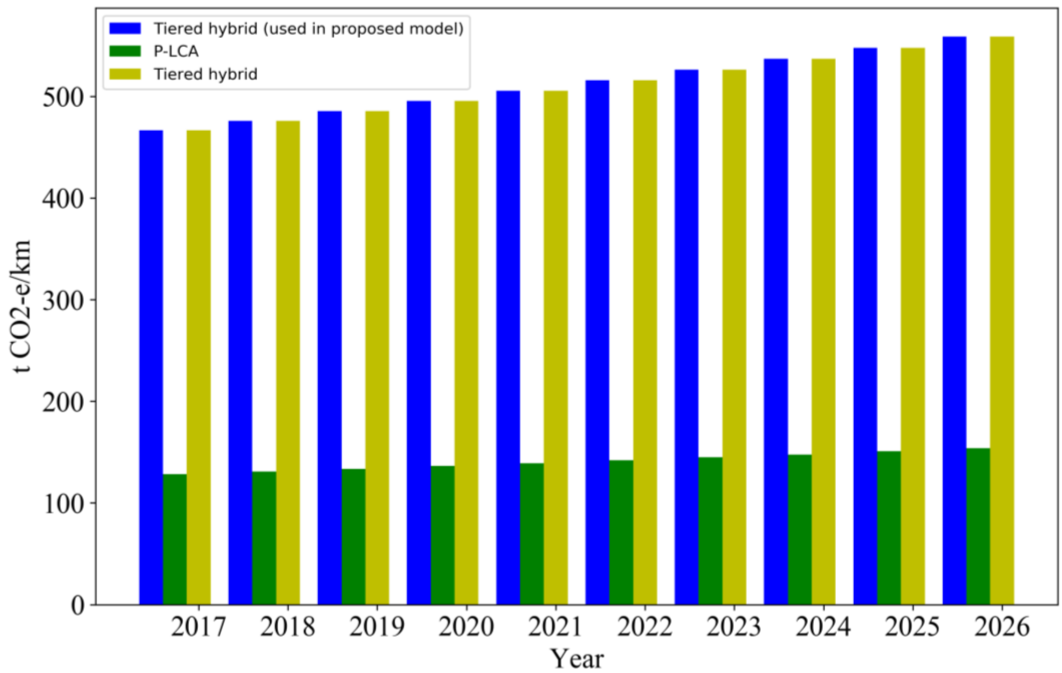

Figure F.2. Comparison of the results of GWP of traffic delays and the use phase generated by P-LCA and tiered methods