

ANNUAL SUMMARY REPORT

Project Title: P106 Assessing the Potential Greenhouse Gas
Emissions Reductions and Sustainability Benefits of
Innovative Pavement Solutions (2018/19)

ARRB Project No: 013950

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SUMMARY

Context

Queensland's greenhouse gas (GHG) emissions are the highest in the nation. The transport sector is the second largest source of Queensland's overall emissions with road transport as the main source of transport emissions (85%).

As the state with the highest greenhouse gas emissions, Queensland has an important role to play in combating climate change. The Queensland Government has made three key climate change commitments:

- powering Queensland with 50% renewable energy by 2030;
- doing its fair share in the global effort to mitigate damaging climate change by achieving zero net emissions by 2050; and
- demonstrating its commitment to reducing carbon pollution by setting an interim emissions reductions target of at least 30% below 2005 levels by 2030.

Queensland's Department of Transport and Main Roads (TMR) has a key role in identifying ways to lower Queensland's road transport GHG emissions profile and contributing to the overall task of decarbonising the economy.

The National Asset Centre of Excellence (NACoE) program is a collaboration between TMR and ARRB. While several transport technologies are researched under the NACoE program, the pavement technologies are the largest component of this program.

TMR requires all major projects to obtain an Infrastructure Sustainability Council of Australia (ISCA) rating. NACoE technologies will soon be subject to this rating process. The assessment process requires quantification of life-cycle GHG emissions saving and the identification of sustainability co-benefits.

Purpose and Scope

The purpose of this project was to identify road technologies that have the potential to assist Queensland to achieve transport sector emissions reductions. Pavements typically represent the largest component of total road construction emissions and present a significant opportunity to reduce total emissions.

The project objective included estimating the life-cycle GHG savings from the use of NACoE pavement technologies against comparable standard technology base cases. Sustainability co-benefits were also identified but were not all quantified.

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Pavement Designs Evaluated

The project evaluated five innovative pavement technologies that have been researched under the NACoE program and have been identified as having potential life-cycle GHG emissions saving benefits. The evaluated pavements include:

- high modulus asphalt (EME2);
- reclaimed asphalt pavement (RAP);
- crumb rubber modified asphalt and crumb rubber modified spray seals;
- stabilisation practices (including foam bitumen stabilisation); and
- marginal materials.

Table i outlines the NACoE pavement technologies and their respective comparable base cases of traditional technologies that were modelled. Pavement designs were developed in consultation with TMR.

Table i: Technologies Evaluated and Design Specifications

No.	Alternative Pavement or Surfacing	NACOE Pavement Technology (A)	Base Case Technology (B)	Design number of cumulative equivalent standard axles (CESA)	Per Lane AADT and % Heavy Vehicles	Road Type
Urban Roads						
U1	EME2	U1A: EME2 high modulus asphalt	U1B: Dense Graded Asphalt	100,000,000	28,207 5%	Urban Motorway
U2	RAP	U2A: Dense graded asphalt with RAP	U2B: Dense graded asphalt without RAP	30,000,000	6,507 5%	Urban Arterial
U3	Crumbed Rubber	U3A: Open graded asphalt with crumbed rubber modified binder	U3B: Open graded asphalt with A15E binder	30,000,000	6,507 5%	Urban Road or Major Rural Road
Rural Roads						
R1	Crumbed Rubber	R1A: Single/Single reseal (HSS1) with crumb rubber modified binder, Unbound granular base.	R1B: Single/Single reseal (HSS1) with polymer modified binder, unbound granular base.	1,000,000	250 10%	Rural Main Road (Lower Traffic)
R2	Crumbed Rubber	R2A: Double/Double reseal (HSS2) with Crumb Rubber Modified Binder, Unbound Granular base.	R2B: Double/Double reseal (HSS2) with polymer modified binder, unbound granular base.	30,000,000	7,489 10%	Rural Main Road (Higher traffic)
R3	Stabilisation	R3A: Foam Bitumen Stabilisation (FBS) Alt Case (low/med traffic)	R3B: Cement Treated Base - Base Case (low/med traffic)	1,000,000	166 15%	Rural Main Road (Lower traffic)
R4	Stabilisation	R4A: FBS Alt Case (high traffic)	R4B: Cement Treated Base - Base Case (high traffic)	30,000,000	7,489 10%	Rural Main Road (Higher traffic)
R5	Marginal Materials	R5A: Marginal quality base: Ridge gravel	R5B: Standard granular base	1,000,000	125 20%	Rural Main Road (Low Traffic)
R6	Marginal Materials	R6A: Marginal quality base: Marginal Gravel Base (MGB) Poorly drained, Wet	R5B: Standard granular base	1,000,000	125 20%	Rural Main Road (Low Traffic)
R7	Marginal Materials	R7A: Marginal quality base: Standard Granular Base Poorly drained, Wet	R5B: Standard granular base	1,000,000	125 20%	Rural Main Road (Low Traffic)

Life-cycle Assessment (LCA) and Cost Benefit Analysis (CBA) of NACoE Pavement Technologies

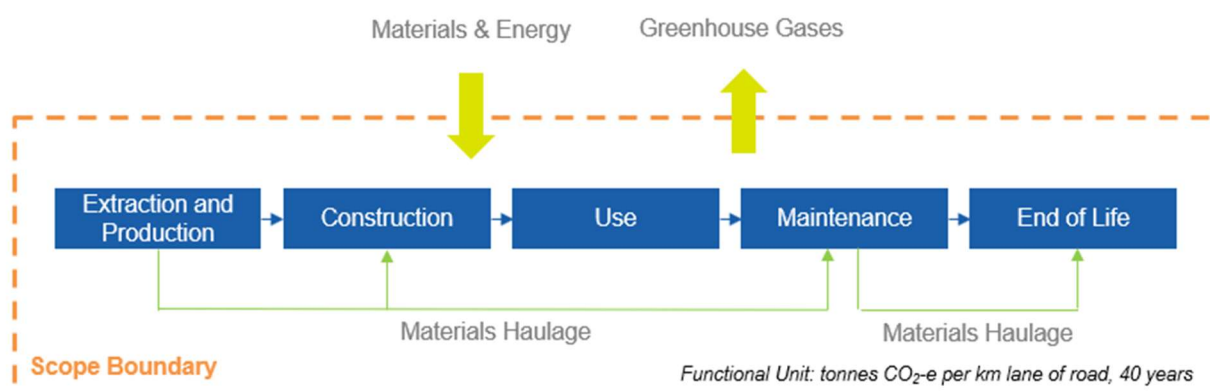
Life-cycle assessment (LCA) modelling was used to quantify GHG emissions (measured in CO₂-e) over the pavement life-cycle. This was done for each NACoE pavement and their comparable standard pavement. The project also undertook a cost benefit analysis (CBA) for each NACoE technology.

The LCA and CBA models developed for this project consist of:

- pavement life-cycle costing (PLCC) model;
- fuel emissions and vehicle operating cost (VOC) model;
- GHG summary model; and
- cost benefit analysis (CBA) model.

Figure i outlines the life-cycle stages included in the scope of modelling. The assessment basis was GHG emissions (CO₂-e) for one lane.km over 40 years.

Figure i: Pavement life-cycle analysis scope diagram



An innovation of the model is that it evaluates the impact of various design, maintenance and operational levers on the use phase (vehicle) emissions and life-cycle costs. This is important as the largest component of Queensland's road GHG emissions are from vehicles and particularly on higher traffic roads. The model also allows the evaluation of a selection of scenarios including pavement rehabilitation needs in response to extreme climatic events by considering the resilience of a selection of the technologies. These are important considerations in the effort to adapt to extreme weather events due to climate change.

Model Development, Inputs and Assumptions

The project considered a range of Australian and international tools in the model development. A range of literature, tools and TMR consultation occurred as sources to inform key model inputs, including:

- embodied carbon factors;
- transport emissions factors and costs;
- construction and maintenance emissions and costs;
- haulage and haulage costs;
- material disposal percentages and costs; and
- carbon costs.

Where relevant Australian and international research was not available, the project developed estimated values, for example the embodied carbon value for crumb rubber.

Modelling Results

Use phase (road vehicles) GHG emissions typically represents more than 97% of road life-cycle emissions. Total use phase emissions are directly proportional to annual average daily traffic (AADT) per lane assumptions.

All five NACoE pavement technologies examined have the potential to deliver GHG emission reductions¹ when compared with traditional pavement technologies. Figure ii summarises GHG reductions (tonnes CO₂-e) possible from the use of NACoE technologies compared with their corresponding base cases. Some technologies (crumb rubber, foam bitumen base stabilisation and marginal materials) showed variable GHG emissions reduction results (i.e. both positive and negative emissions reductions). These variable results can be attributed to several causes, including the different AADT levels of the urban and rural road designs used. In addition, the different life-cycle phases (e.g. construction, maintenance, etc.) produce different amounts of emissions, some may be reductions, other may be increases. Figure iii presents the estimated GHG reduction percentages from the adoption of NACoE technologies compared to the base case. Excluding marginal materials, emissions reductions ranged from 17.2% (emissions reductions) for crumb rubber (high traffic rural road) to – 6.2% (increased emissions) for stabilisation (on low traffic rural roads). GHG emissions reductions varied between 22.7% and – 31.3% (i.e. increase in emissions) from the use of marginal materials.

Figure iv presents the life-cycle costs of the GHG emissions and total costs in net present value (NPV) terms over the 40-year assessment period². The NPV estimates assume a mid-range estimate of \$30.57 per tonne carbon cost. The results showed that the carbon price has a minimal impact on the Total NPV, when compared to other economic factors. For poorly performing marginal materials the construction capital cost savings are negated by increased rehabilitation frequency during the operations and maintenance phase.

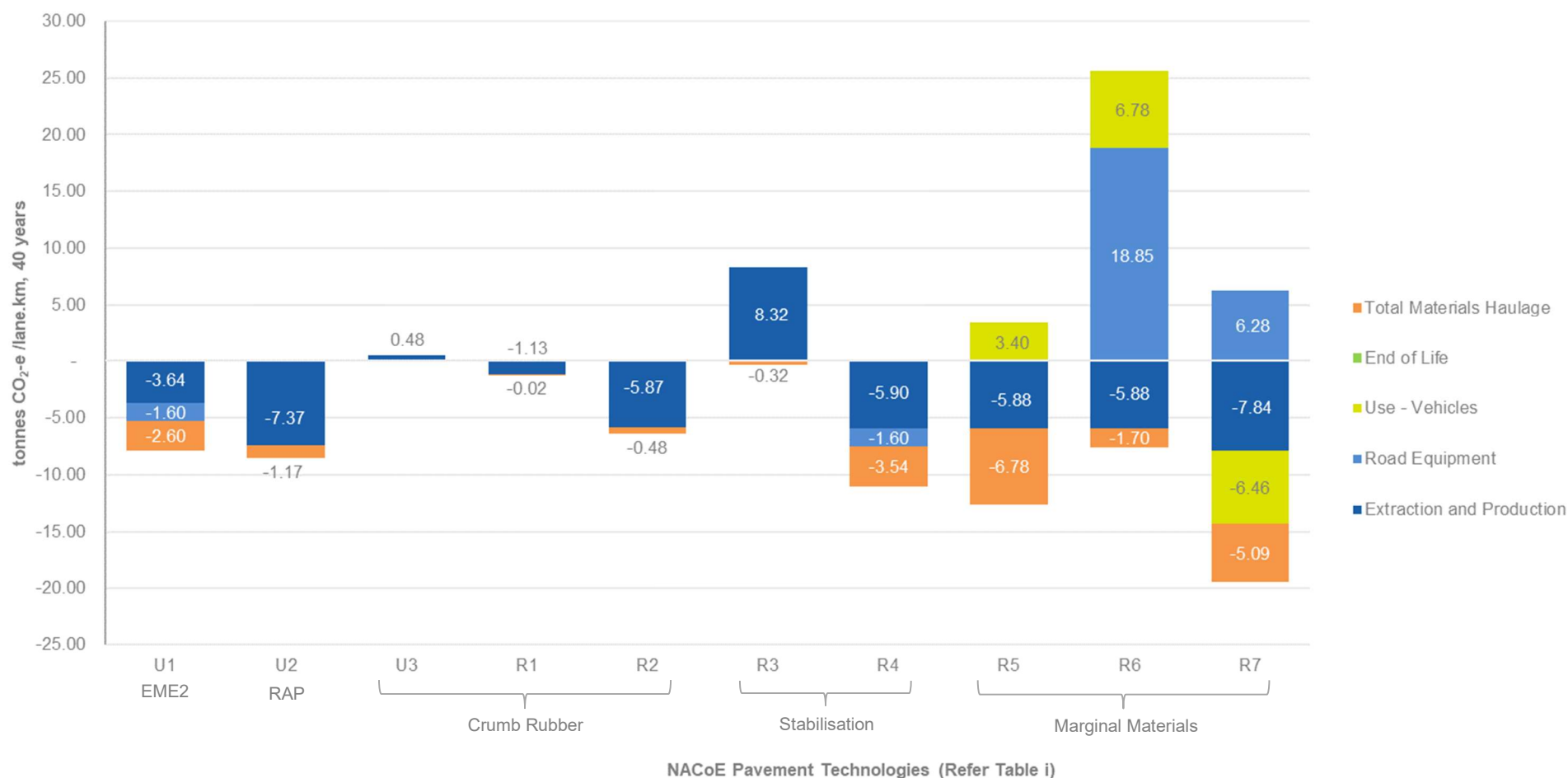
Results from the sensitivity and scenario analysis include:

- Electric vehicles powered by renewables can reduce use phase emissions by up to 45% (assuming electric vehicle use grows to 77% over the next 40 years).
- Emissions increase on steeply graded (high rise and fall) and high curvature roads compared to flat and low curvature free flowing roads. Assuming constant speeds and road roughness, vertical alignment is a more significant factor than horizontal alignment effects on vehicle emissions.
- Emissions increase with both increasing speed and increasing road roughness. Free flowing speed is a more significant factor than road roughness affecting use phase GHGs. Based on modelling results, road roughness can affect annual use phase emissions by between 2–3%.
- Use phase emissions and vehicle operating costs (VOCs) increase with increased road roughness.
- Haulage distances, haulage tonnages, tonnages of pavement material diverted away from landfill and pavement resilience (reduced rehabilitation risk) are significant factors affecting cost savings associated with the use of NACoE technologies.

¹ A GHG reduction is a net emission decrease over 40 years associated with the decision to use the NACoE technology compared to the base case.

² A positive NPV is a discounted life-cycle cost saving associated with the decision to use the NACoE technology compared to the base case.

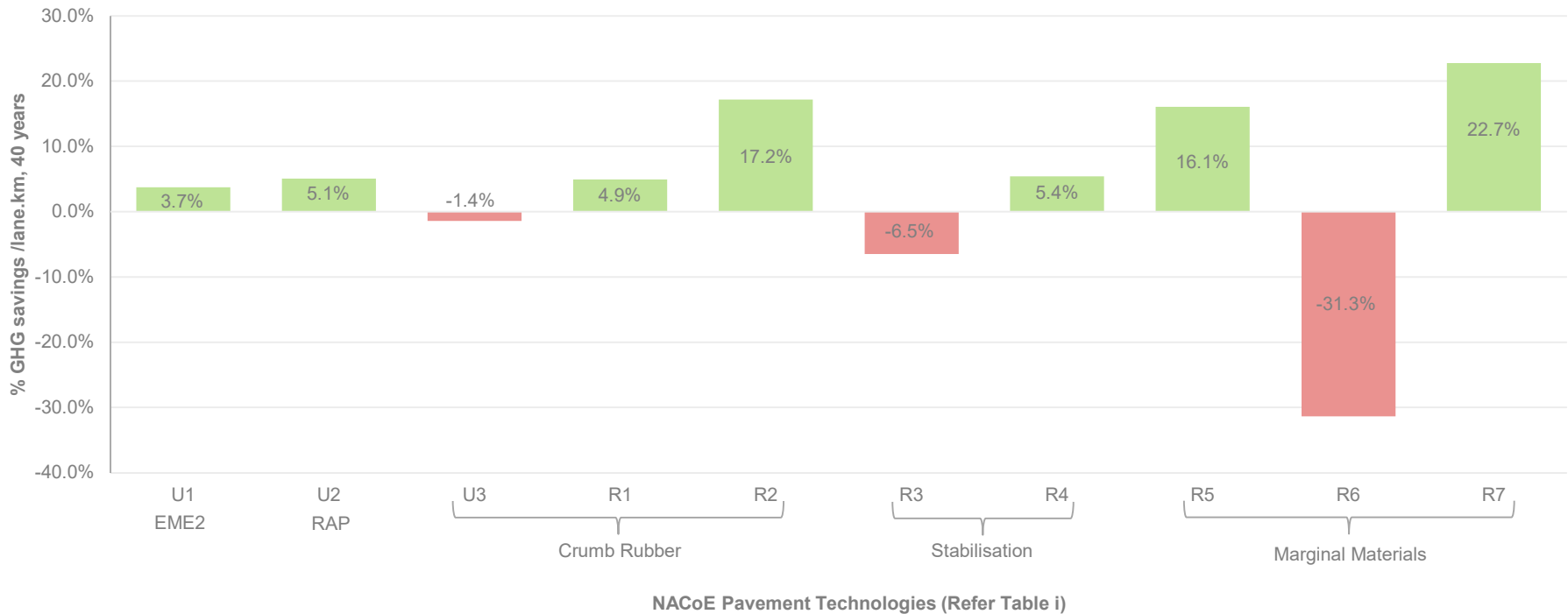
- Embodied Carbon – Haulage Distances: Crumb rubber materials used in spray seals can be hauled large distances (>3,000 km) and still achieve GHG emissions reductions over the pavement life-cycle.
- Significant total life-cycle cost savings may be realised from the use of resilient foam bitumen stabilised pavements due to avoided rehabilitation. The NPV is more sensitive to the rehabilitation costs and then to the haulage costs.
- Potential emissions savings and NPV benefits from the use of marginal materials are dependent on the durability of marginal materials and relative haulage distances of virgin materials. An increase in haulage distances of virgin materials results in improved NPVs.
- Cost benefit analysis conclusions are not significantly affected by different carbon prices (\$/tonne CO₂-e) or discount rates (%).

Figure ii: Net GHGs for different NACoE technologies compared to their base case by life-cycle phase (tonnes CO₂-e /lane.km, 40 years)

Notes:

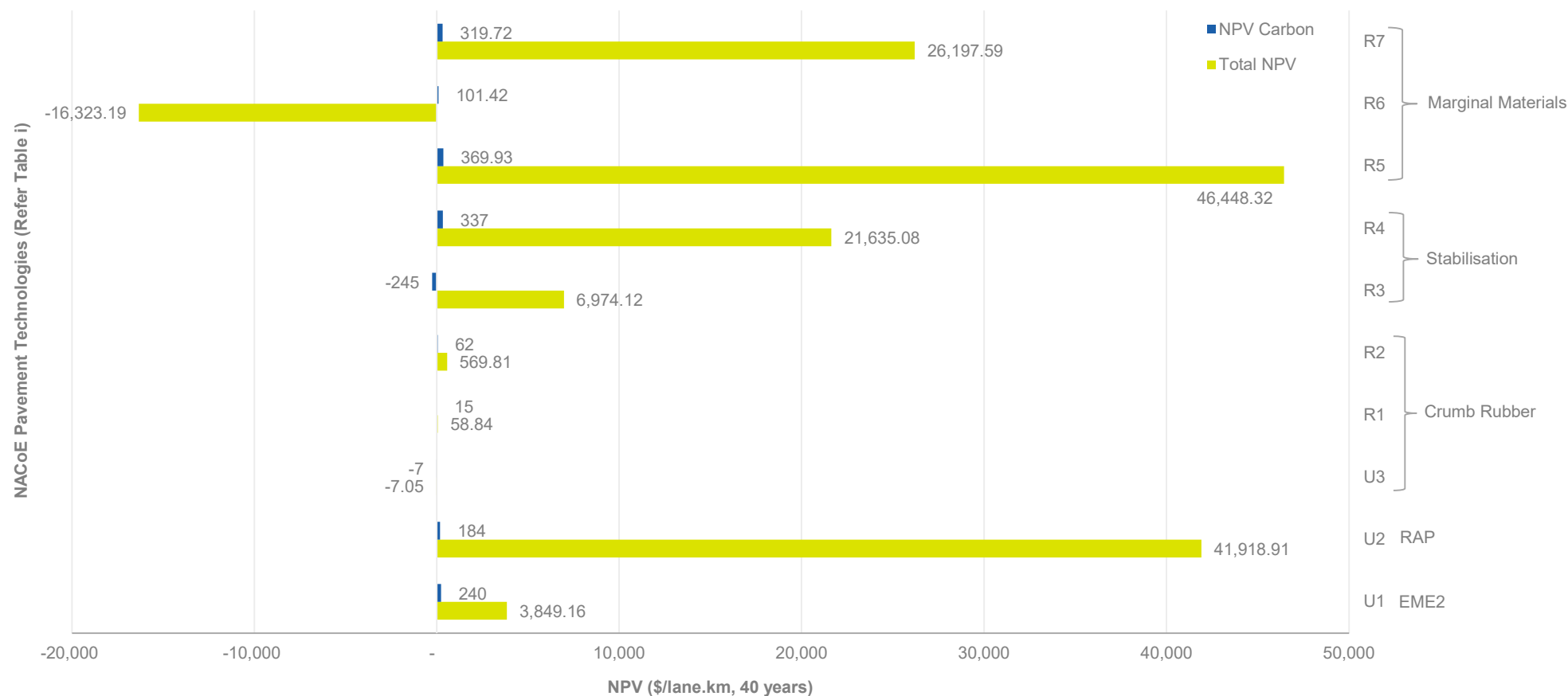
- Refer to Table i for NACoE pavement technology names and pavement designs evaluated.
- A negative value is a reduction in life-cycle GHG emissions from the decision to use the NACoE pavement compared to its traditional pavement alternative.
- A positive value is an increase in life-cycle GHG emissions from the decision to use the NACoE pavement compared to its traditional pavement alternative.
- U denotes Urban roads, and R denotes rural roads.
- The emissions were typically proportional to the thickness of the layers modelled. Crumb rubber U3, R1 and R2 were just resurfacing layers during construction.

Figure iii: Percent emissions reduction results for each NACoE pavement technology (% GHG reductions/lane.km, 40 years)



- Notes:
- Green indicates an emissions reduction achieved i.e. GHG reductions.
 - Red indicates an increase in emissions.
 - Refer Table i for NACoE names and pavement designs evaluated.
 - The emissions were typically proportional to the thickness of the layers modelled. Crumb rubber U3, R1 and R2 were just resurfacing layers during construction.

Figure iv: CBA results – NPV of GHG emissions and total NPV (including GHGs) (\$/lane.km, 40 years)



Notes:

- A positive NPV value represents a discounted life-cycle cost savings to TMR.
- A negative NPV value represents a discounted life-cycle cost increase to TMR.
- The NPV Carbon – indicates the discounted externality savings to society from the mitigations of GHGs.
- The Total NPV is inclusive of the GHG carbon cost – thus indicating total discounted life-cycle costs/benefits and assuming GHG costs are internalised into TMR's decision making process.
- A 7% Discount Rate and \$30.57/tonne CO₂-e cost of carbon was assumed.
- Refer to Table i for NACoE names and pavement designs evaluated.

Discussion and Conclusions

The following conclusions have been drawn from the results and sensitivity and scenario analysis:

1. NACoE pavement technologies present opportunities for win-win environmental benefits and cost savings:
 - (a) Up to 17% GHG reductions are possible relative to standard technologies.
 - (b) Highest GHG emissions reductions are realised on urban roads and foam bitumen stabilised higher traffic rural roads.
 - (c) Embodied carbon is a more significant component of life-cycle emissions reductions compared with construction and haulage.
 - (d) Recycled materials typically have lower embodied carbon compared to virgin materials. There are also significant co-benefits of using recycled materials including diversions away from landfill and associated cost savings.
 - (e) Improved resilience of roads through use of technologies like foam stabilised bases (FSB) can achieve GHG reductions over the pavement life-cycle. Rehabilitation cost savings may be realised from the use of FBS (due to avoided rehabilitation). The NPV was more sensitive to the rehabilitation costs and secondarily haulage costs.
2. Sensitivity of non-use phase findings to changes in key assumptions are directly relevant to TMR:
 - (a) The use of local marginal materials was shown to deliver net GHG reductions and cost savings under low to moderate moisture conditions. Consideration of overall network performance, accounting for the proportion of sections at risk, and those likely to perform satisfactorily is essential.
 - (b) Estimates of the Total NPV from the decision to use NACoE technologies compared to base case technologies are sensitive to net haulage and disposal tonnages where equivalent pavement performance and construction and maintenance costs are assumed between technologies.
3. Opportunities exist for TMR and Queensland Government to reduce road transport-related GHG emissions (assuming all petroleum powered vehicles) include the following:
 - (a) The use phase (vehicle traffic) emissions represent the largest component of life-cycle emissions. The use phase is a key area to achieve significant GHG savings.
 - (b) Improving road alignment (i.e. curvature and rise/fall) in new or reconfigured road construction projects may serve to significantly reduce use phase emissions.
 - (c) Speed reduction can significantly reduce use phase emissions, but it has trade-offs with road user costs (RUC).
 - (d) Improvements in pavement performance through more durable pavement designs, maintenance and rehabilitation solutions can reduce pavement distress and road roughness and therefore use phase emissions. Only modest GHG emissions reductions by up to 2–3% have been estimated from modelling. This is believed to be an underestimate where long-life, 'perpetual' pavements are considered e.g. EME2 with thicker base layers.
 - (e) Electric vehicles (powered by renewables) have the potential to reduce life-cycle use phase emissions by up to 45% over a 40-year period. Whereas this is not directly under TMR's control, it has a significant contribution to make through Government and consumer/producer actions.
4. The methodology presented in this report may be suitable for the evaluation of other NACoE pavements under development including but not limited to use of glass in pavements.

Recommendations

Recommended next steps to assist TMR in reducing Queensland's road transport GHG emissions include:

1. Consider further pavement Research and Development (R&D) and life-cycle modelling of other NACoE pavement technologies:
 - (a) Further R&D with the aim of developing cost-effective and optimised life-cycle low carbon pavement designs. It may be possible to develop design specifications and/or validate performance of pavements that combine NACoE technologies and thus maximise life-cycle CO₂-e/lane.km reductions.
 - (b) The development of pavement performance curves associated with varying key pavement attributes that contribute to life-cycle emissions reduction (e.g. EME2 base thickness). This may be used to evaluate or extrapolate life-cycle GHG emissions.
 - (c) Future GHG modelling of alternative NACoE pavement technologies currently under investigation including, but not limited to, use of recycled glass in pavements.
2. Evaluate other technologies with potential to reduce road transport emissions:
 - (a) Future modelling to evaluate other NACoE technologies that have the potential to significantly affect and thus reduce use phase emissions other than pavement technologies e.g. heavy vehicle network operations. Note that this may be on a CO₂-e per passenger.km or tonne.km freight basis and considering network context effects.
 - (b) Future modelling may choose to evaluate the emissions reduction potential of other road technology levers with high GHG emissions efficiencies potential in addition to electric vehicles e.g. hybrid vehicles and fuel emission standards. In this way the technological contribution to total road transport emissions reductions may be quantified for the use phase.
 - (c) There is potential for other modes of transport to have lower life-cycle GHG emissions (including use phase) for the same freight or passenger movement tasks. Rail or tram transport could be evaluated for life-cycle emissions on a lane.km or tonne.km basis. The potential for shared road and rail or tram corridors could also be explored.
 - (d) Use phase GHG emissions reductions on a road lane.km basis over 40 years may be made with road alignment decisions on high rise/fall roads. There may be a trade-off between alignment cut and fill haulage, drainage and water treatment structures and vegetation clearing compared to use phase emissions savings. ISCA assessments should consider this in their scope when evaluating road projects and subject to road construction cost trade-offs.
3. Consider developing low carbon procurement and GHG reporting policies:
 - (a) Review of non-price related procurement criteria for pavement designs in TMR. Bids on big projects to include traditional and alternative lower life-cycle carbon options. Reportable metrics may also include CO₂-e/\$ to inform cost-effectiveness analysis and thus minimise life-cycle GHG impact per dollar spent within limited road construction and maintenance budgets. Evaluate the potential for using economic incentives structures for high impact low carbon designs in procurement contracts and considering the cost of carbon to the Queensland economy e.g. carbon credits.
 - (b) Incorporate GHG reporting, construction and maintenance cost per lane km into future construction and maintenance bids and contracts including NACoE technologies. This may be for a certain scale project consistent with current waste management reporting e.g. either greater than \$500 000 contract value or a project greater than 3 months in duration. This assists with benchmarking data for NACoE technologies and to inform emissions assumptions required for an ISCA rating.

- (c) A consolidation of carbon emission data for each project location into a central open source database managed by ARRB, TMR and/or ISCA. This allows for a quick reference of emissions factors for different pavement designs and consolidated accounting of emissions efficiencies and cumulative GHG savings over time. In so doing, it may assist with forecasting the contributions towards achieving transport sector and state emissions reduction targets.
 - (d) The sourcing of Australian emissions factors where currently international emissions factors are used or absent e.g. crumb rubber, bitumen, EME2 bitumen, marginal materials etc. Work with industry to identify ways to drive energy efficiency (embodied carbon) of pavement materials or lower emissions during construction processes.
4. Consider undertaking additional economic evaluations:
- (a) Future modelling may choose to consider policy options to TMR or the Queensland Government to incentivise GHG reductions in the transport sector and associated impacts to government, community and/or industry. This may include price incentives.
 - (b) There may be potential to achieve both GHG reduction outcomes and economic benefits to the Queensland economy from cumulative reduced RUCs associated with GHG reduction efforts. This could be estimated as part of CBA modelling in the future.
 - (c) ATAP PV2 regression analysis for fuel use and VOC in the future could be updated and should incorporate electric vehicle power costs and a carbon cost when carbon costing is used. This may also inform and thus affect vehicle fleet distribution and optimisation decisions to minimise VOCs or identify potential barriers to technology transfer.
5. Consider evaluating the Total potential GHG reductions and cost savings across the state road network:
- (a) The total potential GHG savings in Queensland from use of the NACoE pavement technologies evaluated are proportional to the total km of road length available for construction and maintenance, the timing of construction and maintenance activities and accessibility of recycled materials. Other co-benefits from such a network analysis could include identifying potential barriers to technology transfer and quantifying potential latent demand for recycled materials across the Queensland network, which may in turn incentivise circular economy and job creation outcomes.

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CONTENTS

SUMMARY	I
GLOSSARY.....	XX
ACRONYMS.....	XXV
1 INTRODUCTION	1
1.1 Context	1
1.1.1 Australian and Queensland's Emissions Reductions Targets.....	1
1.1.2 Queensland's Road Transport Greenhouse Gas Emissions.....	1
1.1.3 The National Assets Centre of Excellence (NACoE) Program.....	1
1.1.4 ISCA Rating Scheme	1
1.2 Purpose	2
1.3 Objectives.....	2
1.4 Scope	2
2 METHODOLOGY	3
3 LITERATURE REVIEW	4
3.1 Australia's Transport Sector Emission Trends.....	4
3.2 Queensland's Transport Sector Emission Trends	4
3.3 Benchmark Road Projects Life-cycle GHG Emissions	4
3.4 Abatement Options for Australia's Transport Emissions.....	7
3.4.1 Electric Vehicles in Queensland	8
4 NACOE PAVEMENT TECHNOLOGIES AND IDENTIFIED SUSTAINABILITY BENEFITS.....	9
4.1 NACoE Technologies Evaluated	9
4.2 Sustainability Benefits.....	10
5 PAVEMENT DESIGNS.....	15
6 PAVEMENT LIFE-CYCLE ASSESSMENT MODEL	16
6.1 Incorporating the Cost of GHGs into TMR's Decision Making	16
6.2 Evaluating Life-cycle Assessment and CBA Models	16
6.3 Life-cycle Modelling Scope	16
6.4 Model Structure	17
6.5 Sourcing and Validating Assumptions through TMR District Survey.....	21
6.6 Model Assumptions and Calculations	23
7 MODELLING RESULTS.....	24

7.1	Total GHG Emissions of Pavements Evaluated	24
7.2	GHG Emissions Reductions from Use of NACoE Pavements	28
7.2.1	<i>EME2</i>	28
7.2.2	<i>RAP</i>	28
7.2.3	<i>Crumb Rubber</i>	28
7.2.4	<i>Foam Bitumen Stabilisation</i>	28
7.2.5	<i>Non-standard Granular and Marginal Materials</i>	28
7.3	Percent GHG Emissions Reductions from use of NACoE Technologies	29
7.4	Cost Benefit Analysis Savings from use of NACoE Pavement Technologies	29
8	SENSITIVITY AND SCENARIO ANALYSIS	33
9	DISCUSSION AND CONCLUSIONS	36
9.1	Modelling Limitations	37
10	RECOMMENDATIONS	39
	REFERENCES	41
APPENDIX A	LITERATURE REVIEW	48
APPENDIX B	PAVEMENT DESIGNS	84
APPENDIX C	KEY MODEL ASSUMPTIONS AND CALCULATIONS	105
APPENDIX D	DETAILED RESULTS	131
APPENDIX E	SENSITIVITY AND SCENARIO ANALYSIS	135

TABLES

Table 3.1:	Emissions data used for benchmarking.....	5
Table 3.2:	Transport emissions abatement options, by category	7
Table 4.1:	NACoE technologies evaluated.....	9
Table 4.2:	Literature review summary for pavement technologies	11
Table 5.1:	Summary of pavement designs.....	15
Table 6.1:	Life-cycle analysis and cost benefit analysis model components	19
Table 6.2:	Summary of survey information.....	22
Table 8.1:	Summary of sensitivity and scenario analysis and key results.....	33

FIGURES

Figure 3.1:	Emissions per item of construction work per type of road per km.....	6
Figure 3.2:	Emission per GHG generator during construction per type of road	6
Figure 3.3:	Contribution of construction and operation life-cycle emissions (where operation does not include the GHG emissions from vehicles on the road).....	6
Figure 3.4:	Modelling projections of number of vehicles in the Queensland fleet by fuel type in 2018 and projected out to 2048 under the baseline and off-peak, on demand scenarios.....	8
Figure 6.1:	Pavement life-cycle assessment diagram	17
Figure 6.2:	Life-cycle stages and associated tools/Excel workbooks.....	18
Figure 6.3:	Pavement technologies used by TMR survey respondents	22
Figure 7.1:	Total life-cycle GHG emissions for each pavement design (tonnes CO ₂ -e/lane.km, 40 years)	25
Figure 7.2:	Total life-cycle GHG emissions for each pavement design, excluding use phase (tonnes CO ₂ -e per lane.km, 40 years)	26
Figure 7.3:	Net GHG emissions for different NACoE technologies compared to the base case by life-cycle phase (tonnes CO ₂ -e /lane.km, 40 years).....	27
Figure 7.4:	Percent emissions reduction results for each NACoE pavement technology (% GHG savings /lane.km, 40 years)	31
Figure 7.5:	CBA results – the total NPV and NPV of carbon emissions at 7% discount rate and \$30.57/tonne CO ₂ -e cost of carbon (\$/lane.km, 40 years).....	32

GLOSSARY

Aggregate	A material composed of discrete mineral particles of specified size or size distribution, produced from sand, gravel, rock or metallurgical slag, using one or more of the following processes: selective extraction, screening, blasting or crushing (Austroads 2015).
Asphalt	A mixture of bituminous binder and aggregate with or without mineral filler, produced hot in a mixing plant, which is delivered, spread and compacted while hot. In the USA, the term 'asphalt' can also mean bituminous binder (Austroads 2015).
Asset life	The period of time over which an asset is expected to be in service and used to create benefits.
Average annual daily traffic (AADT)	Total number of vehicles passing a point on a road in a year divided by 365 (or 366 for a leap year).
Base case	A cost benefit analysis (CBA) compares two alternative states of the world – the base case and the alternate case. In this project, the base case is the use of traditional, or standard pavement technologies. The alternate case is the use of NACoE pavement technologies.
Benchmarking	The process of measuring performance and analysing practices in key areas and comparing them to other similar operations or functions, to find ways of achieving better results (Austroads 2015).
Benefit-cost ratio (BCR)	Ratio of the present value of economic benefits to the present value of economic costs of a proposed initiative. The BCR is an indicator of the economic merit of a proposed initiative presented at the completion of cost-benefit analysis. BCRs are used to aid comparison of initiatives competing for limited funds.
Binder	1. A material used to fill the interstices between small stones or coarse gravels. It provides mechanical, chemical and physical bonding and holds the aggregate particles together as a coherent mass. 2. A manufactured material used in small amounts in stabilisation to change the properties of the existing material. 3. A bituminous material used for waterproofing the surface and holding an aggregate layer to the base (Austroads 2015). See Modified binder and Polymer modified binder.
Bitumen	A very viscous liquid or a solid, consisting essentially of hydrocarbons and their derivatives, which are soluble in carbon disulphide. It is substantially non-volatile and softens gradually when heated. It possesses waterproofing and adhesive properties. It is obtained from native asphalt or by processing the residue from the refining of naturally occurring crude petroleum (Austroads 2015).

Bituminous	A material that resembles or contains bitumen (Austroads 2015). See Bitumen.
Cement stabilisation	The controlled application of cement to improve the load-carrying capacity of a pavement layer (usually the basecourse) or of the subgrade (Austroads 2015). In this project, cement stabilisation refers to heavily bound cemented pavements. Cement stabilised pavement can be referred to as 'cementitious', meaning they have the properties of cement. See Stabilisation.
Construction phase	The period encompassing the initial construction of the pavement. In this project, construction phase emissions include emissions generated by construction equipment during the initial construction of the pavement, inclusive of the embodied carbon energy contained in the materials used in construction. Construction phase emissions exclude non-pavement structures such as drainage, lighting and support vehicles assumed common between the base case and alternative NACoE pavement technology. Construction phase emissions are assumed to happen in year 0.
Cost benefit analysis (CBA)	An economic analysis technique for assessing the economic merit of a proposed initiative by assessing the benefits, costs and net benefits of the initiative.
Crumb rubber	Rubber particles manufactured from waste or reclaimed rubber products such as tyres and graded to conform to a specified size range. Crumb rubber is used in bitumen to improve binder properties. Crumb rubber modified seal is a sprayed seal in which the binder consists of bitumen modified by the incorporation of crumb rubber (Austroads 2015).
Downstream emissions	Downstream emissions are the emissions produced by a road or structure, post-construction. This includes emissions from the use and maintenance phases.
Embodied carbon	Embodied carbon refers to carbon dioxide (CO₂) emitted during the extraction, manufacture, transport and construction of materials, together with their end of life emissions.
End-of-life phase (disposal)	The period encompassing the disposal, or recycling of materials at the end of their practical life. End of life phase (or disposal) emissions are generated through the disposal of materials in landfill. In a circular economy the materials would be recycled.
Foam bitumen	Hot bitumen temporarily greatly expanded in volume by the introduction of steam or water. It can be used in plant-mixed or in situ stabilisation of granular materials or spray seal enrichment applications (Austroads 2015). See Stabilisation.

Life-cycle costs	The sum of the economic and carbon costs over an asset's entire life (inclusive of materials extraction and production, construction, use, maintenance, materials haulage and end-of-life disposal).
Marginal materials	An aggregate which does not meet conventional aggregate specifications but is suitable for specific use in pavements (Austroads 2015).
Maintenance	Incremental work to restore infrastructure to an earlier condition or to slow the rate of deterioration. Distinct from construction and upgrading.
Maintenance phase	Period encompassing routine, periodic and rehabilitation works. Maintenance phase emissions are generated by maintenance equipment as part of pavement resurfacing and rehabilitation works.
Modified asphalt	An asphalt in which the binder has been modified by the incorporation of polymers, resins, rubber or other material to achieve specific physical properties (Austroads 2015). See Asphalt.
Modified binder	Binder with enhanced performance achieved by the incorporation of additives (polymers, resins, rubber or other material) or special processing to achieve specific physical properties (Austroads 2015). See Binder.
Net emissions	The NACoE pavement emissions less the base case pavement emissions.
Net present value	The present value of a future benefit less the present value of future costs over the appraisal period (Austroads 2015). The term 'net' signifies that it is calculated as benefits minus costs.
Non-standard granular materials	Non-standard road building materials generally comprise naturally occurring gravels and weathered rocks. They do not comply with standard specifications but are known to successfully perform as granular base and subbase materials for selected roads. They may also comprise clay and sands (also known as sand-clays) (Austroads 2018).
Pavement	That portion of a road designed for the support of, and to form the running surface for, vehicular traffic (Austroads 2015).
Pavement design	A process to select the most economic pavement thickness and composition which will provide a satisfactory level of service for the anticipated traffic and environmental loading (Austroads 2015). The pavement design is similar to a blueprint for structures, it includes design aspects such as the materials composition, the layer thickness, the layer configurations, the design load capacity (in this project referred to as AADT), environmental considerations, etc.
Polymer modified binder (PMB)	A binder consisting of polymeric materials dispersed in bitumen with enhanced binder performance for particular applications (Austroads 2015).

Reclaimed asphalt pavement (RAP)	RAP is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. RAP is generated when pavements are removed for reconstruction, resurfacing, or to obtain access to buried utilities. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement (FHWA 2016). The material is reclaimed from an asphalt pavement by various means including cold-milling, grader, backhoe, jackpick or other methods (Austroads 2015).
Rehabilitation (pavement)	Major surfacing action for the purpose of returning the structural condition of the pavement to its as-constructed or design condition (i.e. recurring or maintenance), or to exceed the as-constructed condition (i.e. capital or construction) (Austroads 2015).
Resurfacing	To improve a pavement surface by the addition of a new wearing course (Austroads 2015).
Roughness	A component of surface texture that includes deviations of the surface from its ideal form. Large deviations form a rough surface, whereas small deviations form a smooth surface. Further technical definitions of roughness include: 1. A condition parameter used to characterise deviations from the intended longitudinal profile of a road surface, with characteristic dimensions that affect vehicle dynamics (and hence road user costs), ride quality and dynamic pavement loading (Austroads 2015). 2. A measure of surface irregularities with wavelengths between 0.5 and 50 m in the longitudinal profile of one or two wheel tracks in a traffic lane, reported in dimensionless units as either International Roughness Index (IRI, m/km) or as NAASRA Roughness Meter counts (NRM, counts/km) for the lane (Austroads 2015).
Rutting	A component of surface texture that includes the depression or groove worn into a road caused by the forces of vehicular travel. Rutting is measured as the longitudinal vertical deformation of a pavement surface in a wheel path (rutting) measured relative to a straight edge placed at right angles to the traffic flow and across the wheel path, with a length/width ratio greater than 4:1 (Austroads 2015).
Sensitivity analysis	A technique used to determine how changes to one input (while keeping the other inputs constant) affects the output, or results, of a model. Sensitivity analysis is used to account for uncertainty by varying a model's assumptions (inputs).
Sprayed seal	A thin layer of binder sprayed onto a pavement surface with a layer of aggregate incorporated and which is impervious to water (Austroads 2015).

Stabilisation	The treatment of a road pavement or subgrade material by the introduction of a binder to improve it or to correct a known deficiency and thus enhance its ability to perform its function in the pavement. It can be conducted mechanically or through the use of chemicals (Austroads 2015). See Cement Stabilisation and Foam Bitumen.
Structural number (SN)	A pavement strength parameter, developed during the AASHTO Road Test. The SN describes the structural capacity of a pavement in a single number, regardless of the details of the materials in the pavement. SN is related to the change in cumulative traffic loading and functional condition of the pavement. SNs are used in Australasia in pavement asset management (Austroads 2015).
Surface (asphalt)	The surface of an existing asphalt pavement is planned, milled or heated in place. In the latter case, the pavement may be scarified, remixed, re-laid and rolled. Additionally: bitumen, softening agents, aggregates or combinations of these may be added to obtain desirable mixture and surface characteristics. The finished product may be used as the final surface (Austroads 2015).
Surfacing (wearing surface)	That part of the pavement or bridge deck specifically designed to resist abrasion from traffic and to minimise the entry of water (Austroads 2015).
Upstream emissions	Upstream greenhouse gas emissions are defined as the greenhouse gas emissions produced during the extraction, processing, and transportation of resources from their original state to the point of use in construction (Tjossem 2017).
Use phase	Period that encompasses the use of the pavement, i.e. after the construction phase and before the end-of-life phase. The maintenance phase overlaps with the use phase. Use phase emissions are generated by vehicles using the road. Emissions associated with TMR vehicles (e.g. road sweepers) are included in the AADT estimates.
Vehicle operating costs (VOCs)	The costs of operating a vehicle, including fuel, oil, tyres and repair and maintenance costs. It may include capital costs of vehicles or depreciation.

ACRONYMS

AADT	Annual Average Daily Traffic
ABS	Australian Bureau of Statistics
ARRB	Australian Road Research Board
ATAP	Australian Transport Assessment and Planning
BCR	Benefit Cost Ratio
BITRE	Bureau of Infrastructure, Transport and Regional Economics
CBA	Cost Benefit Analysis
CBR	California Bearing Ratio
CESA	Cumulative Equivalent Standard Axles
CH₄	Methane
CO₂-e	Carbon Dioxide Equivalent
CPI	Consumer Price Index
CRMA	Crumb Rubber Modified Asphalt
CRMB	Crumb Rubber Modified Binder
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTB	Cement Treated Base
C&D	Construction and Demolition
D/D	Double/Double Seal
EME2	Enrobé à module élevé class 2 (High Modulus Asphalt)
EPU	Equivalent Passenger Unit
ESA	Equivalent Standard Axles
FBS	Foam Bitumen Stabilisation
GCCC	Gold Coast City Council
GCM	Gross Combined Mass
GHG	Greenhouse Gas
GVM	Gross Vehicle Mass
HDM-4	Highway Design and Maintenance Standards Model (version 4)
HFC	Hydrofluorocarbon
HMA	Hot-Mix Asphalt
HVOC	Heavy Vehicle Operating Costs
IPCC	Intergovernmental Panel on Climate Change
IRI	International Roughness Index (m/km)
ISCA	Infrastructure Sustainability Council Australia
LCA	Life-Cycle Assessment
MRC	Mackay Regional Council

NACoE	National Assets Centre of Excellence
NPV	Net Present Value
N₂O	Nitrous Oxide
OGA	Open Graded Asphalt
PFC	Perfluorocarbons
PLC	Pavement Life-Cycle
PLCC	Pavement Life-Cycle Costing
PMB	Polymer Modified Binder
RAP	Reclaimed Asphalt Pavement
RUC	Road User Costs
R&D	Research and Development
SAM	Strain Alleviating Membrane
SF₆	Sulphur Hexafluoride
SN	Structural Number
S/S	Single/Single Seal
TAGG	Transport Authorities Greenhouse Group
TMR	Queensland Department of Transport and Main Roads
USC	Unified Soil Classification
VOC	Vehicle Operating Costs
4WD	Four Wheel Drive

1 INTRODUCTION

1.1 Context

1.1.1 Australian and Queensland's Emissions Reductions Targets

The Australian Government has committed to reducing Greenhouse Gas (GHG) emissions by 26–28 per cent below 2005 levels by 2030, in accordance with the Paris Agreement. If Australia is to meet this target, Australia needs to double the emissions reduction progress (ClimateWorks Australia 2018).

In 2015, Queensland released 152.1 million tonnes of carbon dioxide equivalent (CO₂-e) emissions, more than any other Australian state or territory (Department of Environment and Energy (DEE) 2017a). As the state with the highest greenhouse gas emissions, Queensland has an important role to play in meeting the national goal.

The Queensland Government has committed to mitigating the release of GHGs and to helping protect vulnerable ecosystems like the Great Barrier Reef, through the following commitments:

- powering Queensland with 50% renewable energy by 2030;
- doing Queensland's fair share in the global effort to mitigate the damaging effects of climate change by achieving zero net emissions by 2050; and
- demonstrating its commitment to reducing carbon pollution by setting an interim emissions reductions target of at least 30% below 2005 levels by 2030 (Queensland Government 2017).

1.1.2 Queensland's Road Transport Greenhouse Gas Emissions

Queensland's transport sector GHG emissions grew steadily from 11.2 million tonnes of CO₂-e in 1990, reaching 22.5 million tonnes of CO₂-e in 2016. In 2016, the transport sector was Queensland's second largest source of emissions overall. Road transport generates around 85% of all transport emissions or 19.1 million tonnes of CO₂-e (State of Queensland 2017).

Queensland's Department of Transport and Main Roads (TMR) has a key role in identifying ways to lower Queensland's road transport GHG emissions profile and in contributing to the overall task of decarbonising the economy.

1.1.3 The National Assets Centre of Excellence (NACoE) Program

The National Asset Centre of Excellence (NACoE) is an initiative of the Queensland Department of Transport and Main Roads (TMR) and the Australian Road Research Board (ARRB). NACoE delivers professional capability and strategically targeted research. The Pavements program represents the largest proportion of the NACoE program. Several innovative pavement technologies are investigated as part of this program. Other areas of investigation include asset management, structures, network operations, road safety and heavy vehicle management.

1.1.4 ISCA Rating Scheme

TMR requires all major projects to obtain an Infrastructure Sustainability Council of Australia (ISCA) rating. The Infrastructure Sustainability (IS) Rating Scheme is Australia and New Zealand's only comprehensive rating system for evaluating sustainability across the planning, design, construction and operational phases of infrastructure programs, projects, networks and assets (ISCA 2019b). The IS rating evaluates the sustainability performance of infrastructure projects i.e. the quadruple bottom line (Governance, Economic, Environmental and Social) (ISCA 2019b). The findings from this project may be used to estimate potential life-cycle GHG emissions savings and identify other co-benefits of NACoE technologies which would be subject to an ISCA rating if applied across the TMR road network.

1.2 Purpose

The purpose of this project was to identify road technologies investigated under the NACoE program that have the potential to assist Queensland to achieve transport sector emissions reductions and other environmental outcomes.

1.3 Objectives

The objectives of this project included:

- estimating the life-cycle GHG emissions savings of NACoE pavement technologies against a standard technology base case on a 1 lane per km basis;
- converting these savings to an economic value based on accepted practice;
- identifying other sustainability co-benefits and dis-benefits from the adoption of NACoE road technologies; and
- providing a basis for assessing and reporting GHG reduction potential and sustainability benefits of other NACoE initiatives in the future.

1.4 Scope

The scope of the assessment includes:

- A comparison of NACoE pavement technologies compared to their traditional base case technologies, including:
 - high modulus asphalt (EME2);
 - reclaimed asphalt pavement (RAP);
 - crumb rubber modified asphalt and crumb rubber modified spray seals;
 - stabilisation practices (including foam bitumen stabilisation); and
 - non-standard granular and marginal materials.
- The life-cycle assessment of the GHG emissions produced by pavement technologies: including extraction and production, construction, maintenance, use and end-of-life.
- Life-cycle costs indicative of the cost to TMR captured as a net present value (NPV).
- The evaluation of a GHG cost/benefit to society captured as a GHG savings and NPV.
- The identification of sustainability co-benefits.

Scope exclusions include:

- Supporting road infrastructure (e.g. drainage, lighting, vegetation, kerbs etc). It is assumed that these elements of road design, construction and operation are common to both NACoE technologies and traditional pavement designs. Furthermore, supporting road infrastructure tends to be project-specific and therefore difficult to generalise in modelling.
- The quantification or economic evaluation of NACoE pavement sustainability co-benefits. This includes landfill diversions e.g. recycled tyres used to produce crumb rubber.
- The identification and evaluation of safety considerations.
- TMR or industry compliance and/or enforcement costs associated with identified GHG abatement initiatives.
- The quantification of wider economic benefits associated with job creation and/or the creation of local circular economies e.g. crumb rubber in spray seals compared to imported PMB used in seals.

2 METHODOLOGY

The following activities were undertaken as part of the evaluation of NACoE pavement technologies:

- performed a literature review of:
 - Australia’s transport sector emissions (Section 3.1; Appendix A.2);
 - Queensland transport sector emissions (Section 3.2; Appendix A.3);
 - life-cycle GHG emissions of benchmark road projects (Section 3.3 and Appendix A.6);
 - potential life-cycle GHG abatement options for Queensland roads (Section 3.4), including electric vehicles projections (Section 3.4.1);
 - for each NACoE technology – GHG savings and potential sustainability co-benefits, disbenefits and other considerations of NACoE technologies assessed (Section 4; Appendix A.4);
 - Australian and international GHG life-cycle models and references (Appendix A.7).
- selected NACoE technologies for modelling and evaluation (Section 4; A.5);
- sourced design information and developed designs for each NACoE and base case pavement technology – urban and rural roads (Section 5; Appendix B);
- developed fit for purpose pavement GHG life-cycle assessment (LCA) models and cost benefit analysis (CBA) models. This included a review of Australian and international models and studies (Section 6);
- sourced and validated key modelling input information (Section 6) including a survey of TMR districts (Section 6.5; Appendix C);
- Modelled each NACoE pavement technology compared to their base case technology to estimate total life-cycle GHG emissions, emissions savings and CBA results (Section 7; Appendix D);
- sensitivity and scenario analysis on key modelled parameters (Section 8); and
- a workshop with TMR to validate results and key model assumptions and inputs. Advice was also sought on ways to disseminate research findings (Appendix C.5).

3 LITERATURE REVIEW

A literature review was undertaken using the services of the M.G. Lay library, Australia's leading transport library, located at the ARRB, to identify and access relevant material. This section of the report provides a brief summary of the findings of the literature review, refer to Appendix A for further detail.

3.1 Australia's Transport Sector Emission Trends

Transport emissions account for Australia's third largest source of GHG emissions, 18% of total greenhouse gas emissions. Of these emissions, 85% are produced from road transportation, with the remaining 15% being generated by rail, air, marine, etc. (Climate Council 2016).

The transport sector is also the highest growing source of GHG emissions – it has grown 51% since 1990. Transport emissions are projected to increase by 5% on 2017 levels by 2020. The key drivers of emissions growth include population and economic growth. If action is not taken, this is projected to continue to grow to be nearly double 1990 levels by 2035 (Climate Council 2016; Department of Environment and Energy 2017b).

3.2 Queensland's Transport Sector Emission Trends

The Queensland State of the Environment Report (Queensland Government 2019c) reported that Queensland's transport sector greenhouse gas (GHG) emissions grew from 11.2 million tonnes of carbon dioxide equivalent CO₂-e in 1990 to 22.5 million tonnes of CO₂-e in 2016. It showed that the transport sector is Queensland's second largest source of emissions overall and that road transport is the main source of this sector's GHG emissions (85%, or 19.1 million tonnes of CO₂-e).

A 2018 study, commissioned by the Department of Transport and Main Roads Queensland, in collaboration with the Australian Bureau of Infrastructure, Transport and Regional Economics (BITRE) found that CO₂-e emissions from the road transport sector in Queensland increased by 1.58% in 2015–16 compared with 2014–15 and by 14.5% over the previous 10 years (Centre for Transport, Energy and Environment (CTEE) and Pekol Traffic and Transport (PTT) 2018).

3.3 Benchmark Road Projects Life-cycle GHG Emissions

The literature review identified reference materials to obtain benchmark emissions data from similar roads projects. Table 3.2 provides a summary of source material reviewed, benchmark emissions data identified and the alignment of the data with its pavement life-cycle phase. A detailed overview of these studies is provided in Appendix A.6.

Table 3.1: Emissions data used for benchmarking

Study/Reference	Benchmark emissions	Life-cycle phase
The World Bank (2010)	Expressway: 3,234.12 t CO ₂ -e/km National Road: 793.81 t CO ₂ -e/km Provincial Road: 206.56 t CO ₂ -e/km Rural Road – Gravel: 89.82 t CO ₂ -e/km Rural Road – DBST: 102.74 t CO ₂ -e/km Figure 3.1 shows a breakdown of these emissions by component. Figure 3.2 shows a breakdown of these emissions by generator category.	Construction phase
Pérez-Martínez and Miranda (2013)	0.15 t CO ₂ -e./h/lane-km (Pavement) 0.22 t CO ₂ -e./h/lane-km (Pavement and Infrastructure)	Construction Phase and Use Operations Phase
Transport Authorities Greenhouse Group (TAGG) (2013b)	Mickelham Road: 0.178 t CO ₂ -e/m ² Marx Hill Project: 0.256 t CO ₂ -e/m ² Deer Park Bypass: 0.275 t CO ₂ -e/m ² Alpurt Motorway Extension: 0.653 t CO ₂ -e/m ²	Construction Phase
	Figure 3.3 provides a summary of the contribution of the construction and operations phase emissions (e.g. road sweepers) for various projects.	Construction and Operations/ Use Phase
	10–15% of total construction, use and maintenance emissions OR 6 x 10 ⁻⁶ t CO ₂ -e /m ² (0.003% of construction emissions)	Maintenance Phase
European Asphalt Pavement Association (EAPA) & Eurobitume (Beuving et al. 2004)	Total approximately 23 TJ (2% of total life-cycle)	Construction Phase, Maintenance Phase & End-of-Life
	Total approximately 1430 TJ, given a 30-year life period (98% of total life-cycle)	Use Phase

In Table 3.2, the construction phase is the period encompassing the initial construction of the pavement. The operations phase refers to the operation of the road reserve and the road furniture and does not include the GHG emissions from vehicles using the road. The use phase is the period that encompasses the use of the pavement by vehicles. The maintenance phase is the period encompassing resurfacing and rehabilitation works.

Direct comparisons of benchmark data was in many cases not possible because of different assessment periods and scopes. For example, some of the construction phase benchmark emissions data are site-specific and include site vehicles, lighting, vegetation clearing, drainage structures, cut and fill haulage, which are outside of this project's scope.

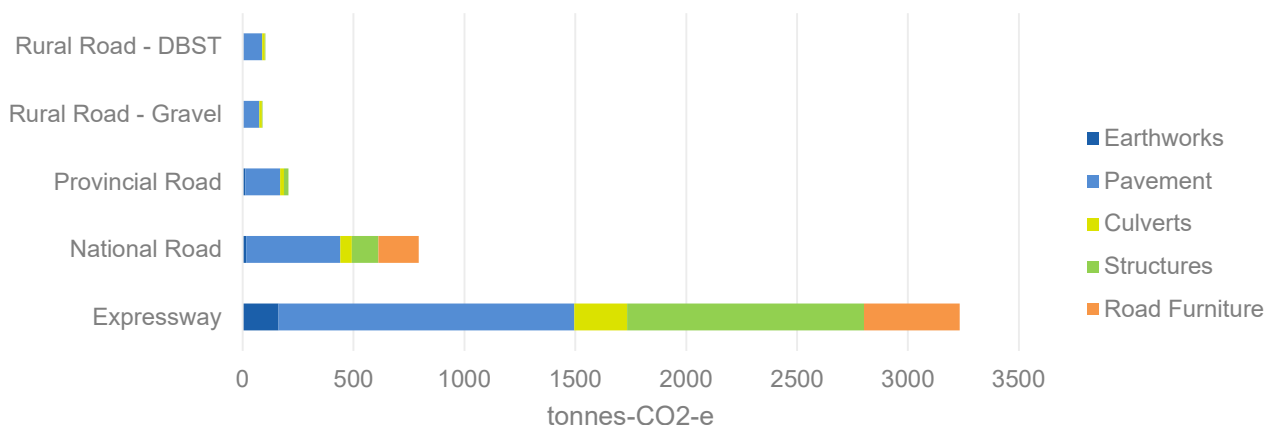
The World Bank (2010) research indicated:

- *pavements are the largest contributor to road construction GHG emissions (Figure 3.1); and*
- *the embodied carbon of materials are the largest contributor to GHG emissions (Figure 3.2).*

This highlights the importance of the research being undertaken in this project, as reducing GHG emissions in pavements and the embodied carbon of pavement materials will reduce overall road construction GHG emissions.

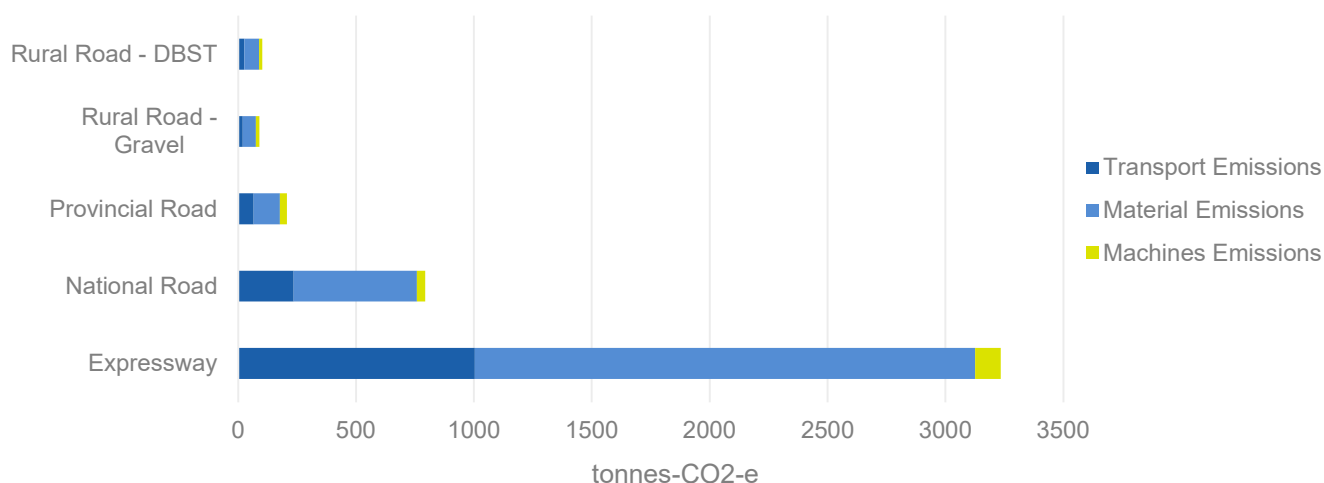
By evaluating NACoE pavement technologies, this project will assist in reducing the most significant component of overall GHG emissions of road construction projects.

Figure 3.1: Emissions per item of construction work per type of road per km



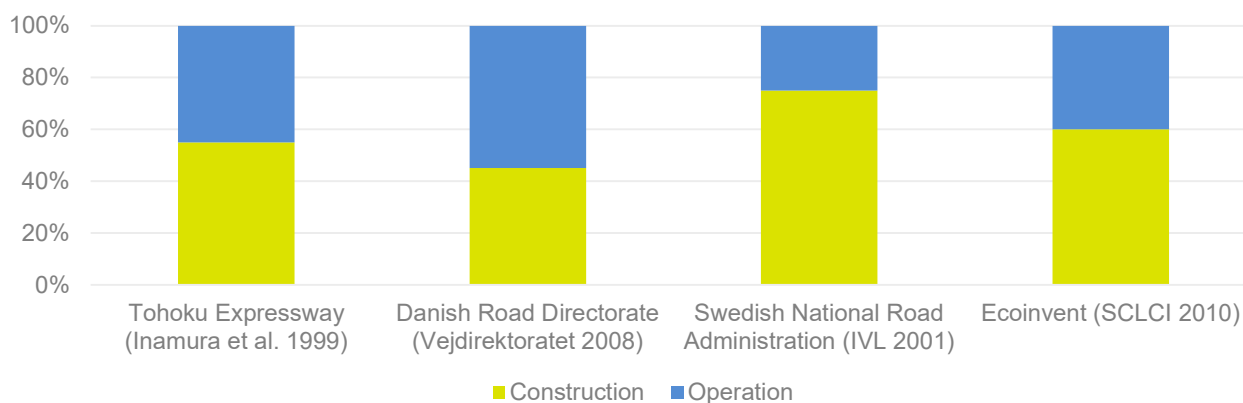
Source: The World Bank (2010).

Figure 3.2: Emission per GHG generator during construction per type of road



Source: The World Bank (2010).

Figure 3.3: Contribution of construction and operation life-cycle emissions (where operation does not include the GHG emissions from vehicles on the road)



Source: TAGG (2013b).

3.4 Abatement Options for Australia's Transport Emissions

Table 3.2 summarises transport sector emissions abatement options as presented at the Australian Low Carbon Transport Forum, 2012 (Cosgrove et al. 2012). This list includes policy options, technology prospects, behaviour change, and urban redesign. Cosgrove et al. specifically identified transport infrastructure in terms of improved road materials and pavement design as options to reduce transport emissions.

Table 3.2: Transport emissions abatement options, by category

Category	Option
Behaviour change	Eco-driving
Passenger vehicle efficiency	Fuel intensity reduction
	Vehicle downsizing
	Low resistance tyres
	Urban road pricing
	Increased urban parking charges
Mode shift	Urban car travel to PT, walking and cycling
	Road passenger or road freight to rail, road freight to coastal shipping
Freight efficiency	Larger combinations than B-doubles
	Engine efficiency improvements
	Larger PBS trucks
	Improved logistics
Transport management	Traffic management
	Reducing speeds
Alternative fuels	Natural gas
	LPG
	Biodiesel
	Ethanol
	Electric vehicles
Transport infrastructure	Improved road materials
	Pavement design
	Optimising asset use
	Road alignment

Source: Cosgrove et al. (2012).

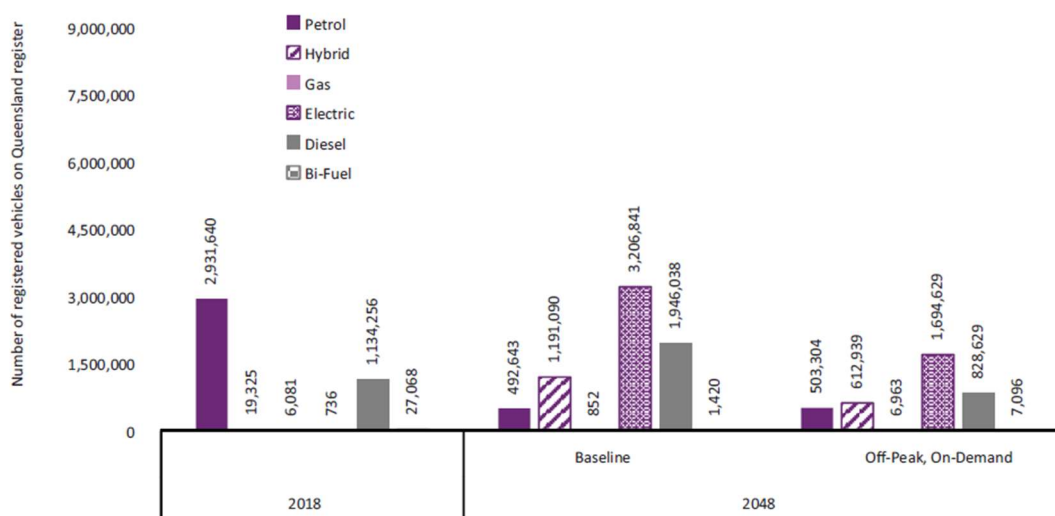
Vehicle emissions can also be reduced by using innovative pavement surface technologies and better asset management practices. Other policy levers and consumer choices also contribute to achieving Queensland emissions reduction targets e.g. increased use of electric vehicles (powered by renewable energy). Alternate pavement technologies also have additional environmental benefits which have contributed to their priority in research. For example, foam bitumen stabilisation (FBS) has the potential to improve pavement resilience to events like flooding due to extreme weather events in rural areas which can result in significant road re-construction with existing pavement technologies.

3.4.1 Electric Vehicles in Queensland

Although Australia is still lagging behind global leaders in the uptake of electric vehicles, over the past few years Australia has seen a 67% increase in the sales of electric vehicles, with 2284 sold in 2017 (ClimateWorks Australia 2016). In 2018, Energeia released a market review of electric vehicle sales, stock and infrastructure as part of their *Australian Electric Vehicle Market Study*. Energeia's research showed that there is a wide variation in the forecasts for electric vehicle uptake, both in Australia and at a global level. Energeia's current forecast in the public domain shows an uptake of electric vehicles to be 20% of new vehicle sales by 2030 (Energeia 2018).

Queensland's transport system is rapidly evolving, suggesting that further changes are on the horizon. The CSIRO and Data 61 recently completed a study forecasting Queensland travel demand and transport system characteristics to 2048. This study considered 'Will people still need to own a car, or will they rely on autonomous vehicles and other mobility services? How will the transport sector respond to future environmental, technological and economic challenges and opportunities? And how will changes in the transport system differ for urban, regional and rural areas?' (Naughtin et al. 2018). Figure 3.4 provides an overview of the forecasted breakdown of the Queensland fleet. As can be seen, in both scenarios, the portion of electric vehicles increases greatly, and is the dominant fuel type in the fleet.

Figure 3.4: Modelling projections of number of vehicles in the Queensland fleet by fuel type in 2018 and projected out to 2048 under the baseline and off-peak, on demand scenarios



Source: Naughtin et al. (2018).

Research has shown that, when linked to a clean energy or renewable energy supply of electricity, electric vehicles can provide emissions reductions of 16– 47% in the passenger and light commercial vehicle category by 2050 (ClimateWorks Australia 2016).

A study undertaken by Beyond Zero Emissions (2016) found that:

- A shift to 100% electric vehicles could eliminate at least 6% of Australia's GHG emissions.
- A rapid shift to electric vehicles operating on 100% renewable electricity is both feasible and affordable.
- Costs could be even lower if Australians adapt their transport behaviours to reduce car ownership.
- Electric vehicles have been shown to be more convenient than traditional combustion engine vehicles.

4 NACOE PAVEMENT TECHNOLOGIES AND IDENTIFIED SUSTAINABILITY BENEFITS

4.1 NACoE Technologies Evaluated

Five NACoE pavement technologies were identified as having a high potential for GHG emissions reduction outcomes and were thus selected for modelling. These included:

- high-modulus asphalt (EME2);
- reclaimed asphalt pavement (RAP);
- crumb rubber modified asphalt;
- stabilisation practices (including foam bitumen stabilisation); and
- non-standard granular and marginal materials.

Table 4.1 summarises NACoE technologies that were evaluated and their associated NACoE projects. Further details are provided in Appendix A.5.

Table 4.1: NACoE technologies evaluated

NACoE technology	Definitions	Related NACoE projects
High modulus asphalt (EME2)	Asphalt characterised by a high stiffness, high durability, superior resistance to permanent deformation and good fatigue resistance (Austroads 2015).	▪ P9: Cost-effective Design of Thick Asphalt Pavements: High Modulus Asphalt Implementation ▪ P10 Asphalt Design at Queensland Pavement Temperatures ▪ P39 Long Life Pavement Alternatives for Queensland
Reclaimed asphalt pavement (RAP)	RAP is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. RAP is generated when pavements are removed for reconstruction, resurfacing, or to obtain access to buried utilities. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by bitumen (Federal Highways Administration (FHWA) 2016). The material is reclaimed from an asphalt pavement by various means including col-milling, grader, backhoe, jackpick or other methods (Austroads 2015).	▪ P57: Implementing the Use of Reclaimed Asphalt Pavement (RAP) in TMR – Registered Dense-Graded Asphalt Mixes ▪ P76 The use of Recycled Glass in Pavements
Crumb rubber modified asphalt (CRMA) and crumb rubber modified binders (CRMB) for sprayed seals – single/single (S/S) and double/double (D/D)	Rubber particles manufactured from waste or reclaimed rubber products such as vehicle tyres are graded (or ‘crumbed’) to conform to a specified size range. Used in bitumen to improve binder properties. Crumb rubber modified seal is a sprayed seal in which the binder consists of bitumen modified by the incorporation of crumb rubber (Austroads 2015).	▪ P31 and P32: Optimising the Use of Crumb Rubber Modified Bitumen in Seals and Asphalt ▪ P75 Transfer Gap Graded asphalt with crumb rubber to QLD and WA.

NACoE technology	Definitions	Related NACoE projects
Stabilisation practices	The treatment of a road pavement or subgrade material by the introduction of a binder to improve it or to correct a known deficiency and thus enhance its ability to perform its function in the pavement. It can be conducted mechanically or through the use of chemicals (Austroads 2015).	▪ P2: Stabilisation Practices in Queensland ▪ P8 Evaluate the Performance of the Transport Network Reconstruction Program ▪ P4 Structural Performance of Unbound Granular Material - Modified C Grading ▪ P49 Quantifying the Benefits of Geosynthetics for the Mechanical Stabilisation of Subgrade Soils ▪ P94 Optimising the use of Recycled Materials in Unbound & Stabilised Pavements ▪ A4 Life-cycle Costing of Rain and Flood Events
Non-standard granular and marginal materials	Non-standard road-building materials generally comprise naturally occurring gravels and weathered rocks. They do not comply with standard specifications but are known to successfully perform as granular base and subbase materials for selected roads. They may also comprise clay and sands (also known as sand-clays) (Austroads 2018).	▪ P34: Performance-based Evaluation Protocol for Non-standard Granular Pavement Materials ▪ P47 Development of an Advanced Performance Model for Unbound Granular Pavements ▪ P66 Facilitating the use of 'Glassy Basalt' in Pavement Materials

Other pavement technologies currently being investigated by ARRB include recycled plastics in bitumen and asphalt, recycled crushed glass in asphalt, low-cost lightly cemented granular materials and unbound granular materials. Specifically, within the NACoE Program two new projects using innovative materials are in the preliminary stages. These include: The Use of recycled Glass in Roads and Optimising the use of Unbound and Stabilised Recycled Pavement Materials in Queensland. These projects provide scope for future life-cycle modelling.

4.2 Sustainability Benefits

Table 4.2 summarises research on the potential areas for GHG savings and potential sustainability co-benefit outcomes for each of the NACoE pavement technologies. Appendix A contains further detail.

Table 4.2: Literature review summary for pavement technologies

Pavement technology	Greenhouse gas savings potential Identified in literature	Other sustainability co-benefits and disadvantages Based on ISCA categories
High-modulus asphalt (EME2)	- Using EME2 can reduce the layer thickness of the base course for heavily trafficked pavements by up to 30%, depending on climatic and traffic conditions. This reduction in layer thickness leads to a reduction in the use of virgin materials, haulage distances and associated CO₂-e emissions (Roads and Infrastructure Australia 2017). - Transurban 's Logan Enhancement Project will be the first wide-use of EME2 in Australia. Transurban are implementing EME2 on 8–10 km of highly trafficked road, estimates show this will reduce the required layer thickness of the asphalt by 17.5%, saving approx. 62 000 tonnes of asphalt (Transurban 2018). These asphalt savings are translated to GHG savings. - EME2 technology can be designed as perpetual pavement, with improved road roughness, leading to lower use phase emissions.	Ecology - As EME2 reduces the amount of material which needs to come from quarries, there are ecological benefits in retaining vegetation or natural habitats of wildlife or other land-related uses. Economic benefits - Lower construction and maintenance costs (Austroads 2017a). - Lower virgin materials cost, due to a reduction in the amount of material required. - Reduction in haulage costs due to the decrease in the amount of material being hauled. - Improved structural life, therefore, less structural maintenance is required during the design life of the pavement, leading to lower life-cycle costs (Distin & Vos 2014). Resilience - Higher stiffness and durability (Austroads 2017a). - Superior resistance to permanent deformation, moisture resistant; and good fatigue resistance (Austroads 2017a; Petho 2014). Resource efficiency - Reduced base layer thickness for the same heavy-duty pavement performance (Austroads 2017a). Social - More workable than standard asphalt pavements in constrained urban areas (Petho 2014). - Longer lasting, and less prone to premature failure from traffic and/or extreme weather events. Therefore, contributing to more resilient transport infrastructure for the community. Disadvantages - EME2 is a premium material and there may be cost trade-offs involved with its use.

Pavement technology	Greenhouse gas savings potential Identified in literature	Other sustainability co-benefits and disadvantages Based on ISCA categories
Reclaimed asphalt pavement (RAP)	▪ Every tonne of RAP means that a tonne of virgin material does not have to be sourced and hauled from quarries to the plant etc – leading to savings in embodied carbon. ▪ RAP requires marginally less virgin binder in the pavement layer mix, saving on all emissions costs associated with producing and transporting the binder. ▪ Recent investigations into the use of RAP in the United States of America have shown that the use of RAP in pavement base and subbase layers can: – reduce global warming potential by 20%; – reduce energy consumption by 16%; – reduce life-cycle costs by 21% (Lee et al. 2010; cited in Newman et al. 2012).	▪ Ecology – As RAP reduces the amount of material which needs to come from quarries, there are benefits in retaining ecological benefits, vegetation or natural habitats of wildlife or other land-related uses. ▪ Economic benefits – Increased value assigned to RAP in the asphalt mix design process incentivises recycling of this material as opposed to sending to landfill thus avoiding landfill costs. – Circular economy achieved through reuse of materials, leading to potential jobs creation in the recycling process. ▪ Environmental impacts – Produces less dust than other crushed materials, and therefore, is recommended for areas and environments where dust can be seen as a nuisance (Alex Fraser Group 2016). ▪ Resource efficiency – Provides a reliable supply of material, as the material currently in the road surface can be reused to rebuild the road surface – can be recycled multiple times (Alex Fraser Group 2016). – Reduction in water consumption by 11% (Lee et al. 2010; cited in Newman et al. 2012). – Reduction in waste generation by 11% (Lee et al. 2010; cited in Newman et al. 2012). – Reusing pavements' high polished stone value (PSV) (i.e. high skid resistance) conserves the amount of high quality/ high PSV aggregates being sourced from quarries, allowing for future use of these materials. ▪ Disadvantages – During the design phase, due to the material being recycled, there can be a view in industry that it is of a lower quality, leading to client bias.

Pavement technology	Greenhouse gas savings potential Identified in literature	Other sustainability co-benefits and disadvantages Based on ISCA categories
Crumb rubber modified asphalt (CRMA)/crumb rubber modified binders (CRMB)	- CRMA is typically used on urban high traffic roads. - CRMA reductions in CO₂-e emissions associated with the virgin materials that the crumb is replacing. - Sousa, Wat and Carlson (2007) concluded that, if the design criteria implemented in California and Arizona Departments of Transportation is used, the CO₂-e savings per lane/mile can vary from 154 to 343 tons per lane mile. - Reducing the number of tyres going to landfill reduces the amount of GHG emissions produced from burning and /or burial of these tyres in waste management.	Economic benefits - Cost savings for community and industry can be seen due to the reduction in or diversion of tyres from landfill. - If less virgin binder is required then there may be a reduction in the shipping requirements of the materials, leading to ecological benefits, lower import costs. - Moving from an imported material to a local material, as most usual polymer modifiers are imported. - Circular economy achieved through reuse of materials, leading to potential jobs creation in the recycling process. Environmental impacts - Use of CRMA/CRMB reduces waste tyres going to landfill. Landfills impose a number of costs on the environment, these include: air pollution; surface water and ground water impacts from leachate to soil and water; and site runoff to nearby receiving waters (Austroads 2014b; Denneman et al. 2015). - Research has shown that when CRMB is used in appropriate asphalt types, it can reduce road traffic noise levels up more than 5 decibels (Carlson 2011; cited in Denneman et al. 2015). Resilience - When used as a binder (i.e. CRMB), potentially more durable asphalt in spray seal surfacing applications. Social - From 2009–10, approximately 66% of end-of-life tyres are disposed of, either into landfill, stockpiled, illegally dumped or characterised as unknown, with only 16% domestically recycled, and 18% exported. Resulting from this are costs to the community and governments through littering of the landscape and waterway, in addition, utilising valuable land for landfill (Department of Environment 2014; cited in Denneman et al. 2015). - Disposed tyres going to landfill, or illegally dumped, can: be a source of health concern, cause fires in stockpiles which can release toxic gases; and provide breeding habitats for pests (Department of Environment 2014; cited in Denneman et al. 2015). Recycling these tyres into crumb rubber provides the opportunity to reduce these outcomes. - Landfilling tyres has an effect on the amenity of a region due to the visual, noise, odour and litter impacts of the disposal facility (Austroads 2014b; Denneman et al. 2015). - Crumb rubber modified asphalt pavement is popular in Arizona, when compared with concrete pavements, as it reduces noise, and provides an improved and safer driving experience in terms of skid resistance.

Pavement technology	Greenhouse gas savings potential Identified in literature	Other sustainability co-benefits and disadvantages Based on ISCA categories
Stabilisation practices (including foam bitumen stabilisation)	Stabilisation practices allow for the continued use of marginal materials, which would otherwise be ripped up, transported and discarded for replacement with higher quality, quarried virgin aggregate (Smith 2005; cited in Grobler et al. 2018).	Economic benefits - Austrroads (2006; cited in Grobler et al. 2018) states that stabilisation can reduce the whole-of-life costs of heavily trafficked pavements. - Reductions in rehabilitation costs due to more resilient pavement. Resilience - Stabilised materials provide improved strength, stiffness and durability, when compared with unbound granular pavements (Griffin, Zhong & Chong. 2015). - Stabilisation provides better resilience to flooding and extreme weather events, and thus avoids reconstruction of pavements. - Provides a more resilient transportation network due to a reduction in the risk of diversions and road closures due to failure. Disadvantages - Stabilised pavements can also exhibit increased shrinkage cracking potential compared to untreated pavements (Griffin, Zhong & Chong 2015). - There is a potential for an increase in the amount of bitumen binders required to be imported. However, if the pavement lasts longer this may be offset by the reduction in materials required for pavement rehabilitation.
Non-standard granular and marginal materials	- Using marginal materials provides savings in haulage and embodied carbon of materials that would otherwise be quarried and transported. - The relative sustainability of subgrade improvements can be informed through calculating CO₂ emissions. Rogers et al. (2009) showed that the lowest emissions option is heavily dependent on the haulage of materials. - As marginal materials tend to be locally available, their haulage distances are vastly lower than imported aggregates.	Economic benefits - Lower construction costs due to reduced materials and materials haulage costs, when compared with virgin materials. Environmental impacts - Community and ecological benefits seen through the reduction in reliance on quarried materials (e.g. vegetation clearance). Social - Community resilience achieved through high access to materials in rural areas due to materials being locally sourced. Disadvantages - Potentially may include reduced road resilience and challenges with reuse for road pavements at end-of-life due to lower quality materials being slightly out of specification requiring rehabilitation at more frequent intervals.

5 PAVEMENT DESIGNS

Pavement designs were developed, in consultation with TMR, for each of the selected NACoE pavement technologies and for a comparable base case technology. NACoE pavement and base case designs were checked by ARRB to ensure comparable performance across different pavement thicknesses e.g. EME2 and FBS (high traffic).

Some designs were suitable for an urban road context and some were suitable for a rural road context, with different traffic and design cumulative equivalent standard axles (CESA) loadings. Table 5.1 summarises the designs.

Table 5.1: Summary of pavement designs

ID U = urban R = rural	Pavement category	NACOE pavement technology (A)	Base case technology (B)	Design CESA	Road type
Urban Roads					
U1	EME2	U1A: EME2 high modulus asphalt	U1B: Dense graded asphalt	100 000 000	Urban motorway
U2	RAP	U2A: Dense graded asphalt with RAP	U2B: Dense graded asphalt without RAP	30 000 000	Urban arterial
U3	Crumb rubber	U3A: Open graded asphalt with crumb rubber modified binder	U3B: Open graded asphalt with A15E binder	30 000 000	Urban road or major rural road
Rural Roads					
R1	Crumb rubber	R1A: Single/Single reseal (HSS1) with crumb rubber modified binder, unbound granular base.	R1B: Single/Single reseal (HSS1) with polymer modified binder, unbound granular base.	1 000 000	Rural main road (lower traffic)
R2	Crumb rubber	R2A: Double/Double reseal (HSS2) with crumb rubber modified binder, unbound granular base.	R2B: Double/Double reseal (HSS2) with polymer modified binder, unbound granular base.	30 000 000	Rural main road (higher traffic)
R3	Stabilisation	R3A: FBS alt case (low/med traffic)	R3B: CTB base case (low/med traffic)	1 000 000	Rural main road (lower traffic)
R4	Stabilisation	R4A: FBS alt case (high traffic)	R4B: CTB base case (high traffic)	30 000 000	Rural main road (higher traffic)
R5	Marginal materials	R5A: Marginal quality base: Ridge gravel	R5B: Standard granular base	1 000 000	Rural main road (low traffic)
R6	Marginal materials	R6A: Marginal quality base: MGB Poorly drained (Wet)	R5B: Standard granular base	1 000 000	Rural main road (low traffic)
R7	Marginal materials	R6A: Marginal quality base: SGB Poorly drained (Wet)	R5B: Standard granular base	1 000 000	Rural main road (low traffic)

Appendix B provides further design details.

6 PAVEMENT LIFE-CYCLE ASSESSMENT MODEL

The following section outlines the life-cycle assessment (LCA) and cost benefit analysis (CBA) purpose, scope and the methodology used.

6.1 Incorporating the Cost of GHGs into TMR's Decision Making

LCA is a technique used to assess environmental impacts associated with all the stages of a pavement's life-cycle. In this study, the total tonnes of GHG emissions each year over the pavement life-cycle were estimated for each pavement technology. By comparing NACoE technologies to their traditional base case, net GHG emissions over the pavement life-cycle could be calculated. Net GHG emissions indicated whether total GHG emissions would go up or down if NACoE technologies were used instead of traditional technologies. A negative net emission indicated a total emissions reduction.

A CBA is a systematic approach method to estimate the strengths and weaknesses of alternatives. Two main applications include:

- to provide a basis for comparing investments or decisions (i.e. NACoE technology compared to the traditional technology base case); and
- to determine if an investment or decision is sound by ascertaining if and by how much its benefits outweigh its costs.

A net present value (NPV) is the difference between the present value of cash inflows and the present values of cash outflows over a period of time. It is used in capital budgeting and investment planning. This study evaluated the life-cycle costs and benefits to TMR from adopting NACoE pavement technologies and compared them to traditional pavement technologies. Discounting determines present value (in today's dollars) of costs or savings that will be realised in the future. A positive NPV indicated a discounted net financial benefit to TMR over the project life-cycle from adopting the NACoE technology.

An externality is a cost or benefit that is incurred to a third party from investments or decisions. GHGs generated from TMR's investments or decisions could result in externality or damage cost to society (e.g. climate change impacts) and vulnerable ecosystems (e.g. the Great Barrier Reef). A carbon cost is indicative of the cost of abatement or the damage cost to society from each additional tonne of GHGs (measured in CO₂-e) released into the atmosphere. When the carbon cost is multiplied by net CO₂-e (tonnes) an NPV of carbon may be generated. A positive NPV of carbon is therefore a mitigated cost (a net benefit) to society. By incorporating the NPV of GHGs into the CBA, a total NPV including the cost of carbon may be evaluated. In this way the externality cost / benefit of GHGs was incorporated into the evaluation of NACoE technologies and thus in TMR's decision making.

6.2 Evaluating Life-cycle Assessment and CBA Models

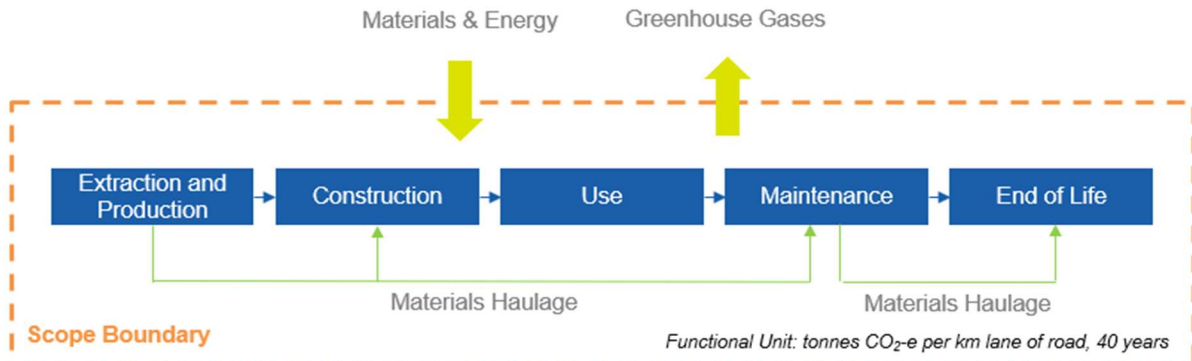
A range of recent Australian and international models and reference databases were identified and evaluated to inform the development of a fit for purpose life-cycle evaluation tool. Refer to Appendix A.7 for further information.

6.3 Life-cycle Modelling Scope

The life-cycle analysis calculates the embodied carbon in the extraction and production of pavement materials and GHGs emissions from construction, use (vehicle emissions), maintenance, end-of-life disposal and haulage over an assumed 40-year period. Materials haulage is inclusive of transporting materials for construction, maintenance and end-of-life disposal. The

pavement life-cycle assessment stages modelled are shown in Figure 6.1. Operational emissions generated by TMR vehicles were assumed to be included within the use phase.

Figure 6.1: Pavement life-cycle assessment diagram



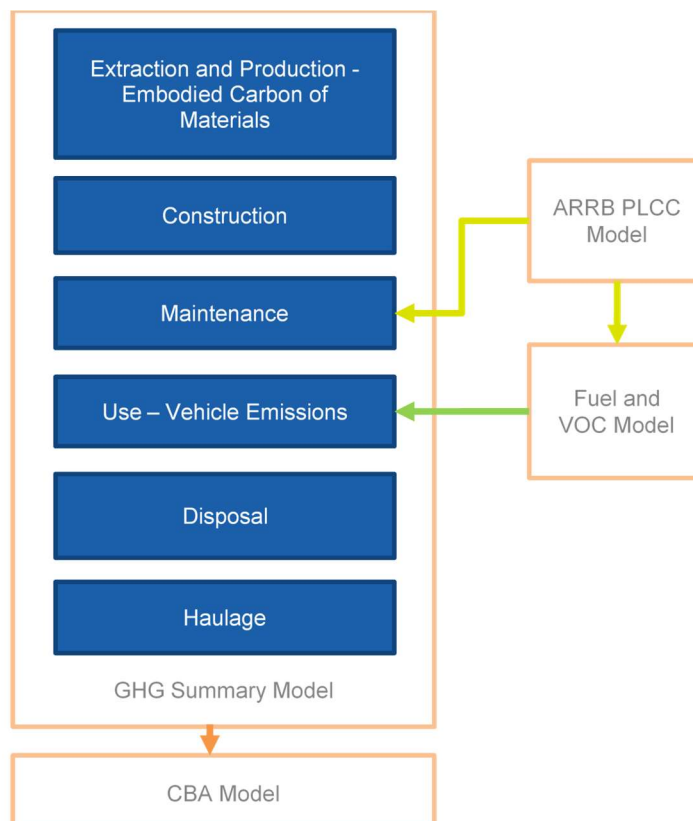
6.4 Model Structure

The final model consisted of four components:

- a GHG summary workbook for calculation of pavement life-cycle GHGs (Appendix C);
- ARRB pavement life-cycle costing (PLCC) tool (Appendix C.2);
- fuel emissions and vehicle operating cost (VOC) model (Appendix C.3);
- a cost benefit analysis (CBA) model (Appendix C.5).

Figure 6.2 illustrates how each model was used in the LCA of GHG emissions and CBA.

Figure 6.2: Life-cycle stages and associated tools/Excel workbooks



The 'GHG Summary Model' is a purpose-built spreadsheet model for modelling life-cycle GHG emissions. This is supported by the 'ARRB PLCC Model' and the Fuel and VOC Model. The CBA Model uses the outputs of the 'GHG Summary Model' as inputs to assesses the GHG economic net benefits and to calculate a Total NPV and includes a cost of carbon. Inputs and calculations from the 'GHG Summary Model' (i.e. life-cycle GHGs and construction, maintenance and haulage costs and disposal costs) are used as inputs into the 'Cost Benefit Analysis (CBA) Model'. Table 6.1 provides a detailed description of the model structure and key data entry requirements for each component of the model.

Table 6.1: Life-cycle analysis and cost benefit analysis model components

Worksheet	Description	Data Entry Required
GHG summary model [Excel tool developed]		
Cover Page [One for workbook]	Provides information on document control and allows for the input of information common to all technology scenarios used in calculations including sensitivity analysis.	- Version date. - Functional basis: lane width, lane length (km) and number of lanes. - Sensitivity analysis – Carbon Price: low, medium and high price. - Sensitivity analysis – Discount Rate: low, medium and high rate. - Sensitivity analysis – Emissions reduction factors for use phase – percentage reduction for each year over 40 years. - Other sensitivity analysis built in as required.
Summary Sheet [One for workbook]	Summarises the results of the technologies and over the life-cycle – extraction and production (embodied carbon), construction, use, maintenance, end-of-life and haulage (to construction, to maintenance and to disposal). Both estimates of total GHGs for each technology, emissions savings of pavement technologies compared to the base case and CBA results – NPV and marginal BCR ratios.	No data entry required as this is a results summary sheet.
Parameters [One for each pavement technology scenario]	There is one 'Parameters' tab for each pavement technology assessed – both NACOE technologies and traditional base case technologies are defined. Here the pavement design and materials recipe for each layer is specified. This is a key input into calculation of materials embodied carbon and total material tonnages for construction and maintenance.	- Pavement name - Layer design description - Layer thickness - Layer density - Layer CBR, layer modulus and layer structural number contribution (for input into life-cycle pavement model). - For each layer component – materials selection (feeds from drop down menu) - For each layer component – mass percentages.
Process Parameters [One for each pavement technology scenario]	There is one 'Parameters' tab for each pavement technology assessed – both NACOE technologies and traditional base case technologies are defined in separate tabs. Here emissions for each life-cycle stage are either summarised or calculated with the use of supporting emissions factors and/or tools.	- Construction - GHG emissions – per lane.km - Cost – per lane.km - Structural number is needed as input into construction cost estimates. - Use – for each year [40 years] - If maintenance or rehabilitation year - Roughness (sourced from PLCC Analysis tool) - AADT per lane (Design) incl. growth factor % heavy vehicles assumed each year - Emissions (from ATAP PV2 – Fuel model). - Maintenance: - For each layer - mm of layer removed - Percentage of layer disposed

Worksheet	Description	Data Entry Required
		- mm of new layer constructed - Cost – per lane.km - Terminal roughness IRI (input into CBA) - GHG emissions – per lane.km. ▪ End-of-life: - Landfill GHG emissions – per lane.km - Disposal cost and levy – per tonne materials. ▪ Transport – for each phase: to construction, to maintenance, to disposal and for each pavement layer - Transport mode – drop down menu - Distance transported - Transport cost – per tonne.km.
Lookup Tables [One for workbook]	Consolidates transport haulage, embodied carbon and density factors from a range of Australian recent tools including ISCA materials calculator v1.2 (Australia), ICE v.2.0 (UK), TAGG (2013a) <i>Greenhouse Gas workbook</i> (Australia).	▪ Material name ▪ Material density ▪ Material embodied carbon ▪ Transport emissions factors.
Reference tables [One for workbook]	Emissions factors and density factors from a variety of tools and reference texts and presents them for reference in one place	▪ N/A – reference sheet only.
CBA model [Excel tool developed]		
Cost Benefit Analysis [One for each NACoE technology and compared to its base case]	This provides an incremental cost benefit analysis for a NACoE pavement technology and compares it to its specified base case.	▪ No data entry is required as information feeds from other tabs in the 'GHG Summary Model' workbook.
PLCC model [existing ARRB Excel tool]		
ARRB Pavement Life-cycle costing (PLCC) analysis [One workbook for all scenarios].	Deterministic pavement life-cycle costing (PLCC) analysis tool which provides inputs for the determination of whole-of-life-cycle costing. The PLCC tool is Microsoft Excel-based. The tool can be used to examine and/or compare different pavement designs over homogenous one-kilometre lengths of road. Intervention levels for roughness, rutting, cracking and strength can be assigned in order to trigger maintenance and rehabilitation works.	▪ Road class ▪ Pavement type ▪ Asphalt thickness, granular thickness ▪ Design life ▪ Pavement design traffic – equivalent standard axles (ESA) ▪ California Bearing Ratio (CBR) ▪ Climate zone ▪ Roughness, rutting, cracking ▪ Traffic growth rate ▪ Daily SARs ▪ Structural number (SN)
Fuel and VOC model [Excel tool developed - ATAP PV2 regressions]		
Fuel Model [One for each pavement technology scenario]	Uses the linear equation available in ATAP PV2 Table 27 (Australian Transport Assessment and Planning Steering Committee 2016) to calculate fuel consumption (litres per 100 km) – vehicle use phase emissions. Fuel emission factors are then used to calculate GHG CO ₂ equivalents. Uses the roughness outputs from the PLCC analysis as input into the model. Outputs include emissions in g/L for carbon dioxide, nitrous oxide and methane. Global warming potentials used to evaluate a CO ₂ -e. A low curvature and flat road is assumed. Sensitivity analysis may be done for different curvature and elevation roads using ATAP PV2 Appendix model coefficient tables. Calculation of VOC has own separate regression coefficients.	▪ Assumptions on fuel types for each vehicle category – diesel or petrol. ▪ Fuel conversion factors (g/L) – to determine GHG emissions incl. nitrous oxide, methane and CO₂. ▪ Global warming potential for different GHGs. ▪ Equation inputs i.e. - GVM for different vehicle types - K1 – k5 model coefficients - IRI values (from PLCC) - Vehicle speeds (posted speeds). - AADT per lane.km - AADT weighting for each vehicle category.

The key reported metrics for each of the pavements are:

- total life-cycle GHG levels (tonnes CO₂-e per lane.km);
- GHG savings for NACoE pavement designs (tonnes CO₂-e per lane.km);
- NPV for just the carbon savings compared to the base case (\$/lane.km); and
- total NPV compared to the base case and including carbon cost (\$/lane.km).

An innovation of the model is that it evaluates the impact of various design, maintenance and operational levers on the use phase (vehicle) emissions and life-cycle costs. This is important as the largest component of Queensland's road GHG emissions are from vehicles and particularly on higher traffic roads. It also allows the evaluation of a selection of scenarios including pavement rehabilitation needs in respond to extreme climatic events by considering the resilience of a selection of the technologies. These are important considerations in evaluating the effort to adapt to extreme weather events due to climate change.

6.5 Sourcing and Validating Assumptions through TMR District Survey

A survey was distributed to pavement asset managers in the 12 TMR districts to obtain real-world information and validate assumptions (the survey is provided in Appendix C.4.1). Five of the twelve TMR districts responded to the survey. A detailed overview of the results is provided in Appendix C.4.2.

The survey revealed that NACoE pavement technologies are already used across Queensland. Figure 6.3 shows which pavement technologies are currently used and how common their use is.

Figure 6.3: Pavement technologies used by TMR survey respondents

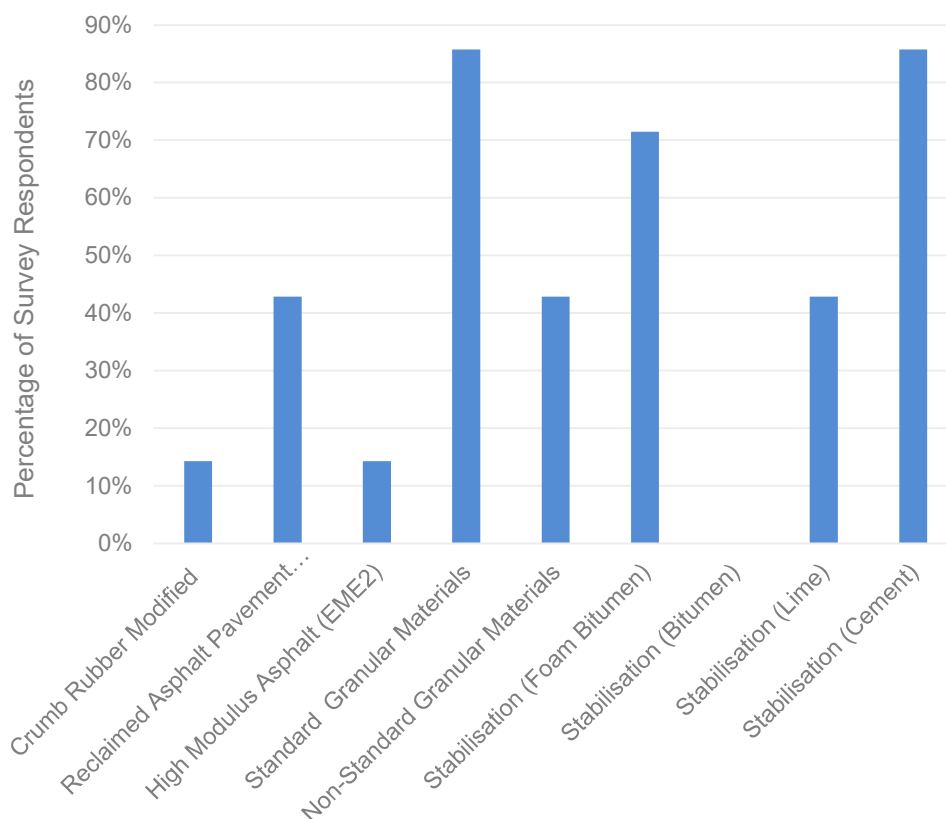


Table 6.2 summaries the most common survey responses for the:

- expected service life of sprayed seals and asphalt pavements;
- typical haulage distances of various products;
- types of vehicles used for transportation of products; and
- end-of-life practices.

Where a variety of responses was received, the most common (majority) response was used to inform the modelling assumptions. In many cases there was insufficient information to differentiate and validate the performance of NACoE technologies compared to their base case technologies, thereby introducing limitations in the modelling results.

Table 6.2: Summary of survey information

Survey topic		Options with majority answer
Expected service life of sprayed seal products	S/S (initial/reseal) Straight run and cutback binders	< 7 years
	S/S (initial/reseal) Polymer modified binders (PMB)	9–12 years
	S/S (initial/reseal) CRMB	7–9 years & 9–12 years
	D/D (initial/reseal) Straight run and cutback binders	9–12 years
	D/D (initial/reseal) Polymer modified binders (PMB)	9–12 years
	D/D (initial/reseal) CRMB	9–12 years
Expected service life of asphalt products	Dense graded asphalt	14–17 years
	Dense graded asphalt with RAP	14–17 years
	Open graded asphalt with PMB	< 10 years

Survey topic		Options with majority answer
	Open graded asphalt with CRMB	< 13 years
Typical haulage distances	Binder	100 km+
	Surfacing aggregate	100 km+
	Asphalt	10–30 km
	Typical granular road base (type 3)	30–50 km
	Excavated waste material	10–30 km
Typical haulage vehicle	Bitumen and binders	Heavy truck (> 28 t average gross mass)
	Asphalt, aggregate or road base products	Heavy truck (> 28 t average gross mass)
Percentage of excavated waste material from existing formations going to disposal		10–20%/80–90%
Use of marginal materials in maintenance program		Rarely (< 10%)

6.6 Model Assumptions and Calculations

Appendix C details the model's assumptions, equations and methodology used to calculate life-cycle emissions and undertake the cost benefit analysis.

7 MODELLING RESULTS

The following section presents the modelling results for each of the pavement technologies. Appendix D presents the results in detail.

7.1 Total GHG Emissions of Pavements Evaluated

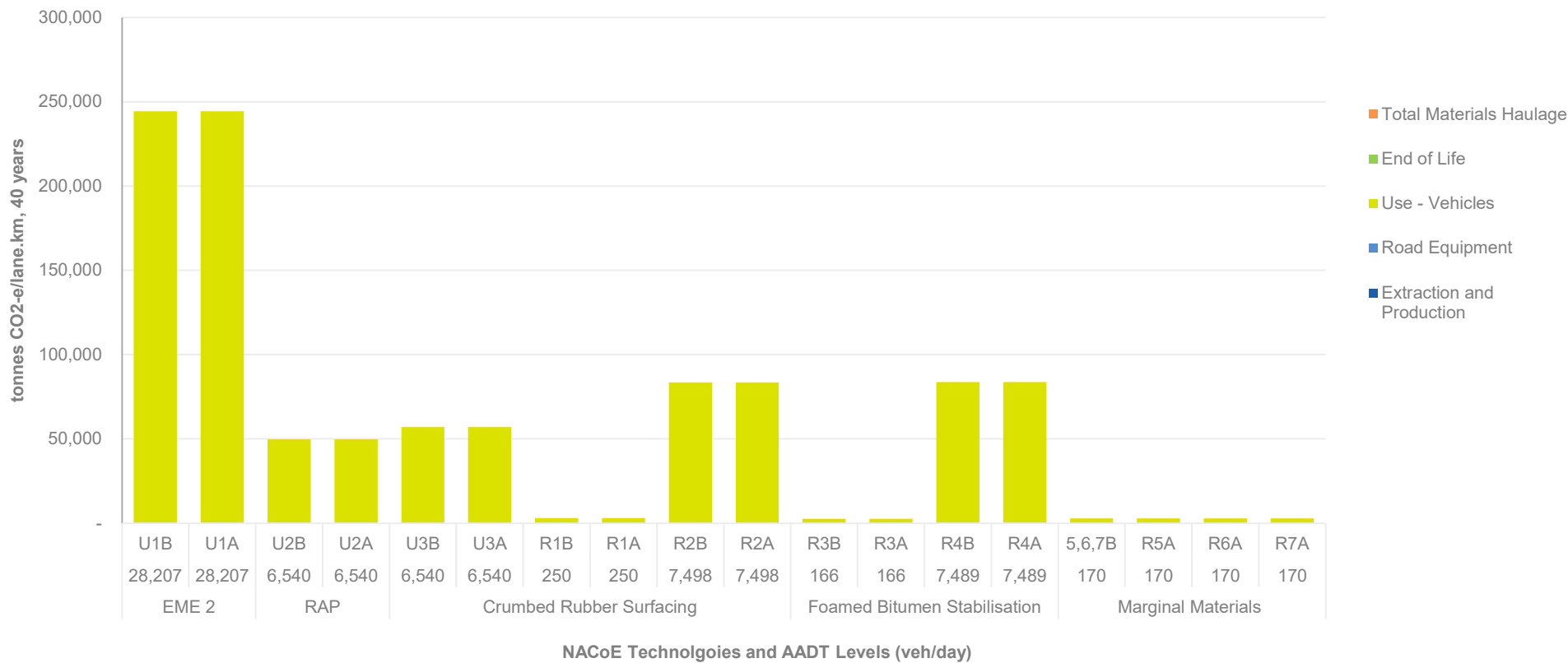
Figure 7.1 presents the total emissions for each pavement design modelled. Typically use phase emissions represent > 97% of all life-cycle emissions except at very low traffic levels. The use phase emissions are affected by the AADT per lane.km assumptions and also the % heavy vehicles assumed. This is the area where the most significant emissions savings are potentially achieved. Use phase emissions are assumed to be equivalent for both NACoE technologies and comparable base cases – as pavements are assumed to perform equivalently. This is with the exception of marginal materials, which do not have comparable performance, albeit at low assumed AADT traffic levels.

Figure 7.2 presents the total emissions for each pavement modelled excluding use phase emissions. Results from Figure 7.2 include:

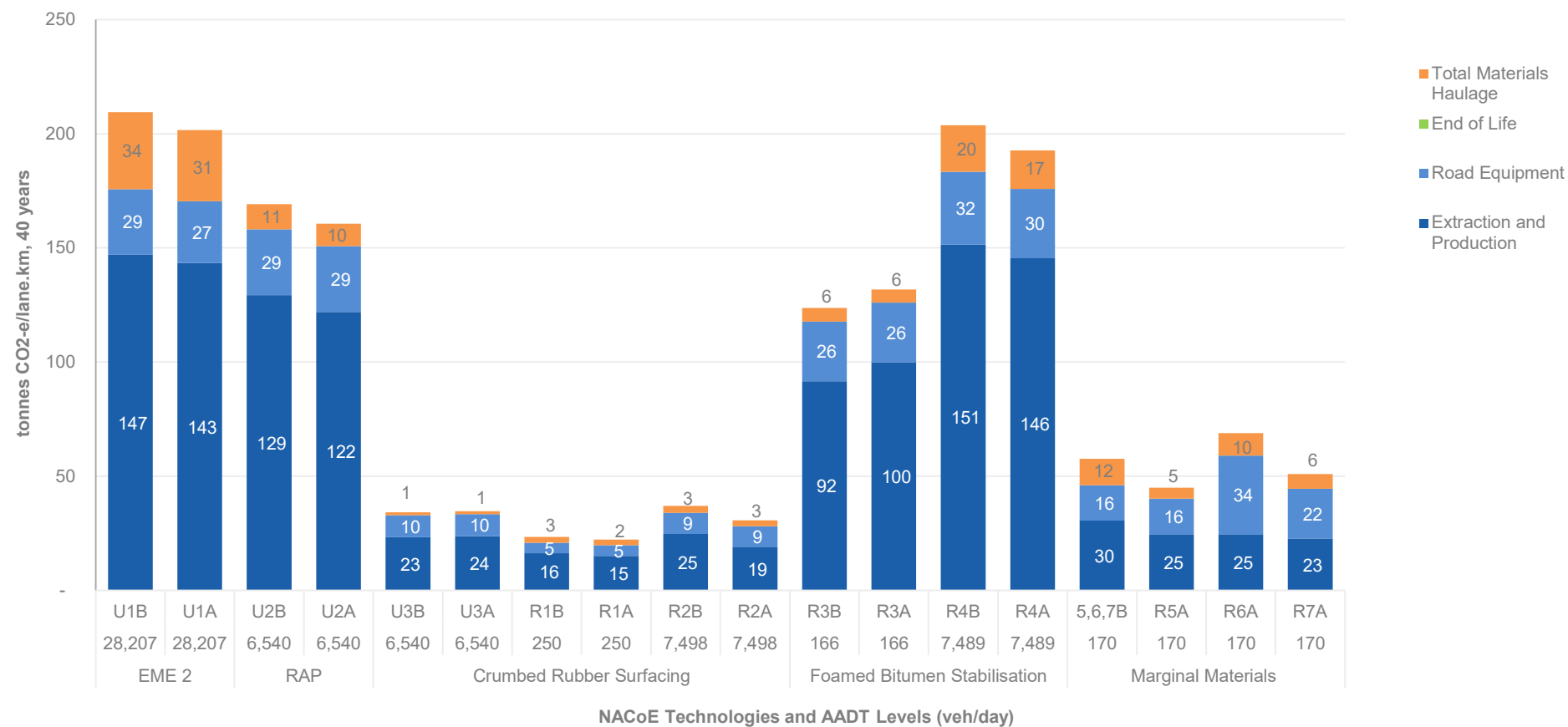
- The emissions were typically proportional to the thickness of the layers modelled. Crumb rubber U3, R1 and R2 were just resurfacing layers during construction.
- Embodied energy formed the largest component of total emissions.
- The road equipment used in the construction and maintenance activities was next highest and was then followed by the haulage of materials over the life-cycle.
- The highest total emission levels were associated with the use of EME2 on an urban highway and the use of foam bitumen stabilisation on a high traffic rural road.
- The relatively higher embodied energy of R4 was associated with the use of stabilisation materials.

Figure 7.3 presents the net emissions of NACoE technologies compared to the base case and by life-cycle phase. A negative value is an emissions reduction and a positive value is an emissions increase.

Figure 7.1: Total life-cycle GHG emissions for each pavement design (tonnes CO₂-e/lane.km, 40 years)

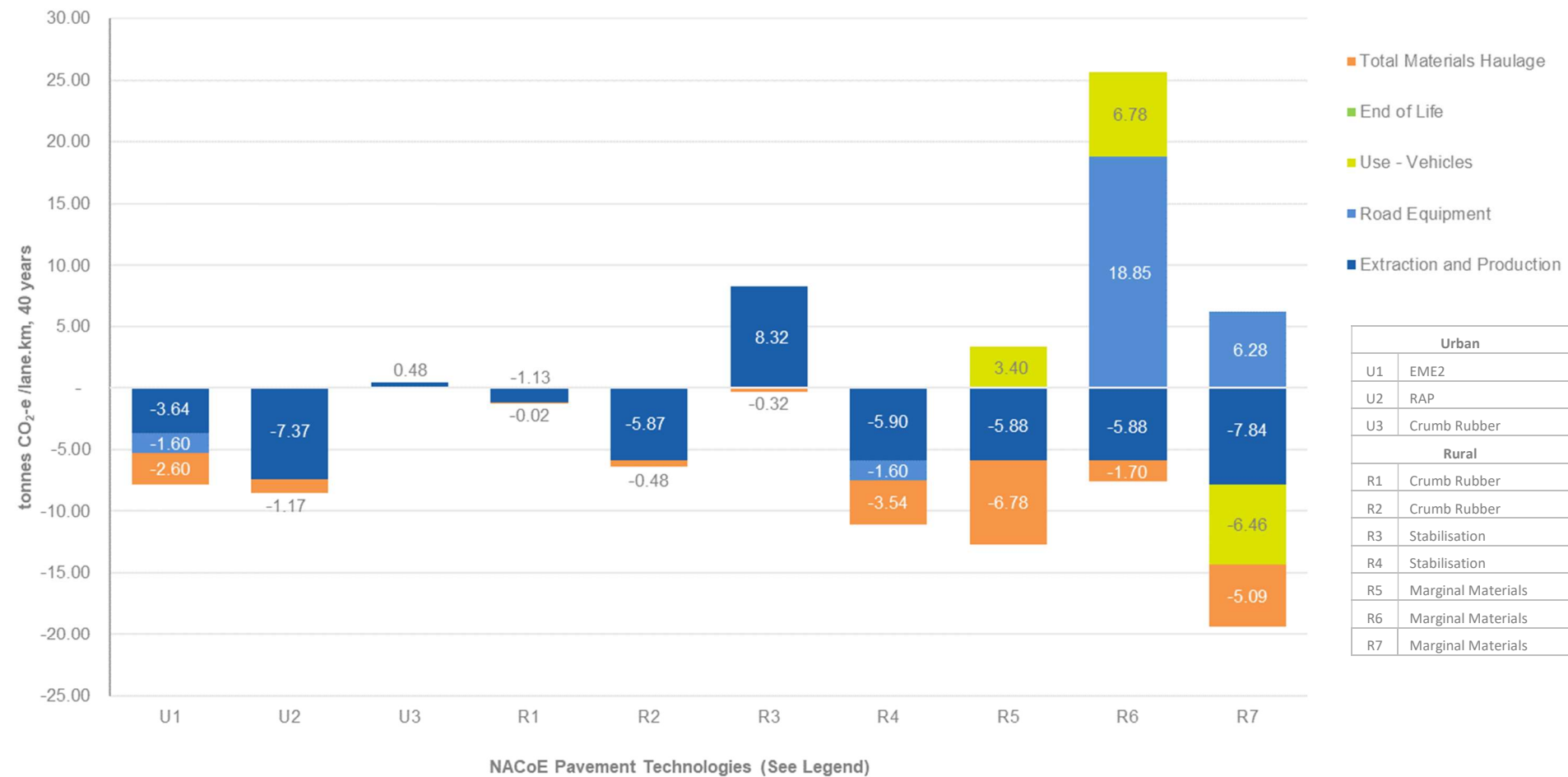


- Notes:
- Refer to Table 5.1 for NACoE pavement technology names and pavement designs evaluated.
 - The A suffix indicates the alternate NACoE technology. The B suffix indicates the base case technology.
 - The U prefix indicates an Urban Road. The R prefix indicates a Rural Road.
 - Urban roads assume two lane roads. Thus, the road AADT is double the per lane AADT assumptions on Urban Roads.
 - Indicative AADT levels per lane-km are provided along the x-axis.

Figure 7.2: Total life-cycle GHG emissions for each pavement design, excluding use phase (tonnes CO₂-e per lane.km, 40 years)**Notes:**

- Refer to Table 5.1 for NACoE pavement technology names and pavement designs evaluated.
- The A suffix indicates the alternate NACoE technology and the B suffix indicates the base case technology.
- Indicative AADT levels per lane-km are provided along the x-axis. Note that on urban roads 2 lanes were assumed on each carriage-way.

Figure 7.3: Net GHG emissions for different NACoE technologies compared to the base case by life-cycle phase (tonnes CO₂-e /lane.km, 40 years)



- Notes:
- Refer to Table 5.1 for NACoE pavement technology names and pavement designs evaluated.
 - A negative value is a reduction in life-cycle GHG emissions from decision to use of NACoE technology.
 - A positive value is an increase in life-cycle GHG emissions from decision to use of NACoE technology.

7.2 GHG Emissions Reductions from Use of NACoE Pavements

7.2.1 EME2

U1 is associated with EME2. The reductions were in the construction phase. Embodied carbon emissions reductions were realised due to the thinner base layer which more than offset the increased use of bitumen. A thinner base layer results in less materials haulage and construction emissions. The maintenance scopes between the EME2 pavement and the base case were considered equivalent. The two pavements were assumed to have the same performance and thus there was no increase/decrease in use phase emissions.

7.2.2 RAP

U2 is associated with the use of RAP in the pavement. The large embodied carbon reductions were due to the use of RAP which has a lower embodied carbon compared to virgin materials. There was also a marginal savings in bitumen use. The haulage saving was associated with less material going to landfill.

7.2.3 Crumb Rubber

U3 is associated with the use of crumb rubber in the asphalt surfacing layer. The increase in the use of bitumen offset any embodied carbon reductions from the use of crumb rubber in the asphalt surfacing.

R1 is associated with the use of crumb rubber in a single seal (S/S) re-surfacing. Embodied carbon reductions were associated with the use of crumb rubber in the surfacing which had a lower average embodied carbon. A marginal haulage reduction was also realised due to the density differences in the surface layer.

R2 is associated with the use of crumb rubber in a double seal (D/D) re-surfacing. Embodied carbon reductions were associated with the use of crumb rubber. A marginal haulage emissions reduction was also realised due to the density differences in the surface layer.

7.2.4 Foam Bitumen Stabilisation

R3 is associated with the use of foam bitumen stabilisation on a low traffic road. The embodied energy was sensitive to the bitumen and lime content which is higher than that of cement. This was only marginally offset by haulage savings during construction and due to density differences between the base layers.

R4 is associated with the use of foam bitumen stabilisation on a higher traffic road. In this case the surfacing layer is thinner during construction due to the stiffer stabilised base layer. This results in construction, haulage and embodied carbon emissions reductions. The thinner base layer more than offset the increase in average embodied energy due to the bitumen and lime content compared to the use of cement.

7.2.5 Non-standard Granular and Marginal Materials

Local marginal materials were assumed to have an embodied carbon value of zero. Emission reductions were achievable due to reduced embodied carbon and reduced haulage distances.

Marginal materials R5 is associated with the use of local ridge gravel in the base compared to an imported base material. Use phase emissions marginally increased over 40 years, due to a marginally poorer performing pavement compared to the base case. There were no rehabilitations of the pavement within 40 years. R5 realised a net emissions reduction overall.

R6 is associated with the use of a very poorly performing marginal material. Rehabilitations occurred every 14 years. This resulted in a significant increase in re-construction emissions that offset maintenance emissions associated with the base case. This also more than offset embodied carbon reductions. Use phase emissions also increased due to the rapidly deteriorating pavement performance vs the base case. R6 realised a significant net emission increase overall.

R7 is associated with a marginal material pavement that deteriorates at a rate between R5 and R6. Rehabilitation occurred every 24 years. The emissions associated with re-construction increased, embodied carbon emissions on net went down due to the use of local materials. The use phase emissions also went down, as rehabilitation reset the roughness and realised emissions reductions over the life-cycle. R7 realised a net emissions reduction overall.

7.3 Percent GHG Emissions Reductions from use of NACoE Technologies

Figure 7.4 presents an estimate of the percentage of emissions reductions for each of the NACoE pavement technologies evaluated and compared to the base case. A positive value is an emissions reduction compared to the base case. Most technologies resulted in net reductions.

- The emissions increases were in U3 (crumb rubber in asphalt), R3 (foam bitumen stabilisation of a low traffic road), and R6 (a poor quality marginal material).
- The highest % reductions were associated with the use of marginal materials R7 at 22.7% saving – due to avoided haulage of virgin materials long distances.
- Approximately 17.2% of emissions reductions were potentially realised with the use of crumb rubber in a D/D seal vs a conventional PMB D/D seal.
- The largest increase in emissions was associated with R6 at a 31.3% increase in emissions compared to the base case. This was due to increased frequency of rehabilitation required due to the poorly performing marginal material.

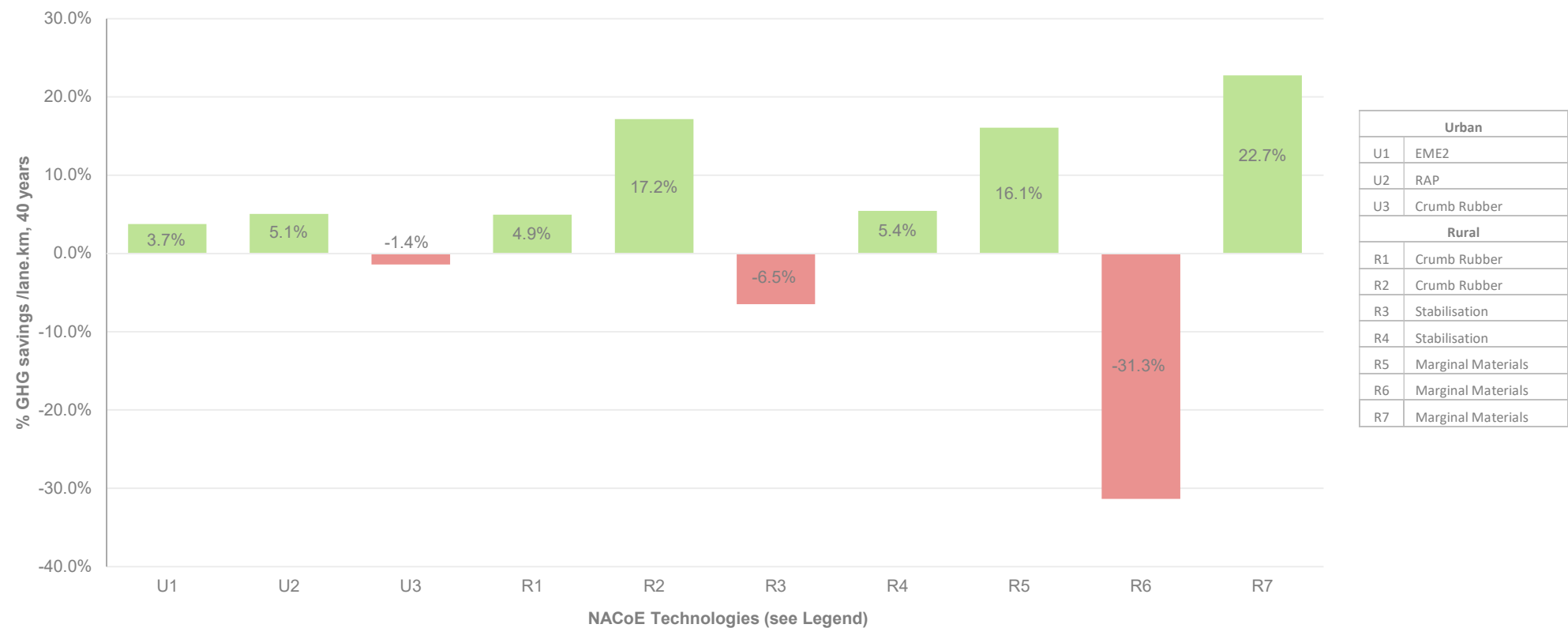
7.4 Cost Benefit Analysis Savings from use of NACoE Pavement Technologies

Figure 7.5 presents the results of the CBA for each of the NACoE pavement technologies evaluated. A positive NPV is associated with a cost savings when discounted back to present values. A 7% discount rate was assumed.

- For U1 through to R4, the construction, maintenance costs and road performance were assumed equivalent to their respective base cases. The Total NPV was therefore sensitive to haulage and disposal assumptions.
- U2 associated with RAP had significant savings and was sensitive to the % of surfacing asphalt that went to landfill.
- For the crumb rubber technologies U3, R1 and R2, the total NPV and the NPV of carbon were similar as the effects applied only to the surfacing layer and there were only marginal density differences affecting haulage.
- R4 also had the potential to realise a positive NPV due to the thinner surface layer during construction.
- Marginal materials R5, R6 and R7 were also sensitive to construction and maintenance costs in addition to haulage effects. The construction costs were also differentiated reflecting a cheaper construction cost when marginal materials were used.
- The largest potential for cost savings was associated with R5. R5 is a cheaper pavement, performs similarly to the base case and uses local ridge gravel in the place of imported base materials hauled over longer distances.

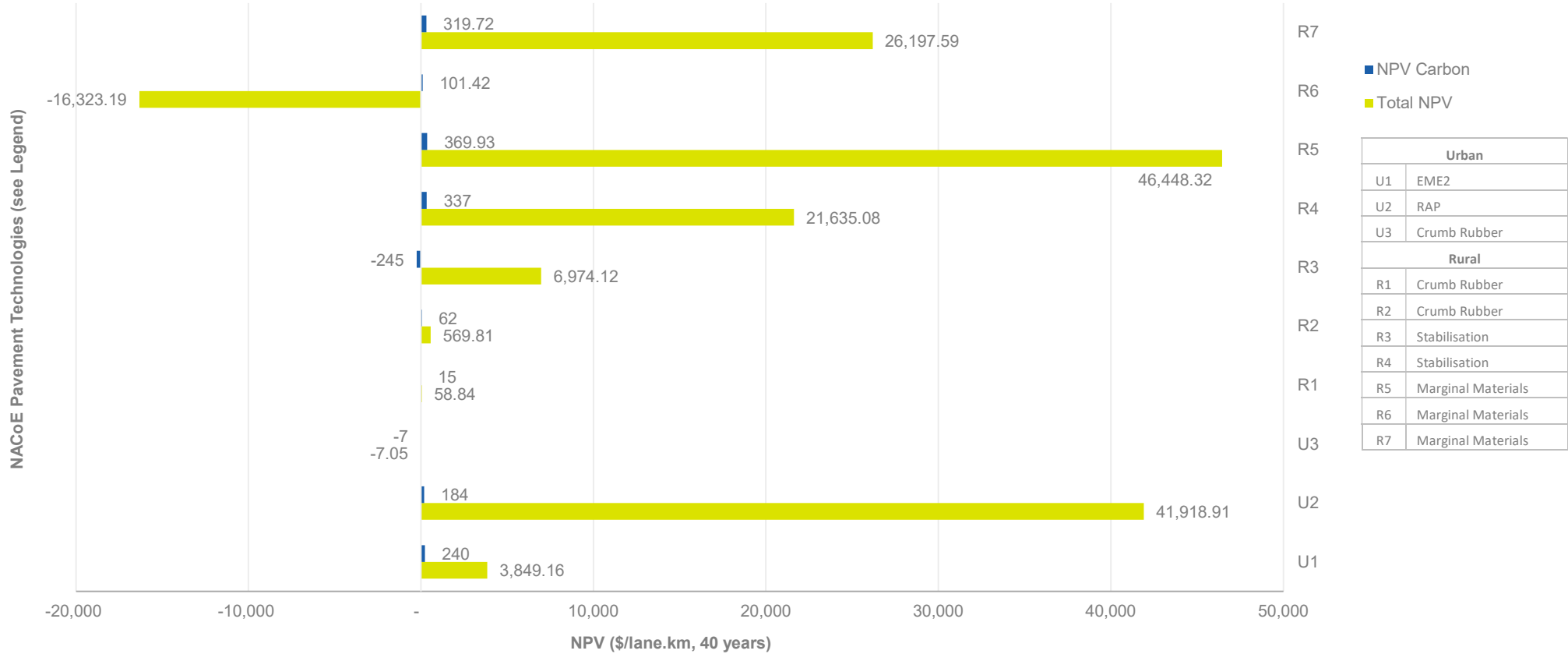
-
- R6 had a large negative NPV. This was due to the high frequency of reconstruction over the life-cycle period associated with a poorly performing material, resulting in additional rehabilitation costs and haulage costs. Any capital cost savings during the construction phase were negated during the operations and maintenance phase.
 - When comparing the NPV of carbon to the total NPV, it was only a small component of the overall NPV and thus did not affect decision making significantly.
 - Generally, the NPV of carbon (associated with net emissions reduction) was positive except for U3 associated with crumb rubber in asphalt surfacing and R3 associated with low traffic foam bitumen stabilised road. Generally, construction phase effects were weighted more heavily than future discounted maintenance, use phase and reconstruction effects. Therefore, R6 had a positive NPV of carbon despite increasing emissions overall, over the 40-year assessment period.

Figure 7.4: Percent emissions reduction results for each NACoE pavement technology (% GHG savings /lane.km, 40 years)



- Notes:
- Refer to Table 5.1 for NACoE pavement technology names and pavement designs evaluated.
 - Green indicates an emissions reduction from the decision to use the NACoE technology.
 - Red indicates an increase in emissions from the decision to use the NACoE technology.

Figure 7.5: CBA results – the total NPV and NPV of carbon emissions at 7% discount rate and \$30.57/tonne CO₂-e cost of carbon (\$/lane.km, 40 years)



Notes:

- A positive NPV value represents a discounted life-cycle cost savings to TMR.
- A negative NPV value represents a discounted life-cycle cost increase to TMR.
- The NPV Carbon – indicates the discounted externality savings to society from the mitigations of GHGs.
- The Total NPV is inclusive of the GHG carbon cost – thus indicating total discounted life-cycle costs/benefits and assuming GHG costs are internalised into TMR's decision making process.
- A 7% Discount Rate and \$30.57/tonne CO₂-e cost of carbon was assumed.
- Refer to Table 5.1 for NACoE pavement technology names and pavement designs evaluated.

8 SENSITIVITY AND SCENARIO ANALYSIS

A sensitivity and scenario analysis were undertaken on key parameters in order to determine the impact of changing key assumptions on the outcomes of results. The below table summarises the sensitivity and scenario analysis that was run and the key results.

A detailed overview of the context, assumptions, methodology and results for each sensitivity and scenario is provided in Appendix E.

Table 8.1: Summary of sensitivity and scenario analysis and key results

Sensitivity or scenario	Scope	Major Results
AA: Embodied Carbon – Haulage Distances Sensitivity. Refer to Appendix E.1.	- Crumb rubber achieved emissions reductions in the use of spray seals, and assuming no transport in the embodied carbon factor for crumbed rubber. - In rural areas large haulage distances may result in haulage emissions outweighing embodied emissions reductions from the use of low carbon materials like recycled materials. - A sensitivity analysis on the haulage distances on crumb rubber materials was done.	Embodied Carbon – Haulage Distances: Crumb rubber materials used in spray seals can be hauled large distances (> 3,000 km) and still achieve GHG emissions reductions over the pavement life-cycle.
BB: Use Phase Emissions – Roughness and Speed. Refer to Appendix E.2.	- Use phase accounts for a large percentage of total road life-cycle GHG emissions. - There may be design, maintenance and road operation levers available for TMR to reduce use phase emissions. - A sensitivity analysis on pavement roughness and posted speed and the impact on use phase emissions was done for an indicative high traffic urban road.	- Use phase – posted speed and road roughness: Emissions increase with both increasing speed and increasing road roughness. - Free flowing speed is a more significant factor than road roughness affecting use phase GHGs. - Based on modelling results, road roughness can affect between 2 and 3% of annual use phase vehicle emissions.
CC: Use Phase – Curvature and Rise/Fall Sensitivity Analysis. Refer Appendix E.3.	- Use phase modelling assumes a flat and low curvature road. - Alternative alignment options have the potential to affect use phase GHG emissions on a lane.km basis. - A sensitivity analysis on use phase emissions for different rise/fall and curvature scenarios and assuming a constant speed and road roughness.	- Use phase – alignment decisions: emissions may increase or on higher rise/fall and curvature roads compared to a flat and low curvature free flowing road. - Note that at the higher elevation and curvature scenarios, speeds may in reality drop for safety or due to limits of engine power (uphill).
DD: Use Phase RUC – Roughness and Speed. Refer Appendix E.4.	- There may be design, maintenance and road operation levers available for TMR to reduce use phase emissions. These were identified in scenario BB. - There may be, however, potential RUC trade-offs to the Queensland Economy. - A scenario analysis was done looking at the roughness and posted speed impacts on RUC for an indicative high traffic urban road.	- Use phase – RUC – RUCs increase with lower speeds in part due to travel time increases. - RUCs and use phase (vehicle) GHG emissions increase with increased road roughness.

Sensitivity or scenario	Scope	Major Results
EE: Whole-of-Life Resilience – Flooding scenarios for foam bitumen stabilisation. Refer Appendix E.5.	- With climate change, extreme weather events have the potential to become more severe and frequent e.g. flooding. - Foam bitumen stabilised base layers have the potential to improve the resilience of roads to extreme weather events like flooding on rural roads and compared to technologies like CTB. - A scenario was run assuming that 5% of an FBS road required rehabilitation after a flood event compared to 20% of a CTB road.	- There are life-cycle GHG emissions reductions possible due to avoided rehabilitation with the use of FBS. - There are, however, net use-phase emissions trade-offs associated with relatively smoother newly rehabilitated CTB pavements, but this excludes traffic re-routing considerations. - Significant total life-cycle cost savings may be realised from the use of resilient pavements due to avoided rehabilitation costs. - The total NPV is more sensitive to the rehabilitation costs and then the haulage costs. - The carbon cost savings do not change significantly between flood and non-flood scenarios.
FF: Use Phase Emissions – Electric Vehicles Uptake. Refer Appendix E.6.	- The modelling assumed 100% petroleum powered vehicles. - There is a trend towards electric vehicles uptake nationally and globally. - The Queensland Government is committed to renewable energy targets in the medium to longer term. - A scenario was run modelling the electric vehicle uptake trend and assuming 100% renewably run.	- Use phase – Vehicle fuel GHG emissions efficiency: i.e. Electric vehicles powered by 100% renewables can reduce up to 45% of total use phase emissions. - This is based on current linear forecasts that assumes 77% electric vehicles on roads in 40 years.
GG: Haulage Distances – Base Case vs Local Marginal Materials. Refer Appendix E.7.	- In rural areas the haulage of virgin materials that meet design specifications may be cost prohibitive. - This sensitivity analysis looks at the overall contribution of haulage distances to the potential GHG emissions reductions and overall emissions and NPV associated with adopting marginal materials. - Each of the scenarios R5, R6 and R7 were representative of various grades of sub-optimal performance materials resulting in more frequent maintenance cycles and more rapid surface deterioration i.e. roughness and rutting. - A 20 km, 100 km and 200 km sensitivity analysis was run on the base case which was the haulage distance of virgin materials. R5, R6 and R7 were assumed to be hauled 20 km from source.	- The differences in GHG reductions reflect the frequency of rehabilitation associated with the marginal materials pavements compared to the base case and associated embodied carbon differences. - At 20 km the base case and the alternative case haulage distances are equivalent. The differences in cost savings reflect the frequency of rehabilitation associated with the marginal materials pavements compared to the base case and associated embodied carbon differences. - The net emissions reductions grow in proportion to the haulage distances. - At 20 km to 100 km haulage range, R6 remains a net-emissions increase overall due to multiple rehabilitations and haulage of materials over 40 years. - For R5 all scenarios resulted in positive NPVs. For R6 for all scenarios total NPV was negative. For R7 (pavement performance between R5 and R6) the NPV was negative at 20 km, suggesting no net benefit from using the local marginal material compared to virgin materials (20 km away).

Sensitivity or scenario	Scope	Major Results
HH: Cost Benefit Analysis – Carbon Price and Discount Rates. Refer Appendix E.8.	▪ In the results section a 7% real discount rate and a \$30.57 per tonne CO₂-e mid-range cost of carbon was assumed. ▪ The discount rate and the cost of carbon assumed have the potential to change the total NPV results. ▪ Typically, TMR undertakes sensitivity analysis at a 4% and 10% discount rate. ▪ There are various methods for estimating a cost of carbon in Australia resulting in values that are lower or higher.	▪ CBA conclusions are not affected significantly from a change in the carbon price (\$/tonne CO₂-e) or discount rate (%). ▪ The total NPV is only marginally affected by a change in the carbon price (\$/tonnes CO₂-e). ▪ Scenario R6 in particular is sensitive to the discount rate due to increased frequency of rehabilitation compared to all other technologies. ▪ Haulage distances, haulage tonnages, tonnages of pavement material diverted away from landfill and pavement resilience (reduced rehabilitation risk) are more significant factors affecting cost savings associated with the use of NACoE technologies.

9 DISCUSSION AND CONCLUSIONS

The following conclusions have been drawn from the results and sensitivity and scenario analysis:

1. NACoE pavement technologies present opportunities for win-win environmental benefits and cost savings:
 - (a) Up to 17% GHG savings is possible relative to standard technologies (excluding marginal pavement materials whose results are highly variable depending on materials composition).
 - (b) Highest GHG emissions reductions are realised on urban roads and foam bitumen stabilised higher traffic rural roads. This is mostly due to the improved stiffness or durability of base layers (thinner pavement layers) and/or use of lower embodied carbon materials.
 - (c) Embodied carbon is a more significant component of life-cycle emissions savings compared with construction and haulage. Embodied carbon reductions are sensitive to the bitumen content of the binder, relative layer thickness and embodied carbon of aggregate materials. Recycled materials typically have lower embodied carbon compared to virgin materials.
 - (d) The use of crumb rubber in asphalt resurfacing increases emissions due to the increased bitumen content assumed in the design. There are, however, significant co-benefits of using crumb rubber including diversion of tyres away from landfill and associated cost savings.
 - (e) The use of crumb rubber in sprayed seals results in relatively large percentages of embodied carbon reductions because of the rubber content having less embodied energy compared to the use of PMB binders in seals. There are significant net GHG benefits even with the haulage of crumb rubber materials over long distances.
 - (f) Improved resilience of roads through use of technologies like foam stabilised bases (FSB) can achieve carbon construction, maintenance and haulage emissions savings over the pavement life-cycle. There are, however, GHG emissions trade-offs in the use phase. Rehabilitation cost savings from the use of FBS (due to avoided rehabilitation) far outweigh marginal increases in carbon costs from use phase impacts over the pavement life-cycle. The NPV was more sensitive to the rehabilitation costs and secondarily to the haulage costs.
2. Sensitivity of non-use phase findings to changes in key assumptions directly relevant to TMR:
 - (a) The use of local marginal materials was shown to deliver net GHG reductions and cost savings under low to moderate moisture conditions. This was due to reduced rehabilitation and haulage compared to the transporting of virgin quarry materials over long distances. Marginal materials do not perform as well where moisture conditions are less favourable, affecting the structural durability of the base and resulting in more frequent rehabilitation cycles over the 40-year analysis period. For poorly performing marginal materials, the construction cost savings are offset by increased rehabilitation frequency during the maintenance and use phase. Consequently, consideration of overall network performance, accounting for the proportion of sections at risk, and those likely to perform satisfactorily is essential.
 - (b) Estimates of the total NPV of NACoE technologies compared to base case technologies are sensitive to net haulage and disposal tonnages where equivalent pavement performance and construction and maintenance costs are assumed between technologies. This is a limitation of the modelling results that may be addressed in the future if differentiated performance and cost data becomes available. These information gaps may be addressed in the future with more experience with NACoE

technology use in Australia and/or through further research. This also emphasises a need to account for a network view, with location and performance risk being critical to estimates.

3. Opportunities exist for TMR and Queensland Government to reduce road transport-related GHG emissions:

GHG life-cycle modelling and economic modelling showed that life-cycle GHG reductions and cost savings can be achieved through interventions within TMR's control. Based on the use phase modelling, those aspects which could have significant input by TMR, assuming all petroleum powered vehicles, include the following:

- (a) The use phase (vehicle traffic) emissions represent the largest component of life-cycle emissions. The use phase is a key area to achieve significant GHG savings.
- (b) Improving road alignment (i.e. curvature and rise/fall) in new or reconfigured road construction projects may serve to significantly reduce use phase emissions.
- (c) Speed reduction can significantly reduce use phase emissions, but it has trade-offs with road user costs (RUC) which increase at lower speeds (due to increased travel time). There may also be safety considerations not evaluated as a part of this study.
- (d) Improvements in pavement performance through more durable pavement designs, maintenance and rehabilitation solutions can reduce pavement distress and road roughness and therefore use phase emissions. More durable pavement surfaces also lower VOCs and thus come with co-benefits to the Queensland economy. Only modest GHG emissions reductions by up to 2–3% have been estimated from modelling. This is believed to be an underestimate where long-life, 'perpetual' pavements are considered e.g. EME2 with thicker base layers.
- (e) Electric vehicles (powered by renewables) have the potential to reduce life-cycle use phase emissions by up to 45% over a 40-year period. Whereas this is not directly under TMR's control, it has a significant contribution to make through Government and consumer/producer actions.

4. The methodology presented in this report may be suitable for the evaluation of other NACoE pavements under development including but not limited to use of glass in pavements.

9.1 Modelling Limitations

The limitations of the modelling undertaken include the following:

- Modelling scope:
 - The current life-cycle scope excluded diversions away from landfill including the application of waste levies and associated savings e.g. rubber tyres. Many NACoE pavement materials may also be suitable for recycling multiple times e.g. RAP asphalt. These were identified as co-benefits.
- Embodied carbon:
 - The accuracy of the modelling was subject to the availability of emissions intensity factors for different pavement material components. Not all materials had readily available emissions factors e.g. crumb rubber. A sensitivity analysis was done on crumb rubber haulage as crumb rubber embodied carbon values excluded haulage in calculations. As far as practicable recent emissions factors used in Australian tools and reports were consolidated and adopted. Many recent Australian tools use international emissions factors in the absence of Australian values. Marginal materials were considered 'soil' or 'other' with an embodied carbon value of zero for the purposes of modelling. Future modelling of marginal materials could allow for crushing and screening processing

activities where they are applicable. EME 2 bitumen embodied carbon values were also not available and thus EME 2 was assumed to be a typical bitumen product in the modelling.

- Construction and maintenance phase GHG emissions:
 - In the absence of a construction plan for each of the pavement types, construction phase emissions were benchmarked against Australian emissions for similar pavement designs and adjusted proportionally to the number of lifts and processes. Future emissions reporting may improve GHG estimates for pavements of different designs.
- Pavement performance and maintenance cycles:
 - There was limited experience and relative performance data available for technology designs, e.g. crumb rubber compared with PMB seals or EME2 pavements vs traditional pavements. The survey did not generate sufficient results to differentiate performance. NACoE technologies were assumed to perform similarly to their respective base cases except for marginal materials. Future modelling may allow for more accurate assumptions and differentiation of NACoE pavement performance compared to base case designs.
- Use phase emissions:
 - ATAP PV2 fuel use equations and VOC equations adopt a standard 8.5 m width road. This may overstate use phase emissions by up to 20% at each AADT level for a flat, low curvature road. It is also a static model assuming free flowing traffic at a chosen speed level. If the emissions due to congestion need to be considered in the future, future modelling may choose to use HDM-4 modelling rather than the use of simplifying regression equations. ATAP PV2 regression equations currently also exclude hybrid, electric or other emerging vehicle technologies.
 - Actual use phase emissions effects in a single lane may be different to indicative modelled effects due to factors including, but not limited to, network distribution effects and traffic and heavy vehicle distributions and particularly on high traffic urban roads with multiple lanes.
- Cost Benefit Analysis:
 - The modelling currently only considers the cost to TMR and incorporating the GHG emissions cost savings. Future modelling may include trade-off costs to the community, e.g. RUCs and other environmental externalities.
 - There was limited ability to differentiate between NACoE technology and traditional pavement construction and maintenance costs. The NPV was therefore sensitive to maintenance, haulage and disposal assumptions. Future modelling may differentiate the costs between technology types where information is available from road agencies.

10 RECOMMENDATIONS

Recommended next steps to assist TMR in reducing Queensland's road transport GHG emissions include:

1. Consider further pavement R&D and life-cycle modelling of other NACoE pavement technologies:
 - (a) Further R&D with the aim of developing cost-effective and optimised life-cycle low carbon pavement designs including techno-economic evaluations. This would consider whole-of-life-cycle low carbon design attributes identified in the modelling (e.g. low embodied carbon materials like recycled materials, stiffer base, low roughness of pavement surfaces, durability and resilience of pavement layers and low bitumen binder content) and associated key environmental, safety and cost trade-offs. It may be possible to develop design specifications and/or validate performance of pavements that combine NACoE technologies and thus maximise life-cycle CO₂-e/lane.km reductions. Cooperation with industry may be beneficial.
 - (b) Modelling assumed NACoE pavement technologies performed equivalently to their respective base cases except in the case of marginal materials. Future life-cycle GHG modelling of alternative NACoE pavement technologies may be improved with the sourcing or development of pavement performance curves associated with varying key pavement attributes that contribute to life-cycle emissions reduction (e.g. EME2 base thickness). This may be used to evaluate or extrapolate life-cycle GHG emissions and thus evaluate the GHG reduction impacts from different optimised NACoE designs and particularly on high traffic roads.
 - (c) Future GHG modelling of alternative NACoE pavement technologies currently under investigation including, but not limited to, the use of recycled glass in pavements. There may be other pavements that have low carbon pavement attributes that could also be investigated. This investigation would follow the methodology presented in this report.
 - (d) Further R&D into transferring the methodology developing in this report to other road components, rather than just pavements. This could include: bridges, structures, barriers, lighting, ITS, etc.
2. Evaluate other technologies with potential to reduce road transport emissions:
 - (a) Future modelling to evaluate other NACoE technologies that have the potential to significantly affect and thus reduce 'use phase' emissions other than pavement technologies e.g. heavy vehicle network operations. Note that this may be on a CO₂-e per passenger.km or tonne.km freight basis and considering network context effects.
 - (b) Future modelling may choose to evaluate the emissions reduction potential of other road technology levers with high GHG emissions efficiencies potential in addition to electric vehicles e.g. hybrid vehicles and fuel emission standards. In this way the technological contribution to total road transport emissions reduction may be quantified for the use phase.
 - (c) There is potential for other modes of transport to have lower life-cycle GHG emissions (including use phase) for the same freight or passenger movement tasks. Rail or tram transport could be evaluated for life-cycle emissions on a lane.km or tonne.km basis. The potential for shared road and rail or tram corridors could also be explored.
 - (d) Use phase GHG emissions reductions on a road lane.km basis over 40 years may be made with road alignment decisions on high rise/fall roads. There may be a trade-off between alignment cut and fill haulage, drainage and water treatment structures and vegetation clearing compared to use phase emissions savings. ISCA assessments should consider this in their scope when evaluating road projects and subject to road construction cost trade-offs.

3. Consider developing low carbon procurement and GHG reporting policies:
 - (a) Review of non-price related procurement criteria for pavement designs in TMR. Bids on big projects to include traditional and alternative lower life-cycle carbon options. Reportable metrics may also include CO₂-e/\$ to inform cost-effectiveness analysis and thus minimise life-cycle GHG impact per dollar spent within limited road construction and maintenance budgets. Evaluate the potential for using economic incentives structures for high impact low carbon designs in procurement contracts and considering the cost of carbon to the Queensland economy e.g. carbon credits.
 - (b) Incorporate GHG reporting, construction and maintenance cost per km into future construction and maintenance bids and contracts including NACoE technologies. This may be for a certain scale project consistent with current waste management reporting e.g. either greater than \$500 000 contract value or a project greater than 3 months in duration. This assists with benchmarking data for NACoE technologies and serves to inform emissions and cost assumptions required for modelling required to achieve an ISCA rating.
 - (c) A consolidation of carbon emission data for each project location into a central open source database managed by ARRB, TMR and/or ISCA. This would allow for a quick reference of emissions factors for different pavement designs and consolidated accounting of emissions efficiencies and cumulative GHG savings over time. In so doing it may assist with forecasting the contributions towards achieving transport sector and state emissions reduction targets.
 - (d) The sourcing of Australian emissions factors where currently international emissions factors are used or absent e.g. crumb rubber, bitumen, marginal materials etc. Work with industry to identify ways to drive energy efficiency (embodied carbon) of pavement materials or lower emissions during construction processes.
4. Consider undertaking additional economic evaluations:
 - (a) Future modelling may choose to consider policy options to TMR or the Queensland Government to incentivise GHG reductions in the transport sector and associated impacts to government, community and/or industry. This may include price incentives.
 - (b) There may be potential to achieve both GHG reduction outcomes and economic benefits to the Queensland economy from cumulative reduced VOCs associated with GHG reduction efforts. This could be estimated as part of CBA modelling in the future.
 - (c) ATAP PV2 regression analysis for fuel use and VOC in the future could be updated for emerging vehicle technologies and should incorporate electric vehicle power costs and a carbon cost when carbon costing is used. This may also inform and thus affect vehicle fleet distribution and optimisation decisions to minimise VOCs or identify potential barriers to technology transfer.
5. Consider evaluating the GHG benefits and cost savings across the state road network:
 - (a) There are various types of existing roads across the Queensland network and a limited number of new roads constructed each year. The total potential GHG savings in Queensland from the use of the NACoE pavement technologies evaluated are proportional to the total km of road length available for construction and maintenance, the timing of construction and maintenance activities and the location of road materials e.g. RAP and crumb rubber recycling plants. This is an area for future investigation in order to quantify the total potential for total GHG savings contributions to state emissions reduction targets. Other co-benefits from such a network analysis could include identifying potential barriers to technology transfer and quantifying potential latent demand for recycled materials across the Queensland network, which may in turn incentivise circular economy and job creation outcomes.

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APPENDIX A LITERATURE REVIEW

A.1 Emissions

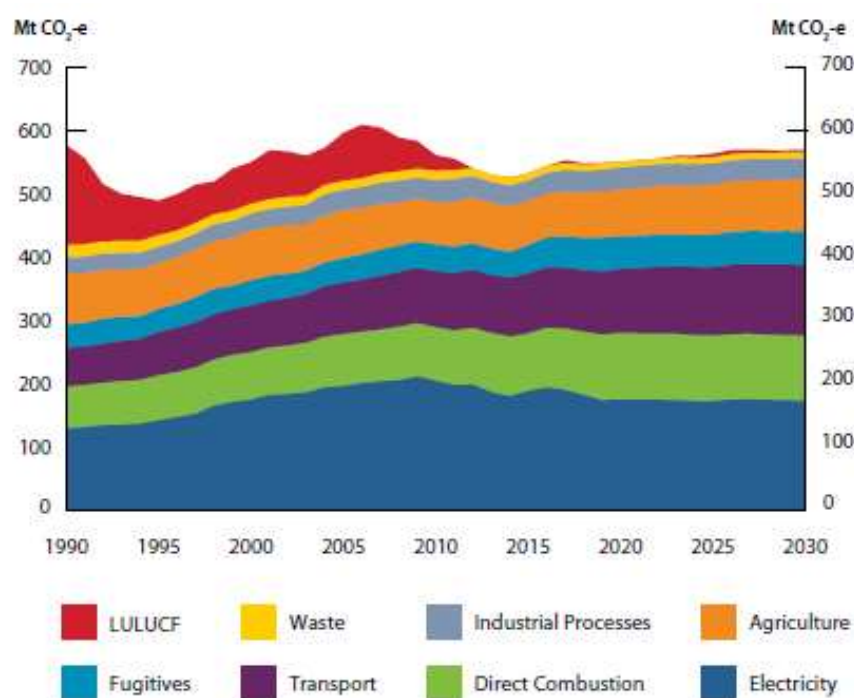
GHG emissions arise from human-based sources and activities, from all sectors of society, with the primary emitters being: energy generation, construction, agriculture, industry, and transport (ATAP 2019).

GHG emissions contribute to human-induced climate change. There are several potential effects of this process including: an increase in extreme weather effects, sea level rise, changes in temperature and rainfall, health impacts (e.g. due to heat stress), expansion of areas amenable to parasitic and vector-borne diseases, ecosystem and biodiversity impacts. More generally, significant social impacts may arise around the world such as increased migration out of areas stressed by climate change and civil unrest (ATAP 2019).

A.2 Australia's Transport Sector Emissions

Transport emissions account for Australia's third largest source of GHG emissions (Figure A.1), equating to 93 MtCO₂-e in 2015, or 18% of total GHG emissions.

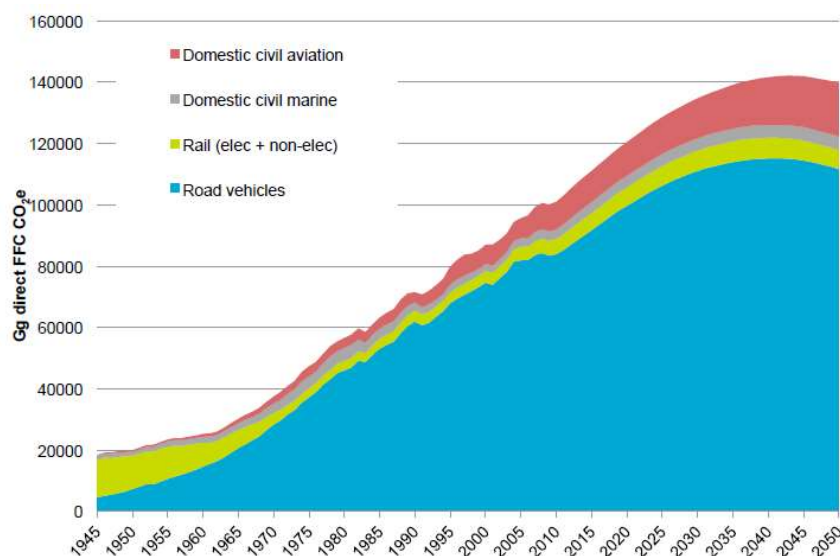
Figure A.1: Australia's emissions, 1990–30



Source: Department of Environment and Energy (2017b).

Figure A.2 shows that 85% of transport emissions are produced from road transportation.

Figure A.2: Base case projections of full fuel cycle emissions from Australian civil domestic transport, by mode to 2050



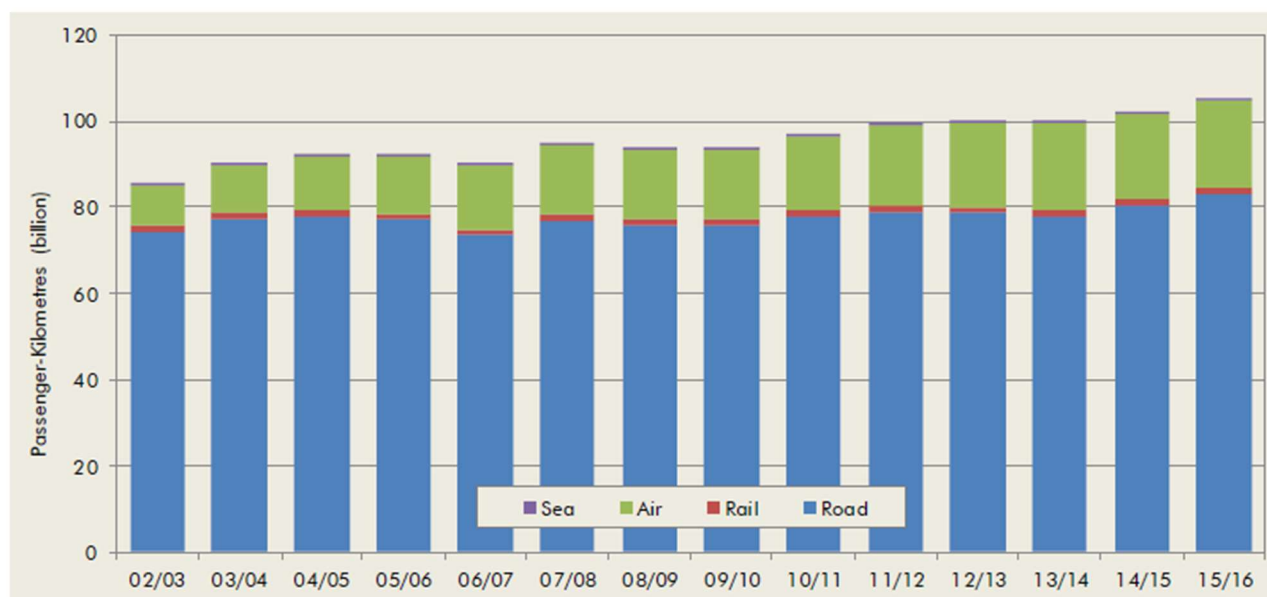
Source: BITRE (2010; cited in Cosgrove et al. 2012).

The Australian transport sector is also the highest growing source of emissions, having grown by 51% since 1990. The key drivers of emissions growth include population and economic growth. If action is not taken, this is projected to continue to grow to be nearly double 1990 levels by 2035 (Climate Council 2016; Department of Environment and Energy 2017b).

A.3 Queensland's Transport Sector Emissions

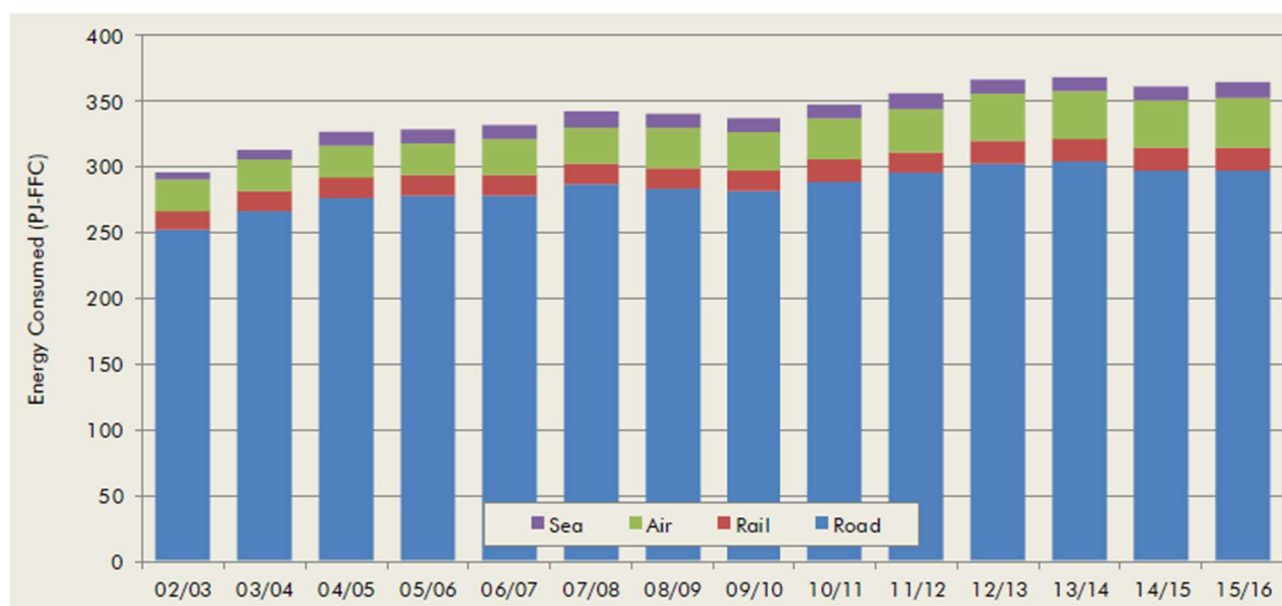
Further to Section 3.2, Figure A.3 and Figure A.4 show that road transportation modes dominated domestic passenger travel and energy consumption in Queensland in the past 17 years.

Figure A.3: Queensland domestic passenger task by mode



Source: CTEE & PTT (2018).

Figure A.4: Energy consumed by domestic transport by mode in Queensland



Source: CTEE & PTT (2018).

In 2015–16 road transport passenger kilometres grew by 3.20% to 83.1 billion passenger-kilometres (79% of the total domestic passenger travel kilometres). Road transport passenger kilometres were projected to increase by 13.5% to 94.3 billion passenger-kilometres over the next 10 years.

The study also estimated that CO₂-e emissions from the road transport sector in Queensland increased by 1.58% in 2015–16 compared with 2014–15 and by 14.5% over the previous 10 years.

A.3.1 Emissions from Road Construction

The bulk of emissions from the transport sector, and in particular road transportation, are associated with decisions made by private passenger car users, and road agencies have little chance to affect these decisions without major changes in policies. Where road agencies can make more of an impact is with how roads are constructed and maintained over time (Hanson & Noland 2015). There is growing recognition within the transport sector that construction and maintenance practices have major environmental impacts (Subedi et al. 2018). For example, during the construction phase, the ecosystem can be affected through the removal of vegetation, erosion, sedimentation, soil compaction, noise, contamination, and toxicity – to name a few. Pavement preservation and performance also has the potential to bring significant environmental benefits in the reduction of CO₂-e emissions, despite the emissions generated at the construction phase (Wang et al. 2019). Research has shown that the life-cycle GHG emissions associated with constructing roads can account for 10–20% of the emissions associated with the lifetime usage of the road by vehicles (Chester & Horvath 2009; cited in Hanson & Noland 2015).

Research has shown that the majority of emissions associated with road construction and maintenance is the upstream emissions associated with the embodied energy of the virgin materials. This includes asphalt, concrete and steel (Chester & Horvath 2009; cited in Hanson & Noland 2015). Therefore, reducing consumption of these is key in reducing road construction emissions and thus overall road transportation emissions.

Concerns for climate change and energy consumption have created motivation for the asphalt industry to lower the carbon footprint (Colbert, Hasan & You 2016). Asphalt is widely used in

construction. It is estimated that a typical hot-mix asphalt (HMA) production plant generates around 15.2 kg CO₂/tonne during regular production processes (Liu et al. 2013).

Pavement construction materials demand a significant amount of non-renewable materials. Aggregate sources are depleting, and the rising price of asphalt binders has pushed the asphalt industry to investigate alternative material for constructing sustainable, yet inexpensive, roads (Colbert, Hasan & You 2016).

Therefore, the need to develop cost-effective construction practices is becoming more urgent in the efforts being made internationally to reduce GHG emissions (Sousa, Wat & Carlson 2007).

A.3.2 Materials Availability and Recycling

The cost of sourcing traditional road construction and pavement materials is increasing, due to sources of these materials being exhausted and access to these traditional materials' sources being lost due to native title and heritage issues. In addition, due to the declining availability of these materials, haulage distances are increasing. As a result, jurisdictions are seeking alternative solutions, one of which is using recycled materials.

All jurisdictions in Australia have sustainability initiatives and strategies in place to manage natural resource consumption. Therefore, moving into the future, significantly more funds will be required to maintain sprayed seal and thin asphalt pavements, to ensure they are sustainable.

As a result, there is a need to investigate the economics associated with both the continued use of traditional pavement materials and the adoption of alternative strategies involving the use of recycled materials.

In 2014, Austroads undertook a study to determine the economics of materials availability and recycling, in order to determine 'the economic costs associated with the decreasing availability of traditional road building materials and the extent to which future availability of pavement materials will impact on road maintenance and construction activities' (Austroads 2014a).

This study included details of a two-year survey process which sought information on the use of local and recycled pavement materials by Australian jurisdictions. The survey focused on construction and demolition waste. The report provided an estimate of the financial cost savings when incorporating recycled aggregates into pavement bases. It also set out the environmental and social considerations associated with recycling and resource use. The report suggested there are significant economic and environmental benefits associated with the incorporation of recycled aggregates in pavement bases.

Austroads stated that a full economic evaluation of using recycled pavement materials would need to consider the social and environmental benefits and costs of its use, as well as the market factors. A full life-cycle approach would consider all impacts associated with recycling versus disposal to landfill. The use of recycled aggregates and materials incurs substantial environmental benefits. The weight of these benefits is dependent on several factors, including the efficiency in the recycled material collection and reuse supply chain. The potential environmental benefits include reduced resource consumption, reduced quarrying, diversion of waste materials from land fill, and reduced energy and greenhouse gas emissions.

Unfortunately, this project found that there was insufficient data suitable for a full analysis of the economic costs associated with decreasing the availability of traditional road building materials and the extent to which future pavement material availability will impact road construction activities, to be undertaken. Therefore, information from VicRoads was utilised to derive the financial cost savings of incorporating recycled materials into pavement bases.

The financial analysis was undertaken using the Sustainable Aggregates Tool, with an addition of up to 15% recycled component within pavement construction. The results showed that there was an annual savings of \$24 million or a 4% reduction in the total cost of pavement materials.

A.4 Previous Work Undertaken in NACoE

A.4.1 Quantitative Review of Economic Benefits of NACoE

The following information is an extract from the summary of NACoE Project O6: 'Quantitative Review of the Economic Benefits of NACoE', undertaken by Beecroft (2016):

The first three years of the National Asset Centre of Excellence (NACoE) research program have delivered many noteworthy outcomes, primarily with respect to delivering potential agency cost savings to the Queensland Department of Transport and Main Roads (TMR), but additionally in terms of indirect process benefits.

While it has been recognised across the Department and industry that NACoE research and initiatives are having an impact, there has not been a comprehensive, project-based effort to quantify the benefits, and subsequently to weigh up these benefits against total costs across the program.

This study has summarised the efforts to quantify benefits of relevant road research around the world, with many of these programs delivering direct benefits to road agencies of many millions of dollars, equating to estimated benefit cost ratios in the range of 1.4–11.6.

The NACoE program has a broad research scope, so a range of strategies were adopted for estimating benefits. The resultant analysis, drawing on data supplied by TMR and industry, found a value of estimated direct agency cost savings of between \$134 million and \$292 million against program costs of \$13.1 million. When including broader road user and accident cost savings, the total benefits are estimated at between \$277.8 million and \$555.4 million.

The calculated benefit/cost ratio sits between 10.2 and 22.3, which is in line or higher than ratios estimated for previous research programs. When incorporating additional potential benefits, including accident and road user cost savings, the benefit/cost ratio rises to 31.4–64.7.

It is also important that a framework for assessing benefits is developed for future NACoE projects. To date, project proposals have only outlined broad benefits prior to approval. This project will place a greater emphasis on calculating and communicating economic benefits and will aid in determining future research priorities. To this point, a greater focus has already been placed on implementation and dissemination of learnings, culminating in the publication of the NACoE Highlights Report 2014–15.

There may be additional advantages in producing benefit/cost estimates before the beginning of projects, based on research hypotheses or experience in previous studies. This can then be re-assessed at the conclusion of the project to determine the actual value delivered by the project.

It was also considered important to further explore the importance of procurement mechanisms for innovation, to ensure that new technology reaches the market in a timely manner to best capture the considerable potential benefits. This has led to the acceptance of a new project focusing on these areas in 2016–17.

A.4.2 Life-Cycle Costing of Rain and Flood Events

A4 *Life-cycle Costing of Rain and Flood Events* (Beecroft & Peters 2017) was a research study by ARRB for TMR, as part of the NACoE Program. This research analysed the life-cycle costing implications of rain and flood events in Queensland, particularly in terms of pavement management, maintenance and rehabilitation practices to decrease this exposure to damage in a cost-effective manner.

Due to the increasing severity and intensity of storms and flooding, Queensland experienced road closures of 23–62% of their roads in the period from 2009 to 2013. Approximately 8741 km, or 26%, of the state-controlled road network required partial or full reconstruction following flood events in this period.

A4 *Life-cycle Costing of Rain and Flood Events* had the objective of clarifying the cost implications, including the funding level required to ensure a desired level of service following rain events, flood events and extreme weather events. This project comprised seven case studies, across four representative regions of Queensland. These regions were chosen based on traffic volume, function and flood event frequency to enable some conclusions to be drawn regarding the whole network. The risk factors chosen to be assessed included the damage to the road, the immediate cost and recovery time of the damage, the eventual reconstruction of the road, and the costs to the community and industry associated with delays.

The life-cycle costing model was run over a period of 30 years, this included a significant amount of time before and after the event occurred, allowing for reasonable assumptions to be made regarding the future recurrence intervals of these events. Furthermore, the model analysis considered the condition of the road. Specifically, the analysis considered the pre-event levels of rutting, roughness, vulnerability of seal width, seal age, pavement age and soil properties – for all 1 km sections of road analysed.

Three cases were analysed in the model, these were the base-case, the full resilience option and the 'stitch-in-time'. The base-case utilised data from actual road closures, reports on completed reconstructions and information sourced from TMR on major works funding to quantify the life-cycle cost implications of rain and flood events on the network. The full resilience options represented a scenario in which the road had been engineered to withstand extreme events, leading to no requirement for reconstruction works and reduced delays following the event. The 'stitch-in-time' option implemented periodic major works which targeted the more vulnerable sections of the network, with more aggressive works plans for remedial works on trigger points. In this scenario the network was more immune to the immediate effects of extreme events, and the repair programs were a fraction of the magnitude of the repair works in the base-case scenario.

It was found that different combinations of full resilience and 'stitch-in-time' could be more suitable for particular roads, based on traffic levels. Using these options, it can be determined that full resilience represents a fully resilient road which was modelled to increase the life-cycle costs over the seven cases, with very high agency costs not sufficiently offset by reduced road user costs. 'Stitch-in-time' is where more proactive, targeted progressive rehabilitation programs in a preventative maintenance approach are estimated to deliver a net life-cycle cost savings much higher than full resilience. This involved a small increase in agency costs being more than compensated for in reduced road user costs due to a more resilient network (Beecroft & Peters 2017).

A.5 Pavement Technologies

A.5.1 High Modulus Asphalt (EME2)

One of the first major projects under the NACoE research program focused on the introduction and development of French class 2 high modulus asphalt (Enrobé à Module Élevé – EME2) in Queensland (and Australia in general) (Petho 2014). The ‘Cost-effective Design of Thick Asphalt Pavements: High Modulus Asphalt Implementation’ project developed a structural design procedure for pavements containing EME2.

Current Austroads guides indirectly specify that asphalt pavements in Queensland must be thicker than those in other Australian states owing to the prevailing environmental and traffic conditions. The incorporation of high modulus asphalt layers would increase overall pavement stiffness, at the same time maintaining the same structural performance.

Pavement design and construction

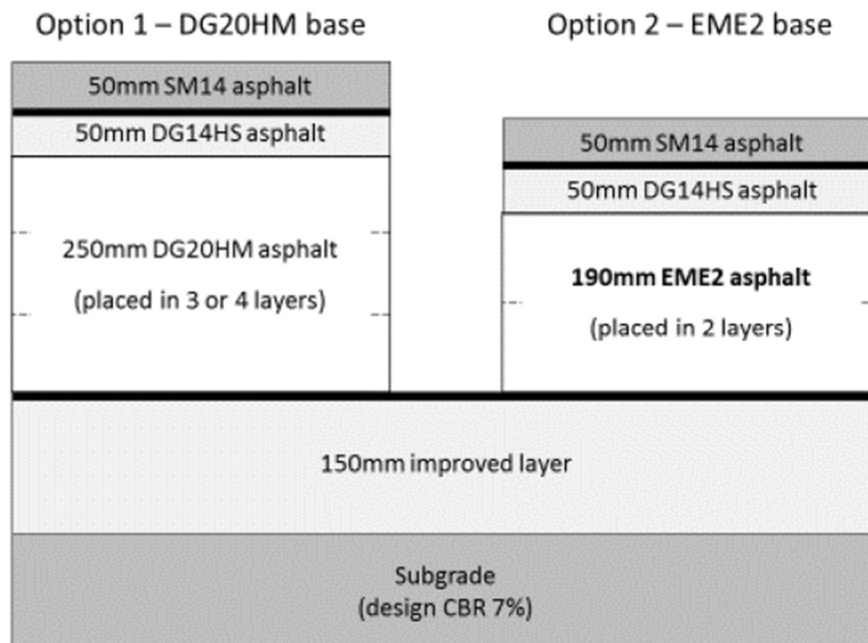
EME (Enrobés à Module Elevé) or simply high modulus asphalt was developed in France in the mid-seventies. EME is predominantly used for the structural layers in asphalt. This includes the base layers, which are more commonly referred to as foundation layers (Austroads 2017a). The distinctive component of EME mixes is a very hard paving grade bitumen applied at a high binder content (approximately 6% by mass) and lower air voids content (less than 6%) (Austroads 2017a).

Figure A.5 provides an indicative comparison between a typical road design and the use of an EME2 base and where the base is thinner.

Compared to conventional bases with unmodified binders, the benefits of EME2 include (Austroads 2017a):

- reduced asphalt thickness for the same heavy-duty pavement;
- lower construction and maintenance costs;
- higher stiffness and durability;
- superior resistance to permanent deformation;
- moisture resistance; and
- good fatigue resistance.

Figure A.5 TMR case study – high traffic road in SE QLD



Source: Petho, Bryant and Jones (2016).

EME provides a high-performance material, suitable for heavy-duty pavements. Specifically, it is known to be suitable in the following situations:

- pavements carrying large volumes of heavy vehicles and requiring strengthening to protect underlying layers;
- where there are constraints to the allowable pavement thickness, especially in urban areas or motorways, where geometric constraints persist; and
- heavily trafficked areas, such as slow lanes, climbing lanes, bus lanes and airport pavement, where there is a need for increased resistance to permanent deformation (Petho 2014).

Environmental impact

The main benefit of EME2 is that it can potentially reduce the layer thickness of the base course for heavily trafficked pavements by up to 30%, depending on climatic and traffic conditions. Therefore, a reduction could be seen in the use of virgin materials, haulage distances and associated CO₂-e emissions (Roads and Infrastructure Australia 2017). Furthermore, EME2 provides the opportunity for improved structural life; this means that less structural maintenance is required during the design life of the pavement, leading to lower life-cycle costs (Distin & Vos 2014).

By replacing asphalt with a product such as EME2, which lasts longer and reduces the required thickness of the pavement for the same traffic loading, the following environmental benefits can be achieved:

- savings in the consumption of resources and road construction materials such as bitumen and aggregates
- savings in haulage distances, and associated emissions, of raw materials
- less structural maintenance required (leading to less traffic disruption)
- the potential to carry heavier axle loadings, therefore, reducing the emissions per tonne/km of freight

- rendering the pavement to be less susceptible to changes in temperature brought about by extreme climatic events, and climate change (Distin & Vos 2014).

Disitin and Vos (2014) concluded that to quantify the benefits in financial terms by substituting long-lasting EME2 for dense graded asphalt on all projects across Australia, this could render a potential materials savings of 1.5 million tonnes per annum. The value of this reduction in asphalt usage is estimated at \$225 million.

National and international outcomes

Transurban have made a commitment to using innovative materials in Queensland, expanding their use of EME2. The Logan Enhancement Project will be one of the first Australian projects to utilise EME2 on a wide scale, and Transurban are planning to use the material over 8–10 km of highly trafficked road. Estimates show that this will reduce the required thickness of asphalt by approximate 17.5%, saving approximately 62 000 tonnes of asphalt (Transurban 2018).

A.5.2 Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement (RAP) is, by far, one of the most used construction waste materials; and using RAP in pavement has become a widely used standard practice in Australia and internationally (Yousefdoost, Rebbechi & Petho 2018).

There are many benefits associated with incorporating RAP in asphalt including a reduction in asphalt cost; asphalt containing 15% RAP is approximately 10% cheaper than asphalt without RAP. At 40% RAP content, the cost reduction may increase to about 30% compared to virgin asphalt (Yousefdoost, Rebbechi & Petho 2018). In addition, RAP has the potential for improved pavement durability and performance, but some studies suggest reduced performance (Liu et al. 2013).

In 2018, as part of the NACoE Program, project P37 Implementing the Use of Reclaimed Asphalt Pavement (RAP) in TMR – Registered Dense-Graded Asphalt Mixes (Year 1 – 2016–17) was undertaken in order to transfer the learnings and implement the findings of the Austroads RAP project into TMR's asphalt and RAP specifications – MRTS30 and MRTS102 (TMR 2017b; cited in Yousefdoost, Rebbechi & Petho 2018). It was hypothesised that the incorporation of learnings from the Austroads project could enable a relaxation in the 'history of proven performance' requirement that currently exists in TMR specification for asphalt mixes containing RAP contents about 15%.

TMR currently has maximum limits of the quantity of RAP in intermediate asphalt layers (generally not used as much in surfacing layers). This project included lab testing and analysis of lot records to evaluate the performance of various percentages of RAP to determine new recommended limits and specifications for the wider use of RAP in Queensland.

Pavement design and construction

If the RAP mix is properly designed, the materials performance can be at least equivalent to asphalt that does not contain RAP (Yousefdoost, Rebbechi & Petho 2018). In Queensland, typically 20–30% RAP is used. RAP behaves as an aggregate. There is also binder in the reclaimed material requiring marginally less virgin binding in the mix. Higher levels of RAP (50–90%) may require modified construction plant equipment.

Potential environmental impacts

Studies have shown that the application of RAP for the base and subbase layers of a road reduced the global warming potential of the road by approximately 20%. In addition, the application of RAP reduced energy consumption in construction by 16%, reduced problems related to water

consumption by 11%, reduced life-cycle costs by 21%, and reduced the generation of hazardous waste by 11% (Lee et al. 2010; cited in Colbert, Hasan & You 2016).

Using RAPs to replace virgin aggregates results in significant environmental benefits, reducing GHG emissions by 20.2% per tonne in asphalt production, with 53.26 kg CO₂-e /tonne of 70% RAP compared to 66.73 kg CO₂-e /tonne in the virgin asphalt (Liu et al. 2013).

There are many other environmental benefits associated with incorporating RAP in asphalt, including:

- Reduction in consumption of virgin natural resources (aggregate and binder) and associated reduction in energy and transport (Levis et al. 2011).
- Reduction in material going to land fill. Instead RAP goes to an asphalt plant. Conversely, there may be some additional expenses if the asphalt plant or RAP storage requires extra transport costs (typically negligible as this material would otherwise likely go to a landfill site anyway) (Levis et al. 2011).
- There are no known limits for the number of times RAP can be recycled in a 30-year window. Under the base case, asphalt is assumed to be sent to land fill. Asphalt pavement is assumed to be an inert material when buried in a landfill. Landfilling also includes transporting the RAP to a land fill and landfill vehicle operations to bury and apply cover and monitor the landfill during post-closure period (Levis et al. 2011).

The avoided emissions are associated with typical road processes. The process of sourcing and using virgin aggregate consists of blasting, drilling, digging and other quarrying activities. Transportation of virgin aggregates are then transported to a mixing plant using a heavy truck. Processing of virgin binder involves extracting crude oil into binder, transport to a mixing plant and storage (Levis et al. 2011). Conversely, there may be some additional expenses if the asphalt plant or RAP storage requires extra transport (typically negligible as this material would otherwise likely go to a landfill site anyway) (Yousefdoost, Rebbechi & Petho 2018). Typical disposal of asphalt involves the transport to landfill, and there are emissions associated with the transport to landfill in a large truck. These end-of-life emissions are avoided with the recycle or asphalt as RAP (Levis et al. 2011).

International outcomes

Recent investigations into the use of RAP in the USA have shown that the use of RAP in pavement base and subbase layers can (Lee et al. 2010; cited in Newman et al. 2012):

- reduce global warming potential by 20%;
- reduce energy consumption by 16%;
- reduce water consumption by 11%;
- reduce waste generation by 11%; and
- reduce life-cycle costs by 21%.

In Japan, RAP has been used for many years, with the recycling rate of asphalt pavements now being 99%. Kawakami et al. (2010) undertook a study of the environmental loads of pavement recycling methods for three use cases including: virgin aggregates, plant recycling aggregates, and in-place recycling aggregates. The study concluded that environmental loads, when using recycled aggregates, were less than when using virgin materials. Furthermore, environmental loads were even less when using in-place recycling methods. However, environmental loads for in-place recycling can increase if the necessary equipment and machinery needs to be transported across long-distances. Kawakami et al. (2010) concluded that when using recycled materials, the environmental load relevant to the situation needs to be considered.

Across Europe, countries like Denmark and the Netherlands have been using 100% RAP materials in their road construction for several years (Eighmy & Holtz 2000; Kandhal & Mallick 1997; cited in Colbert, Hasan & You. 2016). In Canada, RAP has been used to pave over 500 km of roads over the past 17 years (Alkins et al. 2008; cited in Colbert, Hasan & You 2016).

Numerous RAP field demonstration projects have been undertaken in the USA and Canada, in order to evaluate the performance of RAP. Many of these studies showed that the performance of recycled materials in pavements containing RAP had directly comparable or better performance when compared with virgin asphalt pavements (Emery 1993; Hossain et al. 1993; Hossain & Scofield 1992; Kandhal et al. 1995; Paul 1995; cited in Colbert, Hasan & You 2016).

Colbert, Hasan and You (2016) undertook a study to develop a systematic approach towards selecting optimum combinations of sustainable materials for the construction of asphalt pavements. One of the selected materials in the study was RAP. The results showed that specimens prepared with 75% RAP and Advera Warm Mix Asphalt consistently produced the lowest CO₂ emissions among the investigated mixture types.

Jullien et al. (2006; cited in Aurangzeb & Al-Qadi 2014) undertook an investigation of four different samples of asphalt concrete containing 0%, 10%, 20% and 30% RAP, respectively. The study focused on comparing airborne emissions, odour and pollutant release over time, related to the road construction and asphalt laying operations. The results showed an increase in emissions and a decrease in odour as the percentage of RAP content increased. Ventura et al. (2008; cited in Aurangzeb & Al-Qadi 2014) extended the study by comparing binding courses of pavement sections with various RAP percentages, including 0%, 10%, 20% and 30%, with hot-mix asphalt. The results showed that, except for the toxicity and eco-toxicity indicators, the entire set of indicators compared within the LCA revealed a trend of decreasing potential environmental impacts with increasing RAP content.

Aurangzeb & Al-Qadi (2014) utilised a life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) to consider the economic and environmental feasibility of using RAP in asphalt mixtures. The results revealed that there is a reduction in GHG emissions produced with increasing RAP content in asphalt mixtures.

A.5.3 Crumb Rubber Asphalt and Crumb Rubber Modified Binders

Each year, millions of tyres in Australia reach the end of their life. End-of-life tyres have the potential to be a highly valued recyclable material; however, most tyres are discarded to landfill or sent overseas. Seventy per cent of a tyre is made-up of rubber and carbon black, which can be recycled into a high-value resource in road construction by adding rubber to bituminous binders. Crumb rubber modified (CRM) binder has enhanced elastic properties, which can result in more durable asphalt and sprayed seal surfacing applications (Denneman et al. 2015).

From 2015 through 2019, as part of the NACoE Program, projects P30, P31 and P32 were undertaken in order to present the opportunities available to Queensland for using CRM binder technologies for sprayed seal and asphalt applications, and to trial and promote the benefits of these technologies.

Crumb rubber has only been used sparingly over the previous two decades in Queensland, while it has been used more extensively in other parts of the country. The early focus of the NACoE work was on introducing CRM sprayed sealing back into Queensland, and several major projects have followed on from the initial demonstration trials. The focus then shifted to thin asphalt layers with crumb rubber, specifically open-graded crumb rubber asphalt (CRM-OGA) and gap-graded crumb rubber asphalt (CRM-GGA). These technologies have been demonstrated in trials in south-east Queensland.

Pavement design and construction

Crumb rubber is used in the binder and rubberised asphalt surfacing. There is a dry and a wet process for combining aggregates and aggregates and asphalt binder to create crumb rubber modified asphalt mixture. The dry process involves the blending of crumb rubber, typically 1–3% by weight of the total mixture, sizes 2.0 mm/6.3 mm with hot aggregates prior to mixing with asphalt binder. The wet process implies incorporating crumb rubber into asphalt binder prior to mixing with aggregates. Usually the composition is approximately 1% by weight of the total mixture, 18–25% by weight of bitumen and with rubber sizes below 2 mm (Praticò, Moro & D'Agostino 2015).

Table A 1: provides a summary of the benefits and barriers to using crumb rubber in road construction.

Environmental impact

The environmental benefits of recycling and the reuse of recycled materials are largely dependent on the efficiency at which the materials are recycled, their collection and the overall supply chain. Specific environmental benefits of incorporating crumb rubber into asphalt include a reduction of waste tyre stockpiles and landfill; energy savings; reductions in CO₂-e emissions; and road noise reduction.

Landfill

In particular, landfills impose a number of costs on the community; these include:

- GHG emissions arising from the burning and/or burial of waste
- potential for increased odour and fumes
- surface water and ground water impacts from leachate to soil and water
- amenity effects of the disposal facility including visual, noise, odour and litter (Denneman et al. 2015).

Table A 1: Benefits and barriers to increased use of crumb rubber in road construction

Benefits		Barriers	
Environmental	- Crumb rubber is well-suited for use in open-graded surfacings, which deliver reduced tyre noise and water spray compared to dense-graded surfaces - Energy savings and lower carbon emissions due to requiring less virgin binder, and improved properties may allow for a reduction in layer thickness (material saving) - Recycling waste materials that may otherwise be sent to landfill or sent overseas for fuel	Environmental	- Increased smoke and odour during paving, but this can be reduced by using warm-mix additives and lower paving temperatures - Some evidence of increased emissions during production and paving, with studies to date showing an increase in emissions of some compounds and decreases in others when compared to polymer modified binders - Leaching and water quality has been investigated but found negligible impact
Sprayed seal performance benefits	- Increased service life through higher application rates, greater durability and increased UV resistance (less binder oxidation) - Extended durability of skid resistance properties as stones cannot be easily plucked from the surface and reduced risk of bleeding/flushing - Resistant to reflective cracking due to the superior elastic properties - Superior waterproofing of underlying layers	Health and safety concerns	Road workers may be subject to increased fumes with potential for adverse health effects – limited evidence of increased risk but being investigated through ongoing demonstration trials
		Cost	- Cost changes due to additional processing during production of binder/asphalt - Establishment and/or maintenance of specialised equipment needed for blending - Increase in the required binder content in some designs.
Asphalt performance benefits	- Reduced risk of binder drain-down and bleeding through higher binder viscosity - Resistant to fatigue and reflective cracking through superior elastic properties - Superior performance and reduced risk of failure leads to longer service life and reduced whole-of-life costs	Specifications	Tasmania have recently adopted VicRoads specifications. While these specifications allow for the use of crumb rubber in various bituminous surfacing applications, they are prescriptive and therefore limit the amount of crumb rubber that can be used. Development of performance-based specifications may reduce the current limitations on the amount of CRM allowed.

Energy savings and emission reductions

Firstly, there are embodied energy savings from the use of recycled materials in place of virgin materials. Other potential savings are from the haulage of crumb rubber rather than virgin materials. Depending on design and agency specification requirements, CRM asphalt layers may also produce savings over traditional surfacing layers due to thickness reductions (White et al. 2010; cited in Denneman et al. 2015). Studies have shown that utilising CRM in bitumen for road construction has significantly higher energy savings and reduced CO₂-e emissions when compared to other forms of tyre disposal (such as stockpiling, burning or landfill) (Way & Carlson 2007 & 2009; cited in Denneman et al. 2015). It is assumed that the resultant CRM asphalt pavement is 100% recyclable.

Tyre recycling

From 2009 to 2010, approximately 66% of end-of-life tyres were disposed of, either into landfill, stockpiled, illegally dumped or characterised as 'unknown' disposal, with only 16% domestically recycled, while 18% were exported. Resulting from this are costs to the community and governments through littering of the landscape and waterways, in addition to utilising valuable land

for waste disposal. Disposed tyres can be a source of health and environmental concern; can cause fires in stockpiles which can release toxic gases; and provide breeding habitats for pests (Department of Environment 2014; cited in Denneman et al. 2015). Therefore, minimising the growth of tyre stockpiles through use of CRM binders has the advantage of alleviating these issues.

Noise reduction

Research has shown that when CRM binders are used in appropriate asphalt types it can reduce road traffic noise levels by more than 5 decibels (Carlson 2011; cited in Denneman et al. 2015). Open-graded asphalt has well-documented safety and environmental advantages, and CRM binders are widely used in the development of open-graded asphalt. Open-graded asphalt can also provide a reduction of splash and spray in wet weather conditions (Denneman et al. 2015).

National and international outcomes

Approximately 70% of waste tyres in the State of Arizona (USA) are used in asphalt pavements, with the remainder going into various commercial products. CRM asphalt pavements are popular in Arizona, when compared with concrete pavements, as it reduces noise, and provides an improved and safer driving experience in terms of skid resistance. Sousa, Wat & Carlson (2007) studied the benefits of using crumb rubber in asphalt pavements and the savings in CO₂ emissions that result from its application. The study concluded that if the design criteria implemented in California and Arizona Departments of Transportation is used, the CO₂ savings per lane/mile can vary from 154 to 343 tons per lane mile. Sousa, Wat & Carlson (2007) conclude by saying that this is a major contribution when you consider the number of road networks which require maintenance, and the number of road networks which are yet to be built.

Furthermore, a study was undertaken by the Institute for Environmental Research and Education (2009) of the carbon footprint of rubber tyre recycling in the USA. The results of the study showed that when used in road surfaces, recycled rubber has between three and seven times lower carbon footprint than bitumen, on a materials basis. The upstream carbon footprint for the production of asphalt is 840 kg CO₂-e per metric tonne. Comparatively, the weighted average carbon footprint for recycled tyres is 124 kg CO₂-e per metric tonne (Institute for Environmental Research and Education 2009).

Sustainability Victoria maximising the use of crumb rubber in asphalt

Maximizing the Use of Crumb Rubber in Asphalt was developed for Sustainability Victoria. The objective of the study was therefore to identify and assess the benefits and barriers associated with the increased use of CRM asphalt in Victoria. It constituted a step towards potential CRM asphalt market development. The study also aimed to identify directions for further research and development to apply crumb rubber to asphalt in road construction and maintenance processes, while supporting Victoria's resource-recovery industry. The report was based on a literature review of international and Australian practice and stakeholder consultation via a survey. It also provided connections to a related project being delivered under NACoE.

Cost of crumb rubber binder compared to other binders

There are several cost implications which need to be considered when using CRM binders in asphalt products. These include establishment costs, upfront capital costs, material costs, operational costs, contractor risk and production/manufacturing costs (Austroads 2014b). Many of these factors require in-depth analysis in order to quantify their cost, however, material costs can be derived from previous work.

When CRM binder is compared directly to straight-run bitumen (e.g. C170), CRM is likely to be more expensive due to the higher binder application rate and additional processing. Therefore,

CRM binders only become economically viable compared to standard bitumen if their performance benefits and life-cycle costs are considered (Grobler, Beecroft & Choi 2017).

When CRM is compared to polymer-modified bitumen, the cost of CRM is generally comparable, and can even be cheaper in some cases. Polymer binders are quite expensive as they require additional processing, they have a higher material cost and they have higher import costs.

Early CRM sprayed seal projects in Queensland delivered high-quality seals with a 6% reduction in binder costs (Austroads 2013). This cost reduction was achieved through the removal of the need for importing expensive polymers.

A study in California and Arizona showed that there is an agency cost increase of between 23 and 100% when using CRM asphalt over traditional alternatives. However, in the scenarios evaluated, the whole-of-life costs of CRM still made CRM a cost-effective solution in many applications (NACoE 2016).

Recycling of crumb rubber pavement in RAP

Crumb rubber asphalt pavement and pavements built using crumb rubber modified binders are able to be recycled and reused as reclaimed asphalt pavement. A study undertaken by Crockford et al. (1995) (Texas Department of Transportation) concluded that it is possible to recycle CRMA and CRMB. However, in order to reuse these materials in RAP, the techniques used for recycling conventional asphalt mixtures, materials processing and construction would need to be modified in order to ensure the success of the recycled CRMA/CRMB pavement. Furthermore, some techniques may not be appropriate to consider for modification as they may be unsuitable for pavements which contain recycled waste rubber. The results of the aforementioned study were based on experiences in Tyler and San Antonio, Texas, where two of the earliest crumb rubber recycling projects in the United States were undertaken (Crockford et al. 1995).

A.5.4 Stabilisation Practices (including Foam Bitumen Stabilisation)

In 2018, as part of the NACoE Program, project P2 Stabilisation Practices in Queensland (in situ cement/cementitious stabilised materials) was undertaken in order to provide technical guidance on the ideal environmental and operational conditions to maximise the cost/benefit of in situ cement/cementitious stabilisation technologies utilised on the Queensland state-controlled road network.

Due to low quality subgrades, damaging weather events and heavier truck traffic, there has been a rapid increase in the use of various stabilisation practices in unbound pavements across Queensland. P2 looked at two of the currently more popular treatment types, including plant-mixed cement-modified bases and in situ foam bitumen stabilised bases. The research undertaken as part of P2 included laboratory testing and data analysis of performance and practice across the state. The results of the study advocated for more widespread use of these technologies.

The results of the study showed that by embracing the most appropriate treatment type based on the local conditions, thousands of kilometres of the Queensland network could have improved performance and cost savings. Although the exact cost savings were difficult to determine within the project (as the choice of treatment is heavily dependent on local practitioners and the availability of materials and construction expertise), it was estimated that redirecting funding from full-depth asphalt pavements to high-performing stabilised layers showed potential savings of \$50–130 per m² of pavement, or up to \$1 million per kilometre of pavement treated. This could total up to \$5.4 million each year if just 10% of new full-depth asphalt pavements were designed as stabilised granular pavements (Beecroft 2016).

Pavement design and construction

In situ stabilisation, or the process of stabilising natural earth to strengthen and allow it to function as a pavement layer, is a technique that drastically reduces the amount of aggregates needed for road-base construction. There are a number of techniques, such as foam bitumen, cement stabilisation and the use of geopolymers that are all variations of the key principles involved in in situ stabilisation.

The process of stabilisation in pavement engineering alters the engineering properties of soil or aggregate by adding a fixed quantity of stabilisation agent or binder, such as foam bitumen. By implementing stabilisation practices, more marginal road materials can be used in construction, with the addition of relatively small amounts of stabilisation binder, therefore, increasing the environmental sustainability and cost effectiveness of road construction projects (Paige-Green 2008; cited in Grobler et al. 2018).

The engineering properties of road construction materials that can be improved through stabilisation include particle size distribution, plasticity, bearing capacity, moisture resistance, workability and permeability. Additionally, in environments with excessive moisture, stabilisation may be used to dry pavement materials (AustStab 2012; cited in Grobler et al. 2018).

Foam bitumen stabilisation is typically used in the following situations (Roads and Maritime Services (RMS) 2015):

- In a weak granular pavement to improve strength.
- Rehabilitation of previously cementitious stabilised pavements where the addition of further cementitious binder is not feasible.
- An alternative to full-depth asphalt in low to moderate trafficked roads.
- Improving a pavement material's resistance to moisture effects.
- Enables the recycling of new materials which is particularly attractive in areas with remote access to an asphalt plant.

Added performance benefits include (Ramanujam & Griffin 2016):

- resilience to flooding;
- strong and flexible;
- significantly reduces or eliminates shrinkage cracking;
- improved fatigue performance; and
- provides longer working time.

The cost compared to traditional pavements depends on the binder content. The initial cost is higher than cementitious stabilisation but lower than asphalt (RMS 2015). The approximate cost of construction is \$60 to \$120 per m³; which is around 60% less than full-depth asphalt. It also enables the recycling of in situ material except where previously stabilised (Ramanujam & Griffin 2016).

Environmental impact

The main environmental benefits which can be seen through the use of stabilisation practices are the use of marginal materials, which would otherwise be ripped up, transported and discarded for replacement with high-quality, quarried virgin aggregate (Smith 2005; cited in Grobler et al. 2018). Austroads (2006; cited in Grobler et al. 2018) states that stabilisation may also reduce the whole-of-life costs of heavily trafficked pavements. Stabilisation binders typically account for half

the total cost of stabilisation practices; therefore, the direct and whole-of-life costs may be reduced by ensuring the design and construction are optimised for its application (Austroads 2002c; cited in Grobler et al. 2018).

Furthermore, the use of stabilisation practices encourages a shift from using full-depth asphalt to using stabilised materials, which may not save actual material in total volume but will reduce bitumen use.

In addition, stabilisation practices have the ability to reduce the haulage distances required for virgin road construction materials, through the ability to use more marginal in situ materials. However, some marginal materials may require more stabilising agents such as lime, cement, and bitumen (for foam bitumen), but overall, the impact on materials should be net positive for the environment. Potentially improving in situ soils through cement stabilisation can save more than 80% of transport emissions due to construction and transport compared to the supply of traditional granular materials (Giustozzi, Flintsch & Crispino 2015). This, although, is difficult to quantify.

National and international outcomes

TMR has successfully demonstrated the benefits of using in situ stabilisation through the use of foam bitumen on the Cunningham Highway west of Brisbane, resulting in a larger trial on the New England Highway. This trial used higher quantities of lime than had previously been pioneered. The process used a hot bitumen mix to stabilise the pavement, replacing the traditional combinations of lime, cement and fly ash (Newman et al. 2012).

The process of reusing material from old or deteriorating road pavement for the base of new roads has the advantage of requiring very little material to be removed from a site, reducing the GHG emissions associated with the transport of unwanted materials (Newman et al. 2012).

A.5.5 Non-standard Granular and Marginal Materials

Some 20 000 km of the state-controlled Queensland road network is composed of unbound granular pavement layers with a thin bituminous surfacing. Economic and environmental considerations encourage the use of locally available and/or recycled aggregates for the provision of granular pavements. These materials typically do not conform to standard specifications but provide satisfactory performance when properly managed. The suitability of non-standard materials is optimally determined relative to the specific pavement application and local roadbed conditions (fit-for-purpose).

In 2016, as part of the NACoE Program, project P34 Performance-based Evaluation Protocol for Non-standard Granular Pavement Materials was undertaken with the objective of developing an evaluation protocol for determining the risk associated with the use of non-standard granular materials for specific pavement applications.

Economic and environmental constraints are necessitating greater utilisation of locally available and recycled materials. Correspondingly, escalating traffic volumes and axle loads demand more reliable methods to manage the increased performance risks.

Pavement design and construction

Non-standard or marginal materials is the name given to granular materials that do not conform to the standard specifications for aggregates. These materials tend to be unique, locally available, and naturally occurring. However, the term 'non-standard' is preferred to 'marginal' as long-term satisfactory performance can be achieved when the constraints and/or requirements of the construction project were addressed in the design phase (i.e. the material used was fit-for-purpose). Non-standard can also be used to describe more unconventional materials, such as recycled construction materials and industrial waste materials (e.g. plastics, concrete, fly ash,

slag, etc.). For the purpose of this project, non-standard granular materials will specifically refer to naturally occurring granular materials, and all recycled materials will be excluded from the non-standard granular materials treated in this report (Griffin, Rice & Andrews 2019).

There is a known reluctance in industry for the use of non-standard granular materials, especially when the unique characteristics of the extractions, processing, handling and construction phases are not well-established. Thus, in situations where specifications are not well-established, new criteria will need to be established to provide reliability in performance (Griffin, Rice & Andrews 2019).

Improving poor subgrades are essential to enable highway construction (Rogers et al. 2009). If the CBR is less than 15%, then the options for the creation of an improved foundation include (Rogers et al. 2009):

- using crushed rock capping layers;
- increase the subbase thickness; and
- chemical stabilisation (as per previous section).

Environmental impacts

The potential environmental benefits of using local marginal materials result in savings in haulage and embodied energy of materials that would otherwise be quarried and transported. Disbenefits potentially may include reduced road resilience and challenges with reuse for road pavements at end-of-life due to reduced quality materials being slightly out of specification.

Quarried gravel products are transported over long distances, resulting in escalating costs for road construction and maintenance (Austroads 2018), and increasing GHG emissions based on haulage. A direct correlation can be made between the reduction in haulage distances and the reduction in GHG emissions from the vehicles used to transport aggregates.

At the end of pavement life, there may be recycling challenges due to the quality of pavement, requiring disposal.

International outcomes

Rogers et al. (2009) undertook a study to develop a methodology to allow for assessing the relative sustainability, according to CO₂-e emissions, of different highway subgrade improvements. This study concluded that the relative sustainability of subgrade improvements can be informed through calculating CO₂-e emissions. The results showed that the lowest emissions option is heavily dependent on the haulage of materials.

As non-standard granular materials tend to be locally available, their haulage distances are vastly lower than imported aggregates.

A.6 Benchmarking Emissions Data

A.6.1 Construction

In 2010, the World Bank undertook a study of GHG emissions mitigation options in road construction and rehabilitation projects. As part of this study an assessment of the GHG emissions of road construction was undertaken, using what was defined as 'typical' pavement sections within various road classes. This study was intended to provide an indication of the relative importance of various aspects of road construction in regard to GHG emissions production (The World Bank 2010).

Figure 3.1 in this study provides an overview of the emissions produced in the extraction/production of construction materials, the transport of these materials and the consumption of the machinery used in the construction. As can be seen from the graph, the pavement is commonly a large contributor.

Furthermore, Figure 3.2 presents the typical breakdown of GHG emissions by the different generation categories in construction. As can be seen from the graph, expressways and national roads extraction of the construction materials is a high contributor. This is due to the quality of materials required, often resulting in greater haulage distances. This is less of an issue on lower volume roads, where lower quality or non-standard materials are used.

Pérez-Martínez and Miranda (2013) undertook a similar study which focused on the energy consumption and energy intensity of highway transport in Spain. This study was undertaken through the use of regression parameters balanced according to coefficients developed through an empirical analysis based on survey data by vehicle type.

The results showed that the mean energy consumption and subsequent CO₂ emissions on the studied highway sections were estimated to be 1895 MJ/h/lane-km and 0.15 tCO₂ eq./h/lane-km, respectively. Furthermore, these values increased to 2644 MJ/h/lane-km and 0.22 tCO₂ eq./h/lane-km when energy and CO₂ emissions of transport infrastructure were considered based on the life-cycle energy consumption of the studied highway section construction and use.

Lastly, this study showed that when the energy intensity of infrastructure construction was allocated to road users according to the traffic breakdown, it was much higher for motorcycles than for cars and was significantly lower for articulated trucks than for vans (Pérez-Martínez & Miranda 2013).

To generate these numbers, the mean Annual Average Daily Traffic (AADT) used was approximately 35 000 vehicles per day. Assuming there are 24 hours in a day, and 365 days in a year, this study showed that the studied highway sections produced 1314.54 tCO₂-e/year.

A.6.2 Energy Consumption of Traffic

In a study undertaken on the life-cycle assessment of 1 km of a 2 x 2 lane road, the results showed that construction, maintenance, and end-of-life phase emissions represented only 2% of the total energy consumption of the road. The energy consumption of the traffic using the road, during the use phase, over a 30-year period was 1430 TJ, based on French traffic class TC6 (equivalent to a total traffic of 25 million heavy vehicles and 100 million private cars for 30 years). Whereas, the construction, maintenance and end-of-life phases totalled only 23 TJ (Beuving et al. 2004).

A.6.3 Materiality and Major Emissions Sources

On behalf of Australia's state road agencies, the Transport Authorities Greenhouse Group (TAGG) developed the *Greenhouse Gas Assessment Workbook for Road Projects* (2013a). The supporting document (TAGG 2013b) provides a summary of materiality and major emissions sources. This information was used in defining the assessment boundary of this study. In this instance, materiality refers to the quantitative significance of an emission source's contribution to a project's overall GHG emissions.

TAGG (2013b) presented four international case studies that included an assessment of the GHG emissions from construction and operation of a road. In these studies, operation of the road did not include the emissions generated from vehicles using the road. The proportions of GHG emissions for construction and operation in these projects are shown on [Figure 3.3](#).

The contribution of road construction to overall GHG emissions from a road pavement ranges from 46 to 76%, based on the different projects. However, the time spans of the studies undertaken, in regard to the projects above vary from 40 to 100 years. The Swedish IVL study was undertaken over an assessment period of 40 years, similar to the assessment period of the project being reported in this project. Therefore, TAGG (2013a) is the most relevant study for comparison.

These studies show that over a period of time (40 years+) the emissions from the operation of a road are approximately equal to the emissions from the construction of the road and therefore, the operation of a road should be included in a GHG assessment. However, these studies have considered electronics involved with the operation of road structures, which is not considered in the project being analysed in this report.

In addition, further analysis was undertaken which showed that maintenance activities account for approximate 10–15% of the total energy consumption from construction, operation and maintenance activities.

Materiality of construction activities

In addition, TAGG (2013b) reviewed a range of Australian, New Zealand and international GHG assessments of road construction projects, in order to establish the contribution of emissions sources during construction. Table A 2 provides a summary of the GHG emissions per square metre of pavement for the projects listed in the table.

Table A 2: Comparison of GHG emissions (t CO₂-e) per square metre for road construction projects

Emissions source	Units	Mickelham Road	Marx Hill Project	Deer Park Bypass	Alpurt Motorway Extension
Liquid fuel combustion	t CO ₂ -e/m ²	0.027	0.061	0.063	0.251
Plant and equipment	t CO ₂ -e/m ²	0.020	0.032	0.043	0.222
Site vehicles	t CO ₂ -e/m ²	0.007	0.029	0.020	0.028
Electricity	t CO ₂ -e/m ²	0.001	0.002	0.005	0.028
Materials	t CO ₂ -e/m ²	0.150	0.089	0.208	0.298
Cement	t CO ₂ -e/m ²	0.056	0.012	0.075	0.096
Lime	t CO ₂ -e/m ²		0.001		0.078
Steel	t CO ₂ -e/m ²	0.004	0.007	0.031	0.099
Aggregate	t CO ₂ -e/m ²	0.040	0.055	0.024	0.019
Hot-mix asphalt processing energy	t CO ₂ -e/m ²	0.026		0.027	
Imported fill	t CO ₂ -e/m ²			0.023	
Bitumen	t CO ₂ -e/m ²	0.018	0.012	0.020	
Asphalt	t CO ₂ -e/m ²				0.006
Sand/Gravel	t CO ₂ -e/m ²	0.005	0.001	0.006	
Fly ash	t CO ₂ -e/m ²	0.001		0.001	
Aluminium	t CO ₂ -e/m ²		0.001		
Plastic	t CO ₂ -e/m ²		0.0002		
Copper	t CO ₂ -e/m ²				
Transport of materials	t CO ₂ -e/m ²		0.007		0.003

Emissions source	Units	Mickelham Road	Marx Hill Project	Deer Park Bypass	Alpurt Motorway Extension
Waste transport and disposal	t CO ₂ -e/m ²		0.003		0.003
Vegetation removal	t CO ₂ -e/m ²		0.094		0.071
Total	t CO ₂ -e/m ²	0.178	0.256	0.275	0.653

Source: TAGG (2013b).

As roads become more complex and the number of structures increases, the GHG emissions per metre squared of pavement increases. As Table A 2 shows, there is great variability in the emissions sources in road projects.

Operation

In the TAGG (2013b) study, GHG emissions from the operation of a road were defined as including street lighting, traffic signals and intelligent transport systems. As the study being undertaken in this project only considers emissions from the pavement itself, the operation phase from the TAGG project could not be used for benchmarking or comparison.

Maintenance

Within the study undertaken by TAGG (2013b), the maintenance data reviewed showed that minor maintenance activities (i.e. planned and reactive maintenance) contributed to less than 1% of the overall GHG emissions of a road over its life-cycle. In addition, even the GHG emissions related to the material used in minor maintenance activities would not be significant. TAGG provided the following example:

the South Australian Department for Transport, Energy and Infrastructure uses approximately 274 kL/year of diesel to conduct minor maintenance (including inspections) on 6555 km of road. This equates to 0.042 kL/km or 2.1×10^{-6} kL/m² (assuming that the average road pavement width is 20 m wide). This would result GHG emissions of approximately 6×10^{-6} t CO₂-e/m² of road or 0.003% of construction emissions.

A.7 Review of GHG Life-Cycle Model Scopes

Table A 3 provides a summary of Australian and international GHG life-cycle model and reference database scopes and limitations.

Table A 3: Australian and International GHG life-cycle models

	Life-Cycle Analysis Scope							Cost Benefit Analysis	Years of Analysis	General Description	Limitations of GHG Modelling
	Cradle to Gate (Embodied Carbon)	Transport Haulage	Construction	Maintenance	Use Phase – Vehicles	Use Phase – Equipment	Disposal/End-of-Life				
ISCA V1.2 IS Materials Calculator (ISCA 2019c)	♦	♦							1	- ISCA Material calculator is a support tool for the IS rating scheme which evaluates environmental impacts on projects. - The ISCA Material Calculator includes calculated embodied environmental impact factors for the 'cradle to manufacturer gate' for a wide range of typical construction materials. - The ISCA Materials Calculator is based on the best available data from the Australian national Life-Cycle Inventory database (AusLCI) and its shadow database, complemented with data from Worldsteel for steel products.	- Only manufacture and construction and excluding use and maintenance phases. Has reference tables including material densities. - Predefined pavement options – limited flexibility to incorporate other pavement design and construction options. - The transport component from the manufacturer's gate can vary significantly between project/assets, so the ISCA Material Calculator includes options to customise the transport component for each material or product. It may be used to calculate transport emissions where tonnage, distance and vehicle type are known.
ISCA V2.0 rating tools (ISCA 2019a; ISCA 2019b)	Not applicable.									- Infrastructure Sustainability Council Australia (ISCA) tool for the assessment and rating of projects according to environmental and other criteria. - Multiple rating tools for each project phase; planning; design; as constructed; operations and maintenance.	Limited ability to calculate GHG savings. Not applicable.

	Life-Cycle Analysis Scope							Cost Benefit Analysis	Years of Analysis	General Description	Limitations of GHG Modelling
	Cradle to Gate (Embodied Carbon)	Transport Haulage	Construction	Maintenance	Use Phase – Vehicles	Use Phase – Equipment	Disposal/End-of-Life				
World Bank ROADEO Model and User Manual (World Bank & ASTAE 2010)	♦	♦	♦						1	- World Bank Greenhouse Gas Emission Mitigation Toolkit for Highway Construction and Rehabilitation. - A toolkit for the evaluation and reduction of GHG emissions in the road construction industry.	- Developed for developing country context and thus assumptions and factors used in calculations are assumed inadequate for the Queensland context. - References IVL report (Stripple 2001) for construction equipment emission factors. - May be useful in calculating and/or benchmarking construction emissions – subject to productivity factors.
PALATE v2.0 (Recycled Materials Resource Centre (RMRC) 2013)	♦	♦	♦	♦				♦	40	- Pavement Life-cycle Assessment Tool for Environmental and Economic Effects. - Designed by the Consortium on Green Design and Manufacturing from the University of California-Berkeley.	- Useful for calculations and calibration in absence of Australian data and tools – imperial units. - Note – construction productivities too high – thus construction emissions understated compared to benchmark road construction data in Australia.
VicRoads – Carbon Gauge GHG Calculator for Roads Projects (VicRoads 2014; TAGG 2013a)	♦	♦	♦	♦	♦	♦		–	50	- Calculator for the calculation of GHGs on road projects. - Carbon Gauge provides a tool for estimating the materially significant whole-of-life GHG emissions during the major road activities of construction, operation, and maintenance.	- Allows for the entry of pavement designs but predefined pavement types and materials. - Includes embodied carbon and haulage emissions in calculations. - Limited ability to assess NACoE projects which are outside of drop-down options. - Some applicability – may be useful to calculate and/or calibrate/check carbon values. - Note use phase – vehicles require entry of tCO₂-e only.

	Life-Cycle Analysis Scope							Cost Benefit Analysis	Years of Analysis	General Description	Limitations of GHG Modelling
	Cradle to Gate (Embodied Carbon)	Transport Haulage	Construction	Maintenance	Use Phase – Vehicles	Use Phase – Equipment	Disposal/End-of-Life				
The Infrastructure and Services Division (I&S) with Transport for New South Wales (TfNSW). Carbon Estimate Reporting Tool (CERT) (Planning and Environment Services, TfNSW 2018)	♦	♦	♦	♦		♦			50	- Estimates a project's GHG emissions profile from detailed design stage through to construction and operation. Encourages the investigation and implementation of GHG reduction (mitigation) measures. - Sources of information include: AusLCI life-cycle inventory database, Australian national greenhouse accounts (2016), Transport Authorities Greenhouse Gas Workbooks (TAGG) and Environmental product declarations.	- Pre-defined drop-down menus for pavements limited to coarse aggregates, recycled coarse aggregates, ballast, sand, manufactured sand and recycled crushed glass – difficult to differentiate pavement designs. - May be used to calculate and/or calibrate/check entry values. - Also includes operational energy and inputs for road service equipment.
ATAP PV2 – Uninterrupted fuel consumption model. (Australian Transport Assessment and Planning Steering Committee 2016)					♦				–	- ATAP PV2 Road Parameter Values, Uninterrupted flow fuel consumption model. - Derived from an ARRB HDM-4 model which has been calibrated to Australian conditions.	- The ATAP PV2 – HDM-4 simple linear regression model allows for the varying of road parameters including road speed, AADT, roughness and GMV fuel type and by vehicle type. - The model has been modified to allow for the calculation of CO₂-e. from fuel consumption. - It is expected the road vehicle emissions are the largest component of LCA emissions.

	Life-Cycle Analysis Scope							Cost Benefit Analysis	Years of Analysis	General Description	Limitations of GHG Modelling
	Cradle to Gate (Embodied Carbon)	Transport Haulage	Construction	Maintenance	Use Phase – Vehicles	Use Phase – Equipment	Disposal/End-of-Life				
ARRB PLCC analysis tool				♦	♦				50	Pavement life-cycle costing analysis tool with discounted cash flow covering life-cycle road deterioration (RD) and works effects (WE) changes due to maintenance and rehabilitation. Includes general road user cost (RUC) model and RD and WE models.	- Simple life-cycle costing analysis estimating road agency costs (RAC) of maintenance and rehabilitation and associated RUCs. - Will consider a number of chosen options to estimate minimum PV of total life-cycle cost. - Interventions based on roughness and rutting. - Can be applied to a road network analysis using a genetic algorithm for optimisation (Linard, Martin & Thoresen 1996).
PLCC RUC model					♦				50	RUC model based on simplified HDM-4 RUC model amended ATAP PV2 uninterrupted flow fuel model.	Requires only AADT and percentage heavy vehicles (%HV) using a representative heavy vehicle stereotype, curvature, grade, speed and roughness.
RD Models (Austroads 2010a; Austroads 2010b)				♦					50	RD models for roughness, rutting, cracking and strength based on Austroads research (Martin & Choumanivong 2018).	Mechanistic-empirical deterministic models predicting deterioration within the gradual deterioration phase.
WE Models (Austroads 2007; Austroads 2017b)				♦					50	WE models for various forms of maintenance and rehabilitation work based on Austroads research (Martin & Choumanivong 2018).	Mechanistic-empirical deterministic models predicting improvements from various treatments.
Inventory of Carbon & Energy (ICE) Version 2.0 University of Bath, UK. (Hammond & Jones 2011)	♦								–	Developed by the Sustainable Energy Research Team (SERT), Department of Mechanical Engineering University of Bath, UK. Provides an inventory of carbon and embodied carbon.	- Includes an inventory of carbon and embodied carbon for a range of materials including road construction materials. - Cradle to gate calculations. - Note: Australian tools reference this database.

	Life-Cycle Analysis Scope							Cost Benefit Analysis	Years of Analysis	General Description	Limitations of GHG Modelling
	Cradle to Gate (Embodied Carbon)	Transport Haulage	Construction	Maintenance	Use Phase – Vehicles	Use Phase – Equipment	Disposal/End-of-Life				
ECORCE v 2.0 (ECO-comparator applied to Road Construction and Maintenance) (ECORCE 2013)	♦	♦	♦	♦					–	Developed by Ifsttar (French Institute of Science and Technology for Transport, Spatial Planning, Development and Networks) in 2013.	- Raw material extraction to waste disposal. - Developed for French context. - French language – language barrier. - Benchmark comparison in absence of Australian data.
IVL Swedish Environmental Research Institute – Life-cycle Assessment of Road (Stripple 2001)	♦		♦	♦		♦			40	- Study done in Sweden. - Reference text.	- Provides emissions factors for different equipment types – relevant to Swedish context. - Provides some reference productivities for different classes of construction equipment. - Emissions by pollutant type – not consolidated for all GHGs.
Transport Authorities Greenhouse Gas Workbook (TAGG 2013a)	♦	♦	♦						–	- Workbook that provides fuel emissions factors. - An input into other tools e.g. CERT.	- Reference study with carbon emissions factors. - Used to inform and benchmark carbon emissions data.
A comparison of Greenhouse Gas Emissions between pavement types (draft report) (ARBB – McRobert, Houghton & Styles 2005)	♦	♦	♦	♦				–	40	ARRB GHG study done for Roads and Traffic Authority, NSW.	- Reference study only. - Provides examples of emissions factors and data sources for benchmarking purposes. - Whole-of-life pavement cost (construction and maintenance) – but not cost of carbon.

	Life-Cycle Analysis Scope							Cost Benefit Analysis	Years of Analysis	General Description	Limitations of GHG Modelling
	Cradle to Gate (Embodied Carbon)	Transport Haulage	Construction	Maintenance	Use Phase – Vehicles	Use Phase – Equipment	Disposal/End-of-Life				
Environmental Impacts and Fuel Efficiency of Road Pavements – Industry Report March 2004 (European Asphalt Pavement Association & Eurobitume 2004)	♦	♦	♦	♦	♦	♦	♦	–	40	- Study done in Europe by Joint Task Group Fuel Efficiency. - Looks at the whole life-cycle of asphalt pavements and including the use phase. 40-year life-cycle assessment period and excludes lighting. 1 km long and 13 m wide.	- Provides good benchmark data. - Done in Europe. - References the IVL Swedish report (Stripple 2001) - References another European Life-cycle assessment road.

A.8 Emissions Factors

The following tables present the key emissions factors assumptions used in the model and their references. It should be noted that as far as practicable the currently accepted recent Australian factors are used and/or the references adopted in tools accepted by Australian road agencies.

There were no existing emissions factors for crumb rubber available from existing tools. It was therefore estimated from the average of PaLATE tool equipment productivity factors and excluding transport. Other sources from the USA suggested a weighted average of 124 kg of CO₂-e per ton of rubber or 0.124 ton CO₂-e/ton and including diesel for transport (approximately 43% of emissions) (Institute for Environmental Research and Education 2009). This included the steel components. These emissions factors should be validated by Australian data in the future.

Table A 4: Cradle to gate emissions – embodied carbon

Material	Embodied carbon (tonne CO ₂ -e/ tonne material)	Reference
Air voids	0	(TAGG 2013a; TAGG 2013b).
Warm mix asphalt	0.052	(TAGG 2013a; TAGG 2013b).
Asphalt, 4% bitumen (binder) content (by mass)	0.066	ICE v2.0 (Hammond and Jones 2011)
Asphalt, 5% bitumen content	0.071	ICE v2.0 (Hammond and Jones 2011)
Asphalt, 6% bitumen content	0.076	ICE v2.0 (Hammond and Jones 2011)
Asphalt, 7% bitumen content	0.081	ICE v2.0 (Hammond and Jones 2011)
Asphalt, 8% bitumen content	0.086	ICE v2.0 (Hammond and Jones 2011)
Binder – bitumen	0.63	(TAGG 2013a; TAGG 2013b).
Cement – Portland	0.82	(TAGG 2013a; TAGG 2013b).
Coarse aggregate (e.g. crushed rock)	0.0052	(TAGG 2013a; TAGG 2013b).
Concrete – reinforced	–	(TAGG 2013a; TAGG 2013b).
Crumb rubber	0.024	Based on PaLATE productivity factors kWh/tonne and assuming 0.80 kgCO ₂ -e per kWh in Queensland (DEE 2018). Transport emissions excluded.
Crushed brick/glass/concrete	0.004	(TAGG 2013a; TAGG 2013b).
Fine aggregate (e.g. crushed rock)	0.005	(TAGG 2013a; TAGG 2013b).
Lime (calcined)	1.09	(TAGG 2013a; TAGG 2013b).
Other	–	(TAGG 2013a; TAGG 2013b).
Recycled asphalt pavement (RAP)	0.009	(TAGG 2013a; TAGG 2013b; FHWA 2016).
Sand	0.0051	ICE v2.0
Soil – common	0	(TAGG 2013a; TAGG 2013b).

Table A 5: Transport emissions

Vehicle type	Emissions (tonnes CO ₂ -e per 1 tonne moved 1km)	Reference
Articulated truck	0.000072088	IS Materials calculator v 1.2 (ISCA 2019c)
Rigid truck	0.000216470	IS Materials calculator v 1.2 (ISCA 2019c)

Table A 6: Greenhouse gas emissions factor – electricity consumption

State or Territory	Emission factor kg CO ₂ -e/kWh	Reference
New South Wales and Australian Capital Territory	0.82	(DEE 2018)
Victoria	1.07	(DEE 2018)
Queensland	0.80	(DEE 2018)
South Australia	0.51	(DEE 2018)
South Western Interconnected System (SWIS) in Western Australia	0.70	(DEE 2018)
North Western Interconnected System (NWIS) in Western Australia	0.60	(DEE 2018)
Darwin Katherine Interconnected System (DKIS) in the Northern Territory	0.56	(DEE 2018)
Tasmania	0.19	(DEE 2018)
Northern Territory	0.64	(DEE 2018)

A.9 Benchmark Cost Data

A.9.1 Benchmark Construction Costs – BITRE (2018)

The Australian Government Department of Infrastructure, Regional Development and Cities Department of Infrastructure, Transport and Regional Economics releases road construction cost and procurement benchmarking reports annually. The latest release was in 2018 for 2017 data. Table A 7 summarises the results for different roads. The whole-of-project benchmark is the cost per lane kilometre by road class. The study includes motorways, freeways and arterial roads and excludes local roads. Road construction costs are disaggregated by road component. Table A 7 provides costing for road pavements and construction only. For the purposes of modelling, it was assumed that there was zero net cut and fill, thus earthworks costs have been excluded. Property acquisitions, property management, design and investigation were excluded from the values reported in Table A 7. However, typically in the ballpark of 15–20% of the total cost and across road classes (BITRE 2018).

Table A 7: Benchmark Australian construction costs – by road class BITRE

	Rural			Urban	
	Class 1	Class 2	Class 3	Class 6	Class 7
Average pavement costs, 2017 (\$/sq.m)	\$114	\$69	\$32	\$233	\$126
Average construction costs, 2017 (\$/lane.km)	\$399 000	\$241 500	\$112 000	\$815 500	\$441 000
Adjusted construction cost March 2019 (\$/lane.km) – [ABS adjusted and assuming Dec 2017 base]	\$406 119	\$245 809	\$113 998	\$830 050	\$448 868

The following class definitions are adopted for the above table:

- Class 1: Principal rural highways and freeways connecting major regions and capital cities.
- Class 2: Principal rural arterial roads.
- Class 3: Main rural arterial roads, not in Class 1 or Class 2.
- Class 4: Urban motorways and freeways.
- Class 5: Primary urban arterial roads.

Benchmark construction maintenance costs – Victoria 2014 ARRB

Detailed maintenance costs were sourced from previous reports done by ARRB and for BITRE. Table A 8 summarises 2014 costs for different types of maintenance types.

Table A 8: 2014 typical maintenance costs – Victoria

Type	ARRB estimate 2014	\$/sq. m	\$/lane-km
Routine maintenance (annual)			\$2 000
Conventional resurfacing (periodic)	Single (sprayed)	\$6	\$21 000
	Double (sprayed) seal	\$12	\$42 000
	Asphalt 50 mm	\$28	\$98 000
	Single seal + Asphalt		\$119 000
	Double seal + Asphalt		\$140 000
Modified binder resurfacing (periodic)	Single (sprayed)	\$9	\$31 500
	Double (sprayed) seal	\$18	\$63 000
	Asphalt 50 mm	\$31	\$108 500
	Single seal + Asphalt		\$140 000
	Double seal + Asphalt		\$171 500

Source: Roper and Toole (2014).

A.9.2 TMR Construction and Maintenance Cost Data

The cost information in Table A 9 was provided by TMR in May 2019. It is provided for information but was not used in the modelling as it was difficult to differentiate by pavement type and traffic design levels for each pavement type.

Table A 9: TMR cost data – by region

TREATMENTCODE	Treatment Description	Central We	Darling Dov	Far North	Fitzroy	Mackay	Metropolit	North Cost	Northern	North West	South Coas	South Wes	Widebay /E
35AC10	35 mm thick AC layer with 10 mm max stone size.	\$39.20	\$39.78	\$40.10	\$40.74	\$41.09	\$40.86	\$41.37	\$40.34	\$39.20	\$40.21	\$39.20	\$40.94
50AC14	50 mm thick AC layer with 14 mm max stone size.	\$61.96	\$61.35	\$63.37	\$62.90	\$64.19	\$65.77	\$64.90	\$65.12	\$61.74	\$64.92	\$60.83	\$63.02
COR+35AC10	Corrector (fill or mill & replace) with 35AC10 layer (urban)	\$48.08	\$48.66	\$48.97	\$49.61	\$49.97	\$49.73	\$50.24	\$49.22	\$48.08	\$49.09	\$48.08	\$49.82
COR+50AC14	Corrector (fill or mill & replace) with 50AC14 layer (rural)	\$70.84	\$70.23	\$72.25	\$71.78	\$73.07	\$74.65	\$73.78	\$74.00	\$70.62	\$73.80	\$69.71	\$71.90
COR+OG45AC14	Corrector (fill or mill & replace) with 50mm AC overlay	\$71.74	\$68.64	\$68.94	\$68.20	\$68.36	\$70.26	\$67.90	\$69.00	\$71.74	\$68.71	\$68.39	\$68.16
COR+S	Corrector (fill or mill & replace) with a spray seal.	\$13.61	\$13.79	\$13.64	\$13.61	\$13.59	\$13.59	\$13.48	\$13.71	\$13.65	\$13.53	\$13.64	\$13.63
CORRECT	Corrector (fill or mill & replace) treatment only.	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88	\$8.88
FAB_RESE	Non-woven geofabric with reseal. To seal and delay cracking.	\$12.63	\$12.61	\$12.71	\$12.61	\$12.61	\$12.33	\$12.33	\$12.69	\$12.13	\$12.33	\$12.64	\$12.71
OG30AC10	Open graded 30mm AC overlay	\$48.16	\$48.83	\$48.16	\$50.77	\$51.15	\$53.11	\$50.44	\$50.66	\$48.16	\$51.89	\$48.16	\$48.99
OG45AC14	Open graded 45mm AC overlay	\$62.86	\$59.76	\$60.07	\$59.32	\$59.48	\$61.38	\$59.02	\$60.13	\$62.86	\$59.83	\$59.51	\$59.28
PMB Reseal	Polymer Modified Binder Spray Seal	\$6.63	\$6.75	\$6.66	\$6.65	\$6.64	\$6.68	\$6.67	\$6.73	\$6.68	\$6.68	\$6.64	\$6.80
REHAB_A	Rehabilitation with Asphalt Surfacing	\$362.38	\$357.52	\$359.74	\$356.11	\$356.11	\$326.95	\$329.44	\$359.74	\$362.38	\$350.68	\$357.52	\$356.11
REHAB_S	Rehabilitation with Spray seal	\$65.44	\$68.19	\$71.81	\$69.53	\$68.59	\$73.29	\$69.95	\$70.60	\$70.28	\$69.88	\$66.53	\$68.09
RehabFBA	Foamed Bitumen Rehabilitation with AC surfacing	\$126.68	\$124.25	\$125.52	\$125.16	\$125.20	\$121.71	\$121.75	\$125.81	\$126.93	\$121.60	\$124.22	\$125.26
RehabFBS	Foamed Bitumen Rehabilitation with seal surfacing	\$96.84	\$97.32	\$98.70	\$98.55	\$98.51	\$95.41	\$95.34	\$98.71	\$99.83	\$95.26	\$97.45	\$98.54
RehabGA	Granular Overlay with AC surfacing	\$106.61	\$105.56	\$104.94	\$105.02	\$103.79	\$103.53	\$103.26	\$105.13	\$105.38	\$101.38	\$103.88	\$104.47
RehabGS	Granular Overlay with seal surfacing	\$80.43	\$79.39	\$78.44	\$78.02	\$78.14	\$76.91	\$76.89	\$79.04	\$79.35	\$77.31	\$78.86	\$79.06
RehabSS	Stabilisation with spray seal	\$64.64	\$64.57	\$63.02	\$63.70	\$64.28	\$63.27	\$62.45	\$63.65	\$63.80	\$63.25	\$63.82	\$65.00
RESEAL	Basic reseal treatment - not for AC surface if AADT > 5000.	\$4.73	\$4.92	\$4.76	\$4.73	\$4.72	\$4.72	\$4.60	\$4.84	\$4.77	\$4.65	\$4.77	\$4.75
RESHAPE	Reshape &/or modify 100mm of the granular pavement & seal.	\$20.18	\$20.22	\$20.21	\$20.21	\$20.19	\$20.50	\$20.23	\$20.20	\$20.19	\$20.37	\$20.18	\$20.20

A.9.3 Benchmark Disposal Costs

- TMR – RoadTek Data
 - Disposal costs were sourced through TMR. Data was provided for disposal costs for various waste types on RoadTek projects. The information was based on the best available reported data for large projects. There was no way of differentiating between rural and urban costs. It should be noted that disposal costs also included haulage costs. The costs were variable between waste types and for years of data. Table A 10 summarises this information.
- Urban – Gold Coast City Council (GCCC)
 - Data was also sourced from the Gold Coast City Council as indicative of urban disposal costs – which are summarised in Table A 11.
- Rural– Mackay Regional Council (MRC)
 - Data was also sourced from the Mackay Regional Council as indicative of rural disposal costs – which are summarised in Table A 12.

Table A 10: RoadTek data for disposal costs – data provided from TMR

	Average disposal cost per tonne (RoadTek)	
	2017–18 (4 quarters) \$/tonne – average	2018–19 (3 quarters) \$/tonne – average
Excess earthworks	12.97	14.04
Profiled materials	6.82	89.09
Concrete	70.66	28.20
Asphalt	42.71	2.57
Tyres	715.48	1895

Table A 11: Gold Coast City Council waste disposal costs – indicative urban

Material	Cost
Sand, soil and rock	\$100.70/tonne
Concrete disposal	\$41.90/tonne
Tyres	\$5.20 each – \$227.30 each (depending on size)

Source: GCCC (2018).

Table A 12: Mackay Regional Council waste disposal costs – indicative rural

Waste facility	Material	Cost
Paget Waste Management Facility	Commercial – Construction and Demolition Waste	\$143/tonne
Hogan's Pocket	Commercial – Construction and Demolition Waste	\$113/tonne
General	Tyres	\$6–255 each (depending on size)

Source: MRC (2019).

A.10 Construction and Maintenance Estimates

Table A 13: Construction and maintenance phase emissions – GHG Workbook Emission Factors (TAGG 2013b) and lifts/process assumptions per pavement and surfacing type

Emission source	Unit of measure	Diesel (kL/UOM)	Diesel (kL/lane-km)	tonnes GHG (CO ₂ -e/lane-km)	Comments	Lifts/processes on site	GHG per lift/process	Reference case
Pavement Construction								
Full-depth asphalt	m2	0.00169	5.915	15.9705	280 mm of asphalt, 150 mm of 2% cement treated aggregate, 150 mm of aggregate basecourse. 5% bitumen content in asphalt	10	1.59705	U1-U3 and R3-R4
Deep strength asphalt	m2	0.00215	7.525	20.3175	175 mm of asphalt, 200 mm of 4% cement treated aggregate, 150 mm of 2% cement treated aggregate, 150 mm of aggregate basecourse. 5% bitumen content	–	Not calculated	N/A
Warm mix asphalt	m2	0.00158	5.53	14.931	195 mm of asphalt, 175 mm of 4% cement treated aggregate and 150 mm of aggregate basecourse	–	Not calculated	N/A
Granular + spray and seal (Equivalent to chip seal)	m2	0.00182	6.37	17.199	500 mm of aggregate, two coat spray seal pavements.	8	2.149875	R5
Stabilisation – case	m2	0.00172	6.02	16.254	CTB and FBS proportional to asphalt. Unbound granular proportional to spray sealed granular.	–	Not calculated	N/A
Surfacing								
Prime, AMC 00	m2	0.00012	0.42	1.134	Based on 1.2 litres/m ² . Includes diesel rural multiplication factor of 6	–	Not calculated	N/A
Waterproofing layer	m2	0.00023	0.805	2.1735	Based on 0.9 L/m ² bitumen and 170 m ² /m ³ for 7 mm. Includes diesel rural multiplication factor of 7	–	Not calculated	N/A
2 coat, spray seal	m2	0.00049	1.715	4.6305	Based on 0.9 l/m ² x 2 layers, aggregate @ 105 m ² /m ³ for 16 mm and 170 m ² /m ³ for 7 mm. Includes diesel rural multiplication factor of 7	2	2.31525	R1 and R2

Table A 14: Calculations for construction and maintenance phase emissions for each technology – assumptions and calculations

NACoE technology	Code	Description	Corresponding TAGG road design	Construction				Maintenance			
				Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions	Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions
EME2	U1A	U1A: EME2 High modulus asphalt	Full-depth asphalt	13	Full-depth asphalt	20.76165	Assume equivalent to a full-depth asphalt in processing energy. Adjust for number of lifts/processes. Assume EME2 2 lift in base.	2	Full-depth asphalt	3.1941	50 mm surfacing. Asphalt mill and replace.
EME2	U1B	U1B: Dense graded asphalt	Full-depth asphalt	14	Full-depth asphalt	22.3587	Assume equivalent to a full-depth asphalt in processing energy. Adjust for number of lifts/processes. 3 lifts in base.	2	Full-depth asphalt	3.1941	50 mm surfacing. Asphalt mill and replace.
RAP	U2A	U2A: Full depth asphalt with RAP	Full-depth asphalt	14	Full-depth asphalt	22.3587	Assume equivalent to a full-depth asphalt in processing energy. Adjust for number of lifts/processes	2	Full-depth asphalt	3.1941	50 mm dense asphalt mill and replace.
RAP	U2B	U2B: Full depth asphalt without RAP	Full-depth asphalt	14	Full-depth asphalt	22.3587	Assume equivalent to a full-depth asphalt in processing energy. Adjust for number of lifts/processes	2	Full-depth asphalt	3.1941	50 mm dense asphalt mill and replace.
Crumb rubber	U3A	U3A: Open graded asphalt with crumb rubber modified binder	Full-depth asphalt – surface layer only	2	Full-depth asphalt	3.1941	Note – surfacing layer only.	2	Full-depth asphalt	3.1941	Maintenance equivalent to construction scope.
Crumb rubber	U3B	U3B: Open graded asphalt with A15E binder	Full-depth asphalt – surface layer only	2	Full-depth asphalt	3.1941	Note – surfacing layer only.	2	Full-depth asphalt	3.1941	Maintenance equivalent to construction scope.

				Construction				Maintenance			
NACoE technology	Code	Description	Corresponding TAGG road design	Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions	Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions
Crumb rubber	R1A	R1A: Sprayed seal alt case CRM binder (lower traffic)	Granular + spray and seal	1	2 coat, spray seal	1.157625	Note – surfacing layer only. Single seal	1	2 coat, spray seal	1.157625	Maintenance equivalent to construction scope.
Crumb rubber	R1B	R1B: Sprayed seal base case (lower traffic)	Granular + spray and seal	1	2 coat, spray seal	1.157625	Note – surfacing layer only. Single Seal	1	2 coat, spray seal	1.157625	Maintenance equivalent to construction scope.
Crumb rubber	R2A	R2A: Sprayed seal alt case CRM binder (higher traffic)	Granular + spray and seal	2	2 coat, spray seal	2.31525	Note – surfacing layer only. Double seal	2	2 coat, spray seal	2.31525	Maintenance equivalent to construction scope.
Crumb rubber	R2B	R2B: Sprayed seal base case (higher traffic)	Granular + spray and seal	2	2 coat, spray seal	2.31525	Note – surfacing layer only. Double seal	2	2 coat, spray seal	2.31525	Maintenance equivalent to construction scope.
Foam bitumen stabilisation	R3A – low construction emissions	R3A: FBS alt case (low traffic)	Combined asphalt and granular spray and seal	8	Full-depth asphalt	12.7764	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt.	2	2 coat, spray seal	2.31525	SAM Double Seal.
Foam bitumen stabilisation	R3B – low construction	R3B: CTB base case (low traffic)	Combined asphalt and granular spray and seal	8	Full-depth asphalt	12.7764	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt.	2	2 coat, spray seal	2.31525	SAM Double Seal.

				Construction				Maintenance			
NACoE technology	Code	Description	Corresponding TAGG road design	Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions	Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions
Foam bitumen stabilisation	R3A – high construction emissions	R3A: FBS alt case (low traffic)	Combined asphalt and granular spray and seal	12	Full-depth asphalt	19.1646	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt.	2	2 coat, spray seal	2.31525	SAM Double Seal.
Foam bitumen stabilisation	R3B – high construction	R3B: CTB base case (low traffic)	Combined asphalt and granular spray and seal	12	Full-depth asphalt	19.1646	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt.	2	2 coat, spray seal	2.31525	SAM Double Seal.
Foam bitumen stabilisation	R4A – low construction	R4A: FBS alt case (high traffic)	Combined asphalt and granular spray and seal. Surface layer in 2 lifts.	11	Full-depth asphalt	17.56755	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt. 2 lifts in surfacing.	2	Full-depth asphalt	3.1941	50 mm mill and replace surface layer.
Foam bitumen stabilisation	R4B – low construction	R4B: CTB base case (high traffic)	Combined asphalt and granular spray and seal. Surface layer in 3 lifts.	12	Full-depth asphalt	19.1646	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt. 3 lifts in surfacing.	2	Full-depth asphalt	3.1941	50 mm mill and replace surface layer.
Foam bitumen stabilisation	R4A – high construction	R4A: FBS alt case (high traffic)	Combined asphalt and granular spray and seal. Surface layer in 2 lifts.	15	Full-depth asphalt	23.95575	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt. 2 lifts in surfacing.	2	Full-depth asphalt	3.1941	50 mm mill and replace surface layer.

				Construction				Maintenance			
NACoE technology	Code	Description	Corresponding TAGG road design	Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions	Lifts/processes	Reference	Calculation (tonnes CO ₂ -e - lane-km)	Assumptions
Foam bitumen stabilisation	R4B – high construction	R4B: CTB base case (high traffic)	Combined asphalt and granular spray and seal. Surface layer in 3 lifts.	16	Full-depth asphalt	25.5528	Combination of warm mix asphalt and granular spray and seal. Assume lime takes 50% more process energy for stabilised base layer vs asphalt. 3 lifts in surfacing.	2	Full-depth asphalt	3.1941	50 mm mill and replace surface layer.
Marginal materials	R5A – Marginal materials – ridge gravel	5A: Marginal materials	Granular + spray and seal	4	Granular + spray and seal (Equivalent to Chip Seal)	8.5995	Equivalent to a granular spray and seal design. 300 mm instead of 500 mm. Assume D/D seal. 2 lifts and 4 processes.	2	2 coat, spray seal	2.31525	Spray seal D/D.
Marginal materials	R5B – Marginal materials base case	5B: Marginal materials base case Common to 5,6 and 7.	Granular + spray and seal	4	Granular + spray and seal (Equivalent to Chip Seal)	8.5995	Equivalent to a granular spray and seal design. 300 mm instead of 500 mm. Assume D/D seal. 2 lifts and 4 processes.	2	2 coat, spray seal	2.31525	Spray seal D/D.
Marginal materials	R6A – Marginal materials	6A: MGB Poorly drained wet	Granular + spray and seal	4	Granular + spray and seal (Equivalent to Chip Seal)	8.5995	Equivalent to a granular spray and seal design. 300 mm instead of 500 mm. Assume D/D seal. 2 lifts and 4 processes.	2	2 coat, spray seal	2.31525	Spray seal D/D.
Marginal materials	R7A – Marginal materials	7A: SGB Poorly drained wet	Granular + spray and seal	4	Granular + spray and seal (Equivalent to Chip Seal)	8.5995	Equivalent to a granular spray and seal design. 300 mm instead of 500 mm. Assume D/D seal. 2 lifts and 4 processes.	2	2 coat, spray seal	2.31525	Spray seal D/D.

APPENDIX B PAVEMENT DESIGNS

B.1 Pavement Design Information provided by TMR

Pavement designs were developed for each of the technologies and were compared to a traditional pavement in consultation with TMR. Where there was missing information, designs were further developed by ARRB. As far as practicable, designs were checked for equivalent structural performance between the NACoE alternative technologies and the traditional technology base case e.g. EME2 and FBS.

B.1.1 High Modulus Asphalt (EME2) – U1

Table B 1: Design inputs – EME2

Input	Value/details
Road description	Typical urban motorway in south east Queensland
Pavement type	Full-depth asphalt
Annual average daily traffic (AADT)	75 000
Proportion heavy vehicles	10%
Heavy vehicle yearly growth rate	3%
Pavement design period	30 years
Traffic load distribution (details heavy vehicle axle group types and loads)	Qld presumptive (2013–16)
Pavement design traffic	1.20 x 10 ⁸ heavy vehicle axle groups (HVAG) 1.13 x 10 ⁸ equivalent standard axles (ESA)
Pavement design reliability	95%
Subgrade	CBR 3%
Weighted mean annual pavement temperature (WMAPT) and heavy vehicle speed (governs asphalt stiffness)	32 °C, 80 km/h

Table B 2: Pavements – EME2

Course	Base case (dense graded asphalt)	Comparison case (EME2 high modulus asphalt)
Surfacing	50 mm stone mastic asphalt (SMA14)	
Intermediate	50 mm dense graded asphalt (AC14H(A15E))	
Base	260 mm dense graded asphalt (AC20H(C600)) (placed in 3 compacted layers)	200 mm high modulus asphalt (EME2) (placed in 2 compacted layers)
Prime and seal	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)	
Improved layer	150 mm lightly bound (cementitious) Type 2.3 unbound granular material	
Select fill	170 mm CBR 7% select fill	
Natural subgrade	CBR 3%	

Table B 3: Materials – EME2

Description	AC20H(C600)	EME2
Binder type	C600 (MRTS17)	EME2 (MRTS32)
Typical binder content (% by mass)	4.6	5.8

No significant performance differences expected between base case and comparison case.

B.1.2 Full Depth Asphalt with RAP – U2

Table B 4: Inputs – Full Depth Asphalt with RAP

Input	Value/details
Road description	Typical urban arterial in south east Queensland
Pavement type	Full-depth asphalt
Annual average daily traffic (AADT)	20 000
Proportion heavy vehicles	10%
Heavy vehicle yearly growth rate	3%
Pavement design period	20 years
Traffic load distribution (details heavy vehicle axle group types and loads)	Qld presumptive (2013–16)
Pavement design traffic	2.79 x 10 ⁷ heavy vehicle axle groups (HVAG) 2.62 x 10 ⁷ equivalent standard axles (ESA)
Pavement design reliability	90%
Subgrade	CBR 3%
Weighted mean annual pavement temperature (WMAPT) and heavy vehicle speed (governs asphalt stiffness)	32 °C, 50 km/h

Table B 5: Pavements – full-depth asphalt with RAP

Course	Base case (dense graded asphalt without RAP)	Comparison case (dense graded asphalt with RAP)
Surfacing	50 mm dense graded asphalt (AC14H(A15E))	50 mm dense graded asphalt with 15% RAP (AC14H(A15E)RAP)
Intermediate	50 mm dense graded asphalt (AC14H(A15E))	50 mm dense graded asphalt with 15% RAP (AC14H(A15E)RAP)
Base	195 mm dense graded asphalt (AC20H(C600)) (placed in 2 compacted layers)	195 mm dense graded asphalt with 30% RAP (AC20H(C320)RAP) (placed in 2 compacted layers)
Prime and seal	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)	
Improved layer	150 mm lightly bound (cementitious) Type 2.3 unbound granular material	
Select fill	170 mm CBR 7% select fill	
Natural subgrade	CBR 3%	

Table B 6: Materials – full-depth asphalt with RAP

Description	AC20H(C600)	AC20H(C320)RAP
Binder type	C600 (MRTS17)	C320 (MRTS17)
Typical binder content (% by mass)	4.6	4.6
RAP content (% by mass)	0	30

No significant performance differences expected between base case and comparison case.

B.1.3 Open Graded Asphalt with Crumb Rubber Modified Binder – U3

Table B 7: Inputs – open graded asphalt with crumb rubber modified binder

Input	Value/details
Road description	Urban or major rural road with posted speed greater than 80 km/h
Treatment	Open graded asphalt surfacing

Table B 8: Pavements – open graded asphalt with crumb rubber modified binder

Course	Base case (open graded asphalt with A15E binder)	Comparison case (open graded asphalt with crumb rubber modified binder)
Surfacing	30 mm open graded asphalt (OG10(A15E))	30 mm open graded asphalt (OG10(CR))
Other pavement courses	Other pavement courses	

Table B 9: Materials – open graded asphalt with crumb rubber modified binder

Description	OG10(A15E)	OG10(CR)
Binder type	A15E (MRTS18)	C170 with CR (MRTS18)
Binder content (% by mass)	4.8	6.0
Binder details	N/A	18% rubber

B.1.4 Single/Single Reseal (HSS1) with Crumb Rubber Modified Binder – R1

Table B 10: Inputs – single/single reseal (HSS1) with crumb rubber modified binder

Input	Value/details
Road description	Typical rural main road in regional Queensland
Treatment	Single/single (HSS1) reseal
Existing pavement	Unbound granular pavement with 14 mm seal
Design traffic (v/l/d)	500
Equivalent heavy vehicles	30%
Temperature	High

Table B 11: Pavements – single/single reseal (HSS1) with crumb rubber modified binder

Course	Base case (polymer modified binder reseal)	Comparison case (crumb rubber reseal)
Surfacing	X mm seal with Y (PMB) binder Aggregate spread rate: Binder spray rate:	X mm seal with Y (CR) binder Aggregate spread rate: Binder spray rate:
Existing pavement	Unbound granular pavement with 14 mm seal	

B.1.5 Double/Double Reseal (HSS2) with Crumb Rubber Modified Binder – R2

Table B 12: Inputs – double/double reseal (HSS2) with crumb rubber modified binder

Input	Value/details
Road description	Typical rural main road in regional Queensland (higher traffic)
Treatment	Double/double (HSS2) reseal
Existing pavement	Unbound granular pavement with 14 mm seal
Design traffic (v/l/d)	1000
Equivalent heavy vehicles	40%
Temperature	High

Table B 13: Pavements – double/double reseal (HSS2) with crumb rubber modified binder

Course	Base case (polymer modified binder reseal)	Comparison case (crumb rubber reseal)
Surfacing	X mm seal with Y (PMB) binder Aggregate spread rate: Binder spray rate:	X mm seal with Y (CR) binder Aggregate spread rate: Binder spray rate:
Existing pavement	Unbound granular pavement with 14 mm seal	

B.1.6 Foam Bitumen Stabilisation – Low Traffic – R3

See below for R4, as R3 and R4 developed together.

B.2 Pavement Designs Modelled

The following naming convention was adopted for the designs:

A = Alternative NACoE technology

B = Base case traditional technology.

The following sections outline the key assumptions modelled in terms of pavement layers, layer thickness, density and components of each layer.

The use phase roughness performance for each pavement design was determined using RD models (Austroads 2010a; Austroads 2010b; Martin & Choummanivong 2018), with WE models as per typical TMR resets (Toole, Roper & Noya 2018). The initial structural numbers were determined based on ARR390 (Hodges, Rolt & Jones 1975) and American Association of State Highway Officials (AASHTO) (1993).

B.2.1 EME2 Designs and Performance Modelled

Table B 14: U1B dense graded asphalt – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
Surfacing:	50 mm stone mastic asphalt (SMA14)	50	2325.00
Intermediate:	50 mm dense graded asphalt (AC14H(A15E))	50	2325.00
Base:	260 mm dense graded asphalt (AC20H(C600))	260	2375.00
Prime and seal:	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)	10	–
Improved layer:	150 mm lightly bound (cementitious) Type 2.3 unbound granular material	150	2240.00
Select fill:	170 mm CBR 7% select fill	170	1460.00
Subgrade:	CBR 3%	0	–

Table B 15: U1B dense graded asphalt – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Surfacing:	Binder – bitumen	6.00	Mass bitumen at 6%. Air voids at 7%
	Fine aggregate (e.g. crushed rock)	94.00	
Intermediate:	Binder – bitumen	5.50	Mass bitumen at 5.5%
	Fine aggregate (e.g. crushed rock)	94.50	
Base:	Binder – bitumen	4.60	Mass bitumen at 4.6%
	Fine aggregate (e.g. crushed rock)	95.40	
Prime and seal:			Ignore as negligible
Improved layer:	Coarse aggregate (e.g. crushed rock)	100.00	Assume 100% aggregate
Select fill:	Soil – common	100.00	Assume 100% soil
Subgrade:			Assume zero haul and no new material

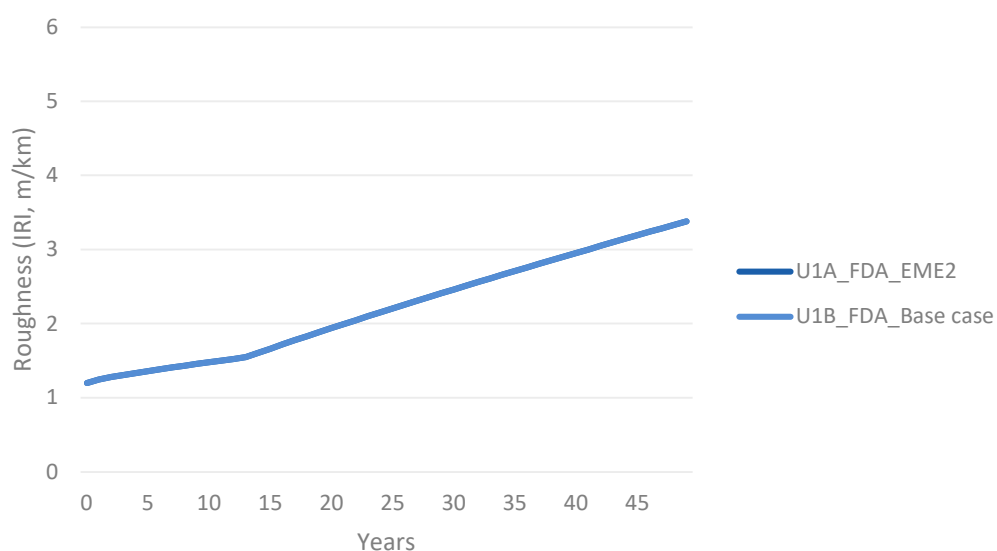
Table B 16: U1A EME2 high modulus asphalt – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
Surfacing:	50 mm stone mastic asphalt (SMA14)	50	2325.00
Intermediate:	50 mm dense graded asphalt (AC14H(A15E))	50	2325.00
Base:	200 mm high modulus asphalt (EME2)	200	2400.00
Prime and seal:	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)	10	–
Improved layer:	150 mm lightly bound (cementitious) Type 2.3 unbound granular material	150	2240.00
Select fill:	170 mm CBR 7% select fill	170	1460.00
Subgrade:	CBR 3%	0	–

Table B 17: U1A EME2 high modulus asphalt – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Surfacing:	Binder – bitumen	6.00	Mass bitumen at 6%. Air voids at 7%
	Fine aggregate (e.g. crushed rock)	94.00	
Intermediate:	Binder – bitumen	5.50	Mass bitumen at 5.5%
	Fine aggregate (e.g. crushed rock)	94.50	
Base:	Binder – bitumen	5.80	Notes
	Fine aggregate (e.g. crushed rock)	94.20	Mass bitumen at 5.8%
Prime and seal:			Ignore as negligible
Improved layer:	Coarse aggregate (e.g. crushed rock)	100.00	Assume 100% aggregate
Select fill:	Soil – common	100.00	Assume 100% soil
Subgrade:			Assume zero haul and no new material

Figure B 2: Use phase roughness performance of U1A and U1B



B.2.2 RAP Designs and Performance Modelled

Table B 18: U2B dense graded asphalt without RAP – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
Surfacing:	50 mm dense graded asphalt (AC14H(A15E))	50	2325.00
Intermediate:	50 mm dense graded asphalt (AC14H(A15E))	50	2325.00
Base:	195 mm dense graded asphalt (AC20H(C600))	195	2375.00
Prime and seal:	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)	10	–
Improved layer:	150 mm lightly bound (cementitious) Type 2.3 unbound granular material	150	2240.00
Select fill:	170 mm CBR 7% select fill	170	1460.00
Subgrade:	CBR 3%	0	–

Table B 19: U2B dense graded asphalt without RAP – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Surfacing:	Binder – bitumen	6.00	Mass bitumen at 6%. Air voids at 7%
	Coarse aggregate (e.g. crushed rock)	94.00	Mass bitumen at 6%. Air voids at 7%
Intermediate:	Binder – bitumen	5.50	Mass bitumen at 5.5%
	Coarse aggregate (e.g. crushed rock)	94.50	Mass bitumen at 5.5%
Base:	Binder – bitumen	4.60	Mass bitumen at 4.6%
	Coarse aggregate (e.g. crushed rock)	95.40	Mass bitumen at 4.6%
Prime and seal:			Ignore – as negligible
Improved layer:	Coarse aggregate (e.g. crushed rock)	100.00	Assume 100% aggregate
Select fill:	Soil – common	100.00	Assume 100% soil

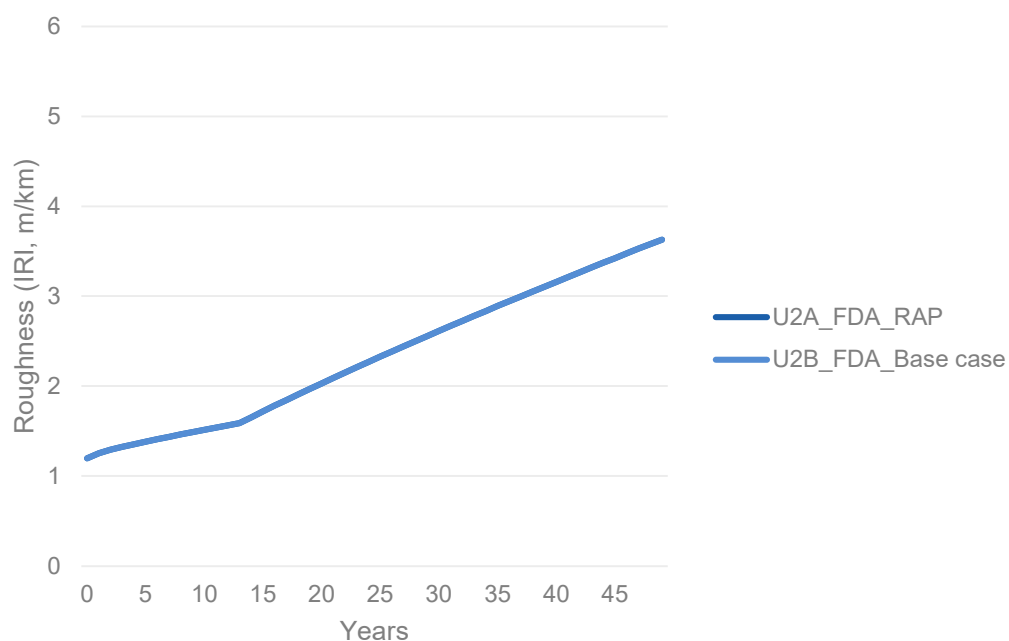
Table B 20: U2A dense graded asphalt with RAP – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
Surfacing:	50 mm dense graded asphalt with 15% RAP (AC14H(A15E)RAP)	50	2325.00
Intermediate:	50 mm dense graded asphalt with 15% RAP (AC14H(A15E)RAP)	50	2325.00
Base:	195 mm dense graded asphalt with 30% RAP (AC20H(C320)RAP)	195	2375.00
Prime and seal:	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)	10	–
Improved layer:	150 mm lightly bound (cementitious) Type 2.3 unbound granular material	150	2240.00
Select fill:	170 mm CBR 7% select fill	170	1460.00
Subgrade:	CBR 3%	0	–

Table B 21: U2A dense graded asphalt with RAP – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Surfacing:	Binder – bitumen	5.50	Mixes with 15% RAP typically have 0.5% less added binder
	Coarse aggregate (e.g. crushed rock)	79.50	
	Recycled asphalt pavement (RAP)	15.00	15% RAP
Intermediate:	Binder – bitumen	5.00	Mixes with 15% RAP typically have 0.5% less added binder
	Coarse aggregate (e.g. crushed rock)	80.00	
	Recycled asphalt pavement (RAP)	15.00	15% RAP
Base:	Binder – bitumen	4.10	Mixes with 15% RAP typically have 0.5% less added binder. Even though RAP is 30% here, use 0.5% reduction to be conservative, ability to cut binder lower than 4% would be riskier
	Coarse aggregate (e.g. crushed rock)	65.90	
	Recycled asphalt pavement (RAP)	30.00	30% RAP
Prime and seal:			Ignore – as negligible
Improved layer:	Coarse aggregate (e.g. crushed rock)	100.00	Assume 100% aggregate
Select fill:	Soil – common	100.00	Assume 100% soil
Subgrade:			Assume zero haulage and no new material

Figure B 3: Use phase roughness performance of U2A and U2B



B.2.3 Crumb Rubber Designs and Performance Modelled

Crumb rubber designs were surfacing layers only in the construction and maintenance phases.

Table B 22: U3B surfacing – open graded asphalt with A15E binder – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	Open graded asphalt (OG10 with A15E binder)	30	2,100.00
Asphalt:	Existing asphalt base layers	150	2,400.00
Granular base:	Lightly bound layer at 2% cement	250	2,240.00
Subbase (insitu):	Type 2.3 unbound granular material	200	2,240.00
Subgrade:	CBR 7%	0	–

Table B 23: U3B surfacing – open graded asphalt with A15E binder – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
AC surfacing:	Binder – bitumen	4.80	OGA design at 4.8% bitumen
	Coarse aggregate (e.g. crushed rock)	95.20	
Asphalt:	Other	12.00	Assume zero haulage and no new material
	–	88.00	Assume zero haulage and no new material
Granular base:	Other	3.50	Assume zero haulage and no new material
	–	16.67	
	–	79.83	
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material

Table B 24: U3A surfacing – OGA with crumbe rubber modified binder – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	Open graded asphalt (OG10 with C170/crumb rubber binder)	30	2100.00
Asphalt:	Existing asphalt base layers	150	2400.00
Granular base:	Lightly bound layer at 2% cement	250	2240.00
Subbase (insitu):	Type 2.3 unbound granular material	200	2240.00
Subgrade:	CBR 7%	–	–

Table B 25: U3A surfacing – OGA with crumb rubber modified binder – layer mass composition assumptions

	Material Assumed – Embodied Carbon	Mass (%)	Notes
AC surfacing:	Binder - bitumen	4.92	CRM-OGA design at 6.0% bitumen
	Crumb rubber	1.08	18% of bitumen is rubber
	Coarse aggregate (e.g. crushed rock)	94.00	CRM-OGA design at 6.0% bitumen
Asphalt:	Other	12.00	Assume zero haulage and no new material
	–	88.00	
Granular base:	Other	3.50	Assume zero haulage and no new material
	–	16.67	
	–	79.83	
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material

Note:

- U3A and U3B have a rehabilitation after the modelled 40 years life-cycle period.

Figure B 4: Use phase roughness performance of U3A and U3B

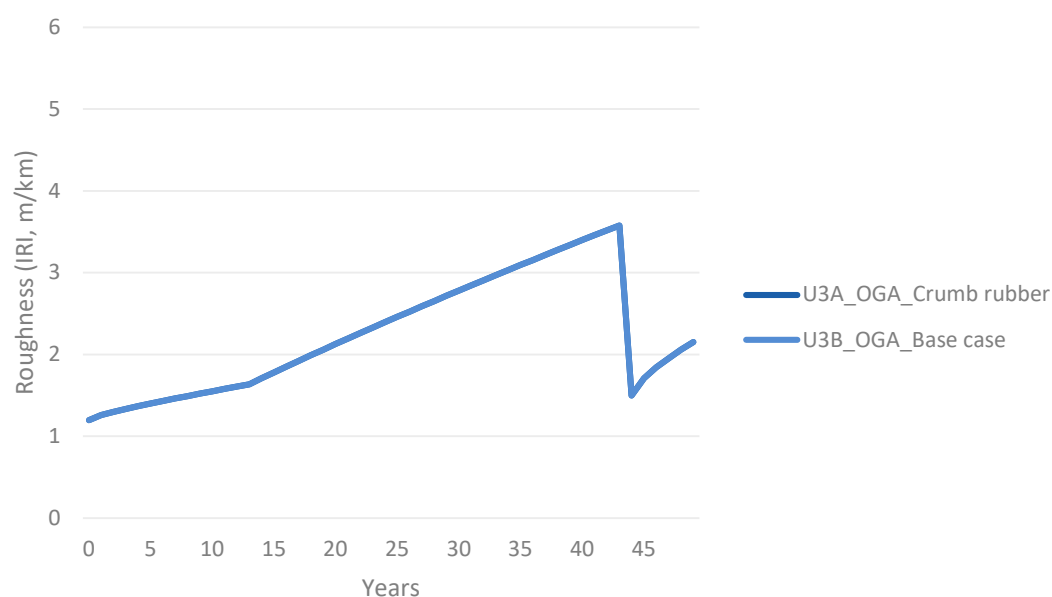


Table B 26: R1B surfacing – sprayed seal base case (lower traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		
Seal:	Single/single (HSS1) PMB reseal (14 mm aggregate)	12	2079.00
Subbase (insitu):	Type 2.3 unbound granular material	150	2240.00
Subgrade:	CBR 7%		

Table B 27: R1B surfacing – sprayed seal base case (lower traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder - bitumen	6.60	Based on 1.6 L bitumen per m ²
	Coarse aggregate (e.g. crushed rock)	93.40	Based on average aggregate depth of 12 mm
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material

Table B 28: R1A surfacing – sprayed seal alt case CRM binder (lower traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	Single/single (HSS1) CRM reseal (14 mm aggregate)	12	2059.00
Subbase (insitu):	Type 2.3 unbound granular material	150	2240.00
Subgrade:	CBR 7%		–

Table B 29: R1A surfacing – sprayed seal alt case CRM binder (lower traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	6.15	Based on 1.8 L bitumen per m ²
	Coarse aggregate (e.g. crushed rock)	92.49	Based on average aggregate depth of 12 mm
	Crumb rubber	1.35	at 18% of binder by mass
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material
	Soil – common	100.00	Assume 100% soil

Figure B 5: Use phase roughness performance of R1A and R1B

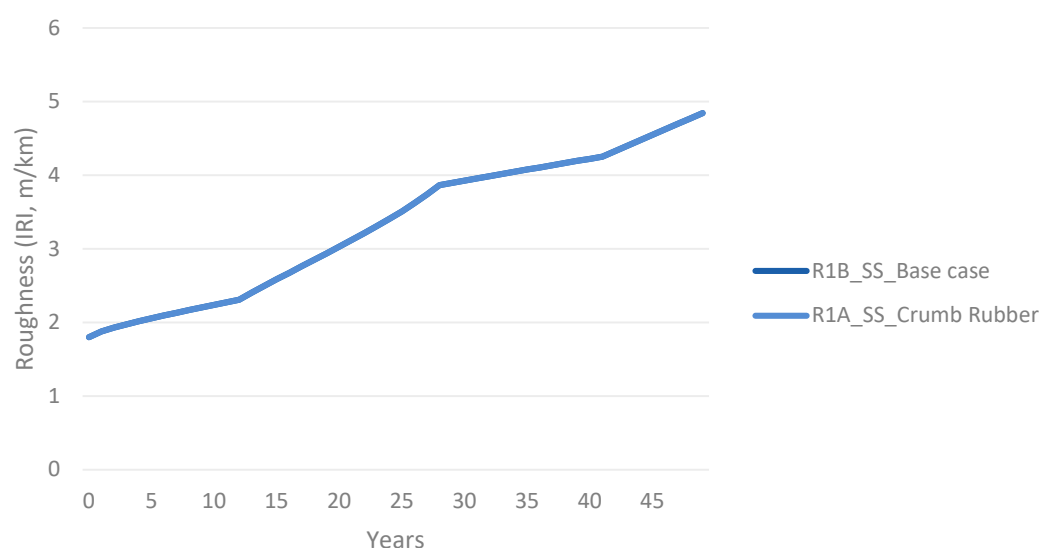


Table B 30: R2B sprayed seal base case (higher traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	Double/double (HSS2) PMB reseal (14/7 mm aggregate)	15	2038.00
Subbase (insitu):	Type 2.3 unbound granular material	250	2240.00
Subgrade:	CBR 7%		–

Table B 31: R2B sprayed seal base case (higher traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	8.40	Based on 2.5 L bitumen per m ²
	Coarse aggregate (e.g. crushed rock)	91.60	Based on average aggregate depth of 15 mm
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material

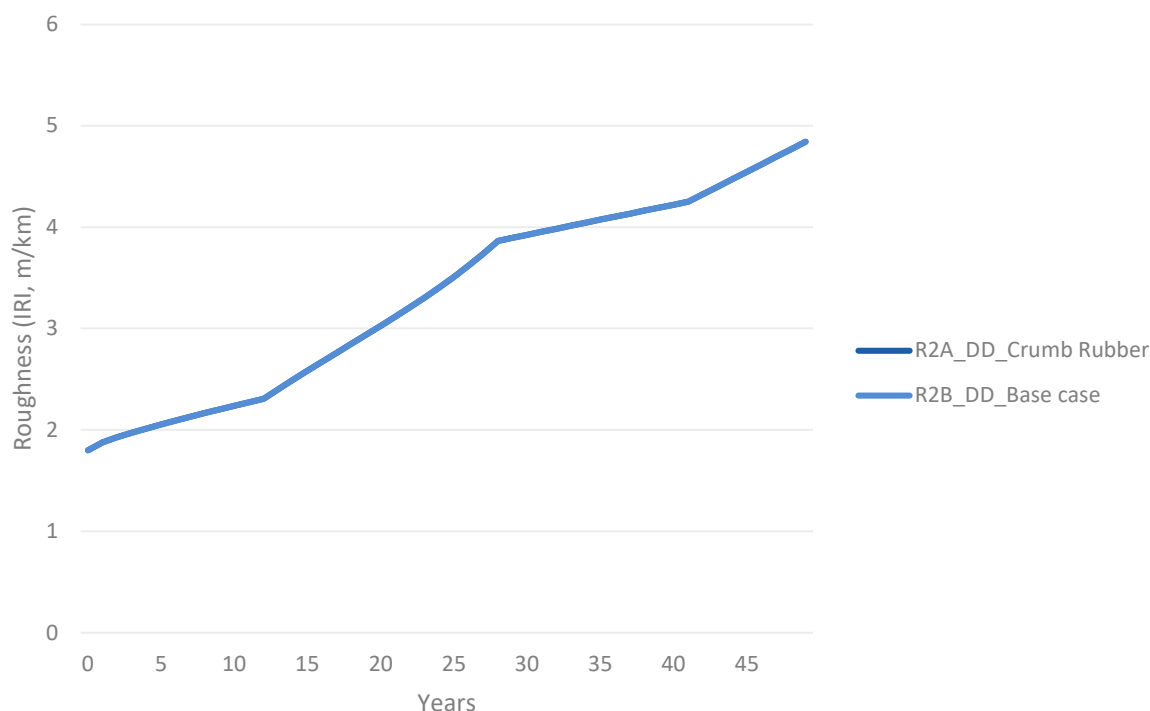
Table B 32: R2A sprayed seal alt case CRM binder (higher traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	Double/double (HSS2) CRM reseal (14/7 mm aggregate)	15	2022.00
Stabilised base:			–
Subbase (insitu):	Type 2.3 unbound granular material	250	2240.00
Subgrade:	CBR 7%		–

Table B 33: R2A sprayed seal alt case CRM binder (higher traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	7.52	Based on 2.7 L bitumen per m ²
	Coarse aggregate (e.g. crushed rock)	90.83	Based on average aggregate depth of 15 mm
	Crumb rubber	1.65	at 18% of binder by mass
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material
	Soil – common	100.00	Assume 100% soil

Figure B 6: Use phase roughness performance of R2A and R2B



B.2.4 Foam Bitumen Stabilisation Designs and Performance Modelled

Table B 34: R3B CTB base case (low/med traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	SAM seal (double/double 14/7)	15	2038.00
Stabilised base:	Cement treated base (CTB) at 3.5% cement (50 mm imported, else in situ)	275	2350.00
Subbase (insitu):	Type 2.3 unbound granular material	200	2240.00
Subgrade:	CBR 7%		–

Table B 35: R3B CTB base case (low/med traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	8.40	Based on 2.5 L bitumen per m ²
	Fine aggregate (e.g. crushed rock)	91.60	Based on average aggregate depth of 15 mm
Stabilised base:	Cement – Portland	3.50	3.5% cement according to design from TMR
	Fine aggregate (e.g. crushed rock)	18.18	Only 50 mm imported
	Other	78.32	IN SITU
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material

Table B 36: R3A FBS alt case (low/med traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	SAM seal (double/double 14/7)	15	2038.00
Stabilised base:	Foam bitumen (FBS) at 3% bitumen and 2% lime	275	2100.00
Subbase (insitu):	Type 2.3 unbound granular material	200	2240.00
Subgrade:	CBR 7%		–

Table B 37: R3A FBS alt case (low/med traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	8.40	Based on 2.5 L bitumen per m ²
	Fine aggregate (e.g. crushed rock)	91.60	Based on average aggregate depth of 15 mm
Stabilised base:	Binder – bitumen	3.00	3.5% cement according to design from TMR
	Lime (calcined)	1.60	2% lime according to TMR design
	Fine aggregate (e.g. crushed rock)	18.18	Only 50 mm imported
	Other	77.22	IN SITU
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material
	Soil – common	100.00	Assume 100% soil

Figure B 7: Use phase roughness performance of R3A and R3B

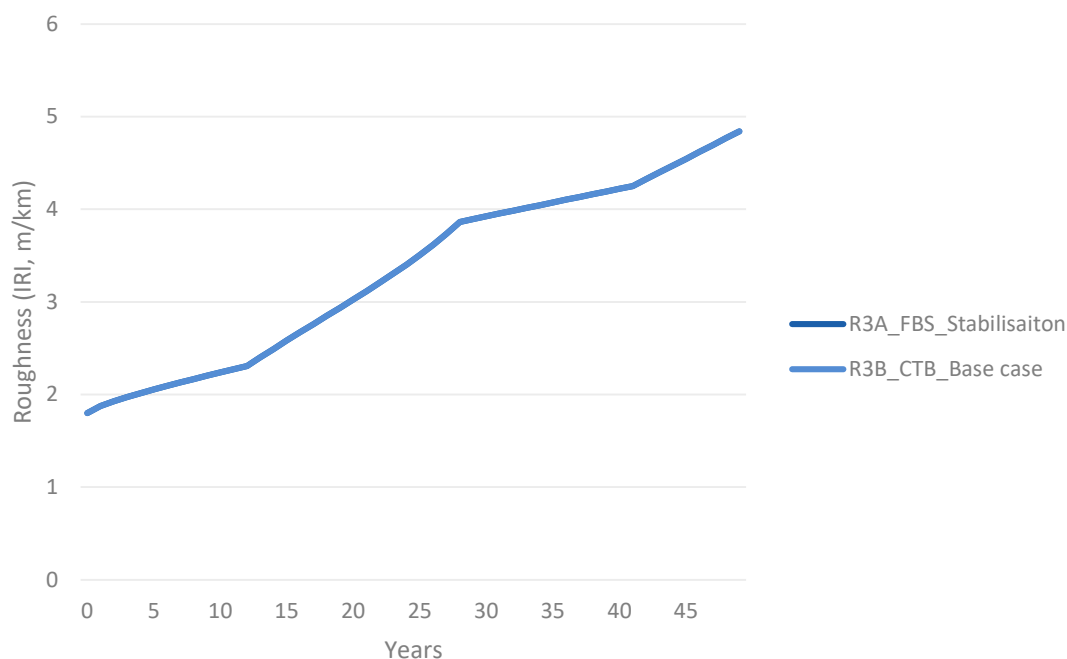


Table B 38: R4B CTB base case (high traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	AC14 or AC20 surface layer in 3 lifts	175	2325.00
Seal:	SAMI seal (single 10 mm)	10	2046.00
Stabilised base:	Cement treated base (CTB) at 3.5% cement (50 mm imported, else in situ)	300	2350.00
Subbase (insitu):	Type 2.3 unbound granular material	250	2240.00
Subgrade:	CBR 7%		–

Table B 39: R4B CTB base case (high traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
AC surfacing:	Binder – bitumen	4.50	Typical AC design at 4.5% bitumen
	Coarse aggregate (e.g. crushed rock)	95.50	Typical AC design at 4.5% bitumen
Seal:	Binder – bitumen	8.10	Based on 1.6 L bitumen per m ²
	Fine aggregate (e.g. crushed rock)	91.90	Based on average aggregate depth of 15 mm
Stabilised base:	Cement – Portland	3.50	3.5% cement according to design from TMR
	Fine aggregate (e.g. crushed rock)	16.67	Only 50 mm imported
	Other	79.83	IN SITU
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material

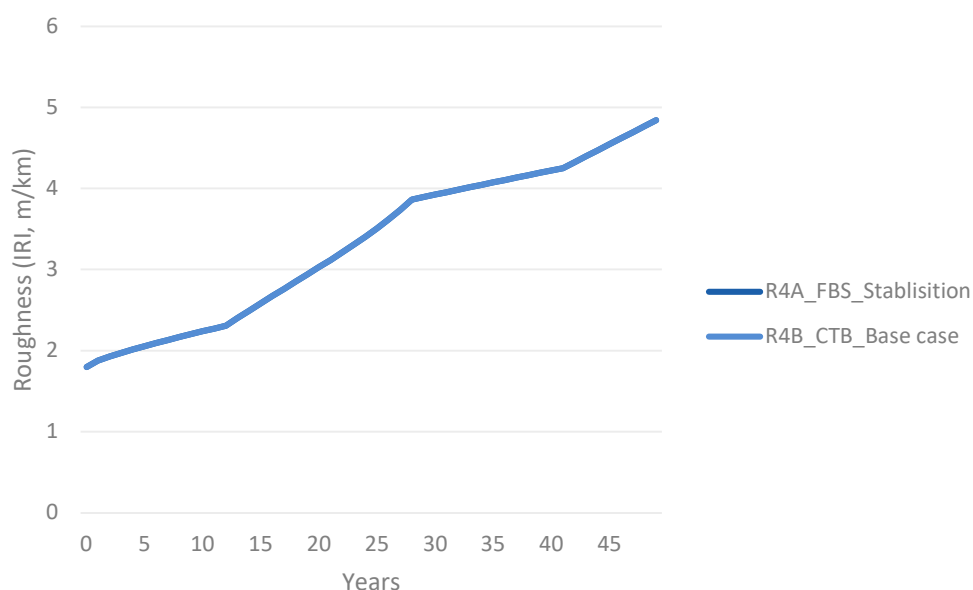
Table B 40: R4A FBS alt case (high traffic) – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	AC14 or AC20 surface layer in 2 lifts	120	2325.00
Seal:	Armourcoat seal (single 7mm)	10	2050.00
Stabilised base:	Foam bitumen (FBS) at 3% bitumen and 2% lime	300	2100.00
Subbase (insitu):	Type 2.3 unbound granular material	250	2240.00
Subgrade:	CBR 7%		–

Table B 41: R4A FBS alt case (high traffic) – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
AC surfacing:	Binder – bitumen	4.50	Typical AC design at 4.5% bitumen
	Coarse aggregate (e.g. crushed rock)	95.50	
Seal:	Binder – bitumen	7.90	Based on 1.1 L bitumen per m ²
	Fine aggregate (e.g. crushed rock)	92.10	Based on average aggregate depth of 15 mm
Stabilised base:	Binder – bitumen	3.00	3.5% cement according to design from TMR
	Lime (calcined)	1.60	2% lime according to TMR design
	Fine aggregate (e.g. crushed rock)	16.67	Only 50 mm imported
	Other	78.73	IN SITU
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Other	100.00	Assume zero haulage and no new material
	Soil – common	100.00	Assume 100% soil

Figure B 8: Use phase roughness performance of R4A and R4B



B.2.5 Granular Materials Designs and Performance Modelled

Figure B 9 and Table B 42 provide a relative comparison of the strength characteristics of typical western Queensland marginal materials. The un-soaked CBR varies for different materials under saturation. They are indicative of different material performance under well-drained and poorly drained conditions.

Figure B 9: Strength characteristics of typical Western Queensland materials

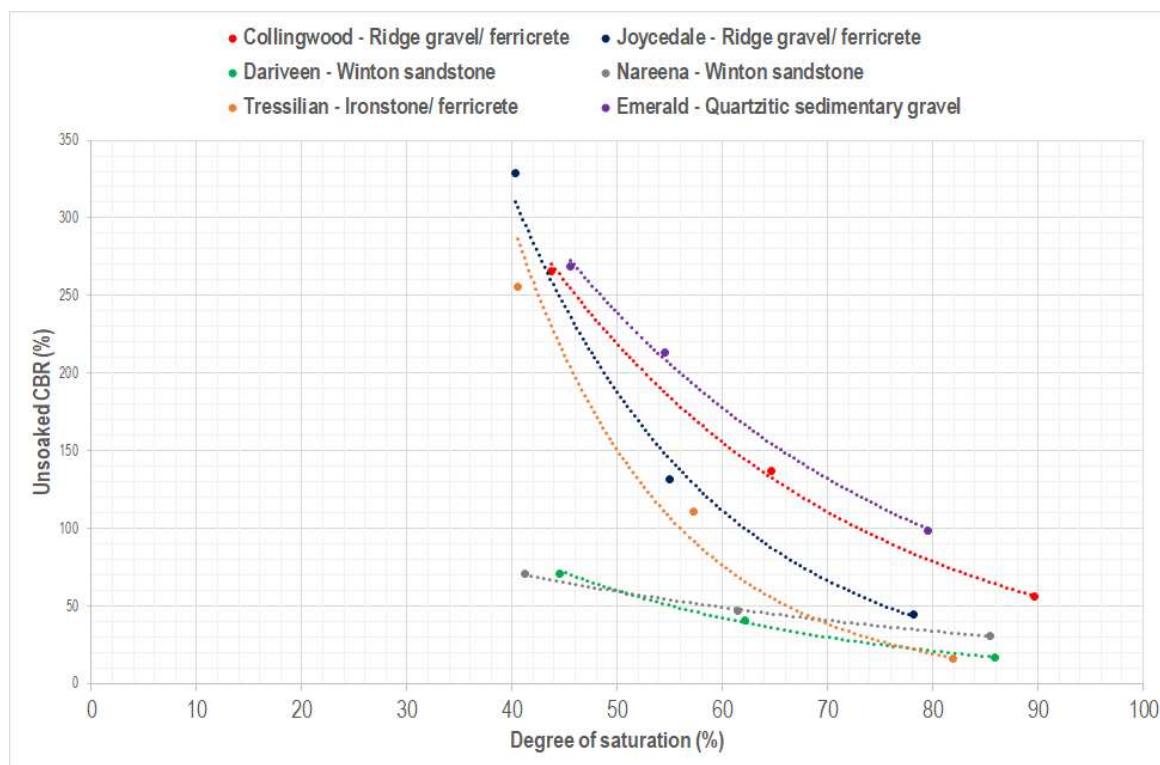


Table B 42: Presumptive subgrade strength values based on soil classification

Description of subgrade		Typical CBR values (%)	
Material	USC ³	Well drained	Poorly drained
Highly plastic clay	CH	5	2–3
Silt	ML	4	2
Silt clay	CL	6–7	4–5
Sandy clay	SC	5–6	3–4
Sand	SW, SP	10–15	5–10

An analysis was undertaken for different marginal materials performances which informed technology scenarios R5A, R6A and R7A. Each of these materials shared a common base case R5B.

³ USC: Unified Soil Classification (USC)

CH: Clay, high plasticity
ML: Silt, low plasticity
CL: Clay, low plasticity
SC: Clayey sand
SW: Well-graded sand
SP: Poorly graded sand

Table B 43: R5B marginal materials – base case – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	Double/double (HSS2) PMB reseal (14/7 mm aggregate)	15	2038.00
Base:	150 mm imported aggregate	150	2240.00
Subbase (insitu):	150 mm selected subbase – unbound granular	150	2240.00
Subgrade:	CBR 7%		–

Table B 44: R5B marginal materials – base case – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	8.40	Based on 2.5 L bitumen per m ²
	Fine aggregate (e.g. crushed rock)	91.60	Based on average aggregate depth of 15 mm
Base:	Fine aggregate (e.g. crushed rock)	100.00	
Subbase (insitu):	Soil – common	100.00	Assume zero haulage and no new material
Subgrade:	Soil – common	100.00	Assume zero haulage and no new material

Table B 45: R5A marginal materials – ridge gravel – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	Double/double (HSS2) PMB reseal (14/7 mm aggregate)	15	2038.00
Base:	150 mm selected ridge gravel base	150	2240.00
Subbase (insitu):	150 mm selected subbase – unbound granular	150	2240.00
Subgrade:	CBR 7%		–

Table B 46: R5A marginal materials – ridge gravel – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	8.40	Based on 2.5 L bitumen per m ²
	Fine aggregate (e.g. crushed rock)	91.60	Based on average aggregate depth of 15 mm
Base:	Soil – common	100.00	
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Soil – common	100.00	Assume zero haulage and no new material

Table B 47: R6A marginal materials – MGB poorly drained wet – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC Surfacing:	NONE		–
Seal:	Double/double (HSS2) PMB reseal (14/7mm aggregate)	15	2038.00
Base:	150 mm marginal materials - wet	150	2240.00
Subbase (insitu):	150 mm selected subbase - unbound granular	150	2240.00
Subgrade:	CBR 7%		–

Table B 48: R6A marginal materials – MGB poorly drained wet – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	8.40	Based on 2.5 L bitumen per m ² .
	Fine aggregate (e.g. crushed rock)	91.60	Based on average aggregate depth of 15 mm.
Base:	Soil – common	100.00	
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Soil – common	100.00	Assume zero haulage and no new material

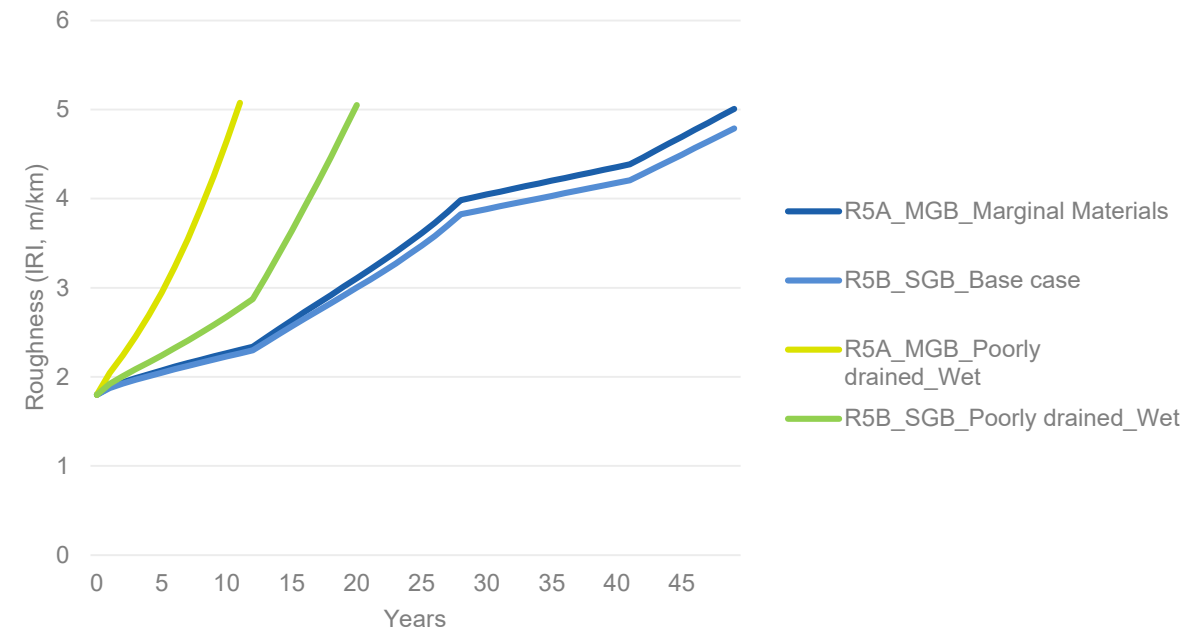
Table B 49: R7A marginal materials – SGB poorly drained wet – pavement design

Layer	Layer description	Layer thickness (mm)	Assumed average layer density (kg/m ³)
AC surfacing:	NONE		–
Seal:	Double/double (HSS2) PMB reseal (14/7 mm aggregate)	15	2038.00
Base:	150 mm marginal materials - wet	150	2240.00
Subbase (insitu):	150 mm selected subbase – unbound granular	150	2240.00
Subgrade:	CBR 7%		–

Table B 50: R7A marginal materials – SGB poorly drained wet – layer mass composition assumptions

	Material assumed – embodied carbon	Mass (%)	Notes
Seal:	Binder – bitumen	8.40	Based on 2.5 L bitumen per m ²
	Soil – common	91.60	Based on average aggregate depth of 15 mm
Base:	Soil – common	100.00	
Subbase (insitu):	Other	100.00	Assume zero haulage and no new material
Subgrade:	Soil – common	100.00	Assume zero haulage and no new material

Figure B 10: Use phase roughness performance of R5A and R5B, R6A and R7A



APPENDIX C KEY MODEL ASSUMPTIONS AND CALCULATIONS

The following section outlines the key assumptions, equations and methodology used to calculate emissions and undertake the CBA.

C.1 Life-Cycle Emissions

C.1.1 Pavement Design

Refer to section 6 for model structure information. The pavement design information was entered into the 'GHG summary workbook' 'Parameters' tab.

The total tonnage of each layer was calculated as per Equation A1:

$$\text{Pavement layer mass [tons/km]} = RW * Thick/1000 * density/1000 * 1000m \quad A1$$

where

RW = road width (m)

$Thick$ = pavement thickness (mm)

$density$ = average pavement layer density (kg/m³)

The road width was assumed to be 3.5 m, and a 1000 m length was assumed given the basis of 1 lane.km.

Density information was assumed based on pavement layer design information.

This information is used to calculate tonnes of materials for materials haulage in both the construction and the maintenance phase.

Each layer also has a reference table where a materials recipe for each pavement layer is entered in. The material type was selected from a drop-down menu. It should be noted that due to limited embodied carbon materials options, categorisation of the key components (i.e. aggregate and bitumen) was required. The mass (%) of each material was estimated from pavement design information. This information was a key input into the calculation of embodied carbon for the pavement design.

C.1.2 Embodied Carbon of Pavement Materials

The embodied carbon of pavement materials is associated with the extraction and manufacture of pavement materials. These are often called 'cradle to gate' emissions.

The embodied carbon of materials was calculated in the 'GHG Summary Model' parameters tab for each respective pavement technology.

The information specified in the pavement design was used to calculate the embodied carbon of each layer as per Equation A2.

$$\text{Mine to Production Emissions} \left(\frac{tCO_2e}{km} \right) = \text{Average Mine to Production Emissions} \left(\frac{CO_2e}{ton} \right) \times \text{Material mass (tons)} \quad A2$$

The average 'mine to production' emissions were based on a weighted average by mass of each component of the pavement layer.

Emissions factors were sourced and consolidated from a range of tools and reference texts in a look-up table. Refer to Appendix A.8 for a list of the emissions factors adopted in the calculations.

C.1.3 Construction Emissions

The scope of emissions was limited to direct emissions from construction equipment and pavement construction. Emissions associated with vegetation clearing and cut and fill haulage were excluded from the calculations. Other road structures including, but not limited to, road furniture, drainage structures, lighting, accommodation, and site vehicles use were excluded. The exclusions are considered common to both the pavement technology and the base case and thus would cancel out in the net emissions and NPV calculations.

There were limited tools available for the calculation of construction phase emissions, based on an input of pavement design information. Tools required the input of kL of fuel and/or months of construction for each equipment type. The PaLATE tool (RMRC 2013) allows for the calculation of construction phase emissions based on input designs. However, the productivity factors of construction equipment were found to be unreasonably high and thus understating construction phase emissions. In the absence of construction plans for each of the pavement technologies, the approach adopted was to take Australian benchmark emissions from road pavement designs of similar scope and adjust according to the estimated number of construction processes and lifts required. The accuracy of this approach is estimated to be within 20% error marginal.

Emissions data was sourced from the Australian Transport Authorities *Greenhouse Gas Workbook*. This estimates and presents emissions which are considered to be materially significant. Table C 1 summarises this input information for construction of pavement (TAGG 2013b).

Table C 1: Greenhouse Gas Workbook construction emissions factors

Emission source	Unit of measure	Diesel (kL/m ²)	Comments
Pavement Construction			
Full-depth asphalt	m ²	1.69 x 10 ⁻³	280 mm of asphalt, 150 mm of 2% cement treated aggregate, 150 mm of aggregate basecourse. 5% bitumen content in asphalt
Deep strength asphalt	m ²	2.15 x 10 ⁻³	175 mm of asphalt, 200 mm of 4% cement treated aggregate, 150 mm of 2% cement treated aggregate, 150 mm of aggregate basecourse. 5% bitumen content
Warm mix asphalt	m ²	1.58 x 10 ⁻³	195 mm of asphalt, 175 mm of 4% cement treated aggregate and 150 mm of aggregate basecourse
Granular + spray and seal (Equivalent to chip seal)	m ²	1.82 x 10 ⁻³	500 mm of aggregate, two coat spray seal pavements
Seals			
Prime, AMC 00	m ²	0.12 x 10 ⁻³	Based on 1.2 litres/m ² . Includes diesel rural multiplication factor of 6
Waterproofing layer	m ²	0.23 x 10 ⁻³	Based on 0.9 L/m ² bitumen and 170 m ² /m ³ for 7 mm. Includes diesel rural multiplication factor of 7
2 coat, spray seal	m ²	0.49 x 10 ⁻³	Based on 0.9 l/m ² x 2 layers, aggregate @ 105 m ² /m ³ for 16 mm and 170 m ² /m ³ for 7 mm. Includes diesel rural multiplication factor of 7.

Source: TAGG (2013b).

For the purposes of calculation, the diesel emissions factor of 2.7 tonnes CO₂-e/kL of diesel was assumed. This is comparable for calculations of diesel emissions from the ATAP PV2 fuel

conversion factors which were calculated and estimated to be 2.681 kg CO₂-e/L diesel for a heavy truck.

Table C 2 summaries the construction and maintenance phase emissions modelled.

Table C 2: Construction and maintenance phase emissions modelled assumptions

Scenario	Construction emissions (tonnes CO ₂ -e per lane.km)	Scope of maintenance	Maintenance emissions (tonnes CO ₂ -e per lane.km)
U1A	20.76165	50 mm surfacing. Asphalt mill and replace.	3.1941
U1B	22.3587	50 mm surfacing. Asphalt mill and replace.	3.1941
U2A	22.3587	50 mm dense asphalt mill and replace.	3.1941
U2B	22.3587	50 mm dense asphalt mill and replace.	3.1941
U3A	3.1941	30 mm OGA with crumb. Same with construction.	3.1941
U3B	3.1941	30 mm OGA. Same with construction.	3.1941
R1A	1.157625	12 mm Single/single (HSS1) CRM reseal. Same with construction.	1.157625
R1B	1.157625	12 mm Single/single (HSS1) PMB reseal. Same with construction.	1.157625
R2A	2.31525	15 mm Double/double (HSS2) CRM reseal. Same with construction.	2.31525
R2B	2.31525	15 mm Double/double (HSS2) PMB reseal. Same with construction.	2.31525
R3A – low construction emissions	12.7764	SAM Double Seal.	2.31525
R3B – low construction	12.7764	SAM Double Seal.	2.31525
R3A – high construction emissions	19.1646	SAM Double Seal.	2.31525
R3B – high construction	19.1646	SAM Double Seal.	2.31525
R4A – low construction	17.56755	50 mm mill and replace surface layer.	3.1941
R4B – low construction	19.1646	50 mm mill and replace surface layer.	3.1941
R4A – high construction	23.95575	50 mm mill and replace surface layer.	3.1941
R4B – high construction	25.5528	50 mm mill and replace surface layer.	3.1941
R5A	8.5995	15 mm Double/double (HSS2) PMB reseal.	2.31525
R5B (base case common to 5,6,7)	8.5995	15 mm Double/double (HSS2) PMB reseal.	2.31525
R6A	8.5995	15 mm Double/double (HSS2) PMB reseal.	2.31525
R7A	8.5995	15 mm Double/double (HSS2) PMB reseal.	2.31525

Due to uncertainty in the number of processes for foam bitumen stabilisation or cement stabilisation, scenario R3 and R4, low and high construction estimates are provided. For the purposes of modelling the base case, the high estimates input into the model are indicative of processes required to achieve high construction standards.

In the future if estimates for construction equipment (months) used or kL of fuel for construction are available, then the estimates may be done in more detail and using emissions factors provided in the *Greenhouse Gas Workbook* for Australia.

C.1.4 Maintenance Emissions

In the model, the maintenance scope is defined by specifying which layer and the layer thickness that is removed and how much of each layer is replaced. It is assumed that the maintenance layers are replaced like for like. There may be multiple maintenance interventions over the 40-year time period. The model assumes that each maintenance intervention is identical. Modelling also allows for full rehabilitation required within the 40-year period e.g. flooding scenarios.

Initial modelling assumed that all sprayed seals underwent a maintenance every 12 years, and every asphalt resurfacing underwent replacement every 16 years. This is in alignment with the survey results.

The diesel emissions factor of 2.7 tonnes CO₂-e/kL of diesel was assumed and was consistent with the construction emissions. It is assumed that the diesel emissions factor remained unchanged over the 40 years.

C.1.5 Use Phase Emissions

The use phase emissions were calculated using the PLCC model and the ATAP PV2 fuel emissions calculator model developed.

Key inputs into the use phase emissions modelling included:

- maintenance frequency information – surface performance for each pavement design;
- road traffic information e.g. AADT per lane-km, percentage of heavy vehicles and traffic growth rate
- pavement design: pavement layer materials, pavement thickness and pavement design life;
- climatic zone assumptions.

Outputs from the PLCC model were input into the 'Fuel model' to get GHG estimates. Results were then inserted into the 'GHG Summary' model and these included:

- maintenance years (assumption);
- roughness for each year (output from PLCC model);
- AADT for each year (based on pavement design and assuming a 2.5% growth factor); and
- total emissions for each year (output from Fuel model calculations).

The use phase modelling allowed for a sensitivity analysis where the per cent of use phase emissions reduction may be input each year. This functionality was used for the modelling of electric vehicles powered by renewables.

C.1.6 Haulage Emissions

Materials haulage emissions are the emissions associated with the transport of materials from source to site. Haulage emissions were assumed average for a whole pavement layer rather than by material type. Separate haulage distances were specified for construction, maintenance and disposal.

The calculation for transport emissions are as per Equation A3:

$$\text{Transport emission (tonnes CO}_2\text{e)} = \text{emission factor (tonnes CO}_2\text{e.ton.km)} * \text{mass (tonnes)} * \text{distance (km)} \quad \text{A3}$$

Emissions factors for materials haulage was adopted from the ISCA materials calculator. Refer to Appendix A.8 for transport emissions by vehicle type. Drop-down options were provided in the

'GHG Summary' Excel model to select the most appropriate transport vehicle. The ISCA emissions factor includes the return haul distance in their emissions factors.

TMR survey results were used to inform a range of haulage modelling assumptions (Appendix C.4). The type of truck selected for use in the model was based on survey results. The majority of respondents selected a heavy truck. Thus 'articulated truck', was used as a standard drop-down selection in the model. Table C 3 summarises the haulage distance assumptions used in the modelling.

Table C 3: Standard haulage distance assumptions – urban and rural road

Life-cycle phase	Urban road	Rural road
Haulage – binder, asphalt, surfacing aggregate	25 km	100 km
Haulage of excavated waste material	25 km	25 km

C.1.7 Disposal and End of Life

The end-of-life life-cycle emissions was determined by specifying at each maintenance cycle what fraction of the pavement layer goes to landfill.

Estimates of percentage of materials that go to disposal were informed by the TMR survey results. The majority of respondents either selected 10–20% disposal or 80–90% disposal of pavements. For purposes of modelling the assumptions in Table C 4 are stated.

Table C 4: Per cent assumed to go to landfill

Scenario	Scope of maintenance	Fraction to landfill
U1A: EME 2 base layer	50 mm re-surfacing. Asphalt mill and replace.	50%
U1B: Dense graded asphalt	50 mm re-surfacing. Asphalt mill and replace.	50%
U2A: Dense graded asphalt with RAP	50 mm re-surfacing dense asphalt mill and replace.	20%
U2B: Dense graded asphalt without RAP	50 mm re-surfacing dense asphalt mill and replace.	100%
U3A: Surfacing – OGA with crumb rubber modified binder	30 mm Open graded asphalt (OG10 with C170/crumb rubber binder)	20%
U3B: Surfacing – Open graded asphalt with A15E binder	30 mm Open graded asphalt (OG10 with A15E binder)	20%
R1A: Sprayed seal alt case CRM binder (lower traffic)	Single/single (HSS1) CRM reseal (14 mm aggregate)	0% (seal over existing)
R1B: Sprayed seal base case (lower traffic)	Single/single (HSS1) PMB reseal (14 mm aggregate)	0% (seal over existing)
R2A: Sprayed seal alt case CRM binder (higher traffic)	Double/double (HSS2) CRM reseal (14/7mm aggregate)	0% (seal over existing)
R2B: Sprayed seal base case (higher traffic)	Double/double (HSS2) PMB reseal (14/7mm aggregate)	0% (seal over existing)
R3A: FBS alt case (low/med traffic)	SAM seal (double/double 14/7)	0% (seal over existing)
R3B: CTB base case (low/med traffic)	SAM seal (double/double 14/7)	0% (seal over existing)
R4A: FBS alt case (high traffic)	AC14 or AC20 surface layer. 50 mm mill and replace	50%
R4B: CTB base case (high traffic)	AC14 or AC20 surface layer. 50 mm mill and replace	50%
R5A: Marginal materials – ridge gravel	Double/double (HSS2) PMB reseal (14/7mm aggregate)	0% (seal over existing)
R5B: (Base case common to 5A, 6A and 7A)	Double/double (HSS2) PMB reseal (14/7mm aggregate)	0% (seal over existing)
R6A: MGB Poorly drained wet	Double/double (HSS2) PMB reseal (14/7mm aggregate)	0% (seal over existing)
R7A: SGB Poorly drained wet	Double/double (HSS2) PMB reseal (14/7mm aggregate)	0% (seal over existing)

It was assumed that all pavement disposal emissions could be regarded as inert construction and demolition waste and thus an emissions factor of zero was adopted. Landfill management emissions were excluded from calculations. If it was not disposed – then it was assumed to have gone for recycling or reuse (e.g. RAP). New sprayed seals were assumed to go on top of old spray sealed with none of the existing layer going to disposal. Estimates of materials tonnage for disposal fed into transport to disposal calculations and disposal cost estimates for each year of maintenance.

C.2 ARBB PLCC Model – Maintenance and Use Phase

ARRB have developed a deterministic Pavement Life-Cycle Costing (PLCC) analysis tool which provides inputs for the determination of whole-of-life-cycle costing. The PLCC tool is Microsoft Excel-based. The tool can be used to examine and/or compare different pavement designs over homogenous one-kilometre lengths of road. Intervention levels for roughness, rutting, cracking and strength can be assigned in order to trigger maintenance and rehabilitation works. Intervention levels were set in the model based on those used in common practice by road agencies.

The key inputs used in the model, based on the pavement designs are summarised in Table C 5.

Table C 5: Key inputs for the ARRB PLCC model

Information source	Inputs	Description
Pavement design information	Road class	
	Pavement type	
	Asphalt thickness	
	Granular thickness	
	Design life	
	Pavement design traffic – Equivalent Standard Axles (ESA)	
	California Bearing Ratio (CBR)	
Assumed	Climate zone	Urban – South-East Qld (Brisbane) - Thornthwaite Moisture Index 35 - Minimum Average Monthly Temperature 8 °C - Maximum Average Monthly Temperature 17.5 °C Rural – Central West Qld (Barcaldine) - Thornthwaite Moisture Index –50 - Minimum Average Monthly Temperature 17 °C - Maximum Average Monthly Temperature 25 °C
	Roughness	1.2 (new road) 2 (reclaimed asphalt pavement)
	Rutting	0
	Cracking	0
	Traffic growth rate	2.5% per annum
Calculated	Daily SARs	$\text{Daily SARs} = \frac{\text{MESA}}{365}$ $\text{MESA}^4 = \text{ESA} * \text{CGF}$ $\text{CGF} = (1.025^{\text{design life}} - 1) / (\text{traffic growth rate})$
	Structural number (SN)	See Section C.2.1.

⁴ MESA = Millions of Standard Axles per lane per year.

C.2.1 Calculation of the Structural Number

A key input into the PLCC model is the structural number of the pavement design.

The concept of structural number was first introduced as a result of the AASTHO Road Test as a measure of overall pavement strength (AASTHO 1972). It is essentially a measure of the total thickness of the road pavement weighted according to the 'strength' of each layer and calculated using Equation A4:

$$SN = \sum_{i=1}^n a_i h_i \quad A4$$

where

SN = structural number of the pavement

n = number of pavement layers

a_i = strength coefficient of the i th layer

h_i = thickness of the i th layer, in inches

Pavement/subgrade strength, SNC_0 , is related to the annual traffic load capacity of the pavement, in terms of millions of equivalent standard axles per lane per year (MESA), over its design life. Examination of the LTPP database for arterial road sites enabled the development of an empirical relationship between the initial modified structural number, SNC_0 , immediately post construction at zero pavement age and the cumulative traffic load capacity, CAP, based on an annual traffic load, MESA, over a design life of 30 years at an annual growth rate of 2.5%. Values of SNC_i were estimated from the maximum deflection, D_0 , measured by a falling weight deflectometer (FWD) and back-calculated using a SNC_i deterioration relationship to estimate SNC_0 .

The relationship of the initial modified structural number, SNC_0 , with the cumulative traffic load capacity of the pavement, CAP, is calculated using Equation A5 (Martin & Choummavong 2018):

$$SNC_0 = 1.128 * CAP^{0.1033} \quad A5$$

where

CAP = design traffic load capacity in equivalent standard axles (ESAs) over a defined service life (years)

The modified structural numbers used in the modelling are summarised in Table C 6: . A higher structural number is indicative of a more durable pavement and subject to the traffic loading task.

Table C 6: Structural numbers used in modelling

Pavement design No.	Modified structural number SNC_0
U1	10.4
U2 & U3	8.4
R2 & R4	8.4
R1 & R3	4.7
R5B	4.7
R5A	4.2

C.3 ATAP PV2 Model – Use Phase

Calculation of road vehicle fuel consumption over the road life-cycle is based on ATAP PV2 Road Parameter Values uninterrupted flow fuel consumption regression model.

In the ATAP guide, the simplified model was developed by employing the ARRB Australianised HDM-4 VOC models to generate estimates of fuel consumption for a wide range of vehicles and operating conditions. This data was used as input for developing multiple regression equations (Australian Transport Assessment and Planning Steering Committee 2016).

The following regression equation (Equation A6) was adopted for the purposes of modelling fuel emissions:

$$\text{Fuel Consumption (litres/km)} = \text{BaseFuel} * (k_1 + \frac{k_2}{V} + k_3 * V^2 + k_4 * \text{IRI} + k_5 * \text{GVM}) \quad \text{A6}$$

where

BaseFuel = Lowest fuel consumption point in curve from raw HDM-4 output

V = Vehicle speed in km/h

IRI = International Roughness Index in m/km

GVM = Gross vehicle mass in tonnes

k₁ to k₅ = model coefficients

C.3.1 Model Coefficients

The ATAP PV2 report provides a range of model coefficients (*k₁* to *k₅*) (see Appendix E) for 15 different curvature and slope road scenarios. A sensitivity analysis was done across a range of curvature and elevation scenarios.

C.3.2 Vehicle Speed

The velocity assumed on the road was as per design road speeds. It should be noted that motorways typically have a proposed speed limit of between 80 km/hr and 110 km/hr. High speed rural roads typically have a proposed speed limit of 100–110 km/hr and urban arterial and sub-arterial roads have a proposed speed limit of 60–80km/hr. The ATAP PV2 model is sensitive to road speeds assumed in the model. It should be noted that this is not a dynamic model where speeds are adjusted to roughness. Thus, a sensitivity on posted speeds is done in Appendix E.2. Table C 7 summarises road design speeds assumed for the different scenarios.

Table C 7: Speed, AADT and percentage heavy vehicles assumed for each pavement design scenario

Scenario	NACoE technology description	Road class	AADT per lane.km	% Heavy vehicles	Road speed (km/h)
U1	EME2	Urban motorway	28 207	5	90
U2	RAP	Urban arterial	6 507	5	70
U3	Crumb rubber asphalt	Urban road or major rural road	6 507	5	90
R1	Crumb rubber S/S	Rural main road (lower traffic)	250	10	90
R2	Crumb rubber D/D	Rural main road (higher traffic)	7 489	10	90

R3	FBS (low)	Rural main road (lower traffic)	166	15	90
R4	FBS (high)	Rural main road (higher traffic)	7 489	10	90
R5	Non-standard granular materials – ridge gravel	Rural main road (lower traffic)	125	20	90
R6	Marginal Materials – MGB Poorly drained wet	Rural main road (lower traffic)	125	20	90
R7	Marginal Materials – SGB Poorly drained wet	Rural main road (lower traffic)	125	20	90

C.3.3 IRI Values

The evaluations of IRI values were derived from the PLCC modelling as input into the ATAP PV2 regression equation. For all pavements, a newly constructed pavement was assumed to have an IRI of 1.8 m/km.

C.3.4 GVM

Table 24 of the ATAP PV2 guidelines provides Gross Combined Mass (GCM) (tonnes) information for each corresponding vehicle type. It was assumed that gross vehicle mass (GVM) and GCM were equivalent for the purpose of modelling and that vehicles were 75% loaded. Table C 9: summarises the assumed unadjusted GVM used as input for the purposes of modelling.

C.3.5 Greenhouse Warming Potential

GHG emissions refer to the release of GHGs into the atmosphere. The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) has limited the number of GHGs that are reportable. These include (TAGG 2013a):

- Carbon dioxide (CO₂);
- Methane (CH₄);
- Nitrous oxide (N₂O);
- Sulphur hexafluoride (SF₆);
- Hydrofluorocarbons (HFCs);
- Perfluorocarbons (PFCs).

The global warming potential (GWP) is a calculation of how much a particular GHG contributes to global warming. The standard used to calculate carbon-dioxide equivalents is 100 years. For example, one tonne of methane in the air has the same effect as 12 tonnes of carbon dioxide over a 100-year time frame, or 1 tonne of CH₄ is equivalent to 12 CO₂-e.

Only carbon dioxide, methane and nitrous oxides were modelled. The global warming potential for identified GHGs is assumed based on the IPCC 5th assessment report as show in Table C 8.

Table C 8: Global warming potential of modelled greenhouse gases

Common name	Chemical formula	GWP values
Carbon dioxide	CO ₂	1
Methane	CH ₄	28
Nitrous oxide	N ₂ O	265

Source: Greenhouse Gas Protocol (2014).

C.3.6 Conversion of Fuel to CO₂-e

A regression equation was used to calculate fuel consumption litres/100 km for each vehicle class. This was then adjusted to get fuel consumption per 1 km.

Emission factors for each vehicle, fuel type and emission type were sourced from Appendix B of the ATAP Guideline (Australian Transport Assessment and Planning Steering Committee 2016). This included carbon dioxide, methane and nitrous oxide emission factors (g/L) for petrol and diesel. The global warming potentials (Table C 8) were then used to calculate the CO₂-e GWP for each GHG emission type. In the model, petrol fuel was assumed for all passenger vehicles. Trucks and buses were all assumed to be diesel except the 4WD mid-sized petrol light commercial vehicle. Emission factors were based on an average for all years of manufacture for that vehicle and fuel type.

Table C 9: Vehicle assumptions – GVM and fuel type

Vehicle type	GVM (tonnes)	Vehicle category	Fuel type assumption	CO ₂ -e kg/100 km
01. Small Car	1.2	Passenger Car	Petrol	19.2
02. Medium Car	1.4	Passenger Car	Petrol	21.9
03. Large Car	1.6	Passenger Car	Petrol	26.2
04. Courier Van-Utility	2.15	Light Commercial Vehicles	Diesel	25.7
05. 4WD Mid-Size Petrol	2.73	Light Commercial Vehicles	Petrol	28.7
06. Light Rigid	3.75	Light Commercial Vehicles	Diesel	35.9
07. Medium Rigid	10.4	Medium Truck	Diesel	53.6
08. Heavy Rigid	22.5	Medium Truck	Diesel	93.2
09. Heavy Bus	19	Buses	Diesel	77.5
10. Artic 4 Axle	31.5	Heavy Trucks	Diesel	132.7
11. Artic 5 Axle	39	Heavy Trucks	Diesel	140.2
12. Artic 6 Axle	42.5	Heavy Trucks	Diesel	150.1
13. Rigid + 5 Axle Dog	59	Heavy Trucks	Diesel	173.2
14. B-Double	62.5	Heavy Trucks	Diesel	182.3
15. Twin steer + 5 Axle Dog	64	Heavy Trucks	Diesel	182.8
16. A-Double	79	Heavy Trucks	Diesel	205.3
17. B Triple	82.5	Heavy Trucks	Diesel	212.7
18. A B Combination	99	Heavy Trucks	Diesel	234.2
19. A-Triple	115.5	Heavy Trucks	Diesel	256.9
20. Double B-Double	119	Heavy Trucks	Diesel	264.4

C.3.7 AADT

The AADT for traffic was a key input into the model. The outputs from the PLCC modelling were used as inputs into the ATAP PV2 modelling, including assumptions for AADT growth factors. A 2.5% growth factor was adopted. The AADT was back-calculated from SNC₀ and axle loads, in terms of equivalent standard axle (ESAs). On urban roads AADT levels were divided by 2 to indicate the distribution of traffic between 2 lanes. It should be noted that there may be different AADT distributions between lanes and AADT growth distributions between urban and rural roads and different districts. A 2.5% annual growth factor results in approximately 7% higher use phase emissions over 40 years compared to a 2.19% annual average growth factor for Qld. In the future, as required, a sensitivity analysis on the growth factor may be done.

C.3.8 Vehicle Usage Distributions

Vehicle usage distributions for the AADT figures were based on the Australian Bureau of Statistics (ABS) Survey of vehicle use ended June 2018 (Table C 10). The vehicle use distributions in the model were assumed based on Table C 11. It assumed a simple distribution of vehicle proportion between vehicle classes and excluded motorbikes. Non-freight carrying trucks were considered a rigid truck in the allocation between vehicle classes. The model allows for a drop-down menu to select the road location (capital city, other urban area and other area) and thus the corresponding vehicle distribution for the purposes of calculation.

Table C 10: The Australian Bureau of Statistics survey of vehicle use Survey of Motor Vehicle Use, Australia, 12 months ended 30 June 2018

Queensland	Capital city (million)	% of vehicles	Other urban areas (million)	% of vehicles	Other areas (million)	% of vehicles
Passenger vehicles	16 939	73.4%	10 607	66.6%	7 277	53.5%
Motorcycles	307	1.3%	145	0.9%	99	0.7%
Light commercial vehicles	4 216	18.3%	3 863	24.3%	4 624	34.0%
Rigid trucks	1 018	4.4%	834	5.2%	639	4.7%
Articulated trucks	316	1.4%	262	1.6%	830	6.1%
Non-freight carrying trucks	41	0.2%	28	0.8%	22	0.2%
Buses	241	1.0%	184	1.6%	98	0.7%
Total	23 077	100%	15 922	100%	13 589	100%

Source: The Australian Bureau of Statistics survey of vehicle use Survey of Motor Vehicle Use, Australia, 12 months ended 30 June 2018 (ABS 2019).

Table C 11: Vehicle use distributions – modelling assumptions for different roads – ABS data

Vehicle type	Vehicle Category	Capital City Road AADT weighting (%)	Other Urban Areas AADT weighting (%)	Other Areas AADT weighting (%)
01. Small Car	Passenger Car	24.797	22.410	17.981
02. Medium Car	Passenger Car	24.797	22.410	17.981
03. Large Car	Passenger Car	24.797	22.410	17.981
04. Courier Van-Utility	Light Commercial Vehicles	6.172	8.162	11.426
05. 4WD Mid-Size Petrol	Light Commercial Vehicles	6.172	8.162	11.426
06. Light Rigid	Light Commercial Vehicles	6.172	8.162	11.426
07. Medium Rigid	Medium Truck	2.325	2.732	2.450
08. Heavy Rigid	Medium Truck	2.325	2.732	2.450
09. Heavy Bus	Buses	1.058	1.166	0.726
10. Artic 4 Axle	Heavy Trucks	0.126	0.151	0.559
11. Artic 5 Axle	Heavy Trucks	0.126	0.151	0.559
12. Artic 6 Axle	Heavy Trucks	0.126	0.151	0.559
13. Rigid + 5 Axle Dog	Heavy Trucks	0.126	0.151	0.559
14. B-Double	Heavy Trucks	0.126	0.151	0.559
15. Twin steer + 5 Axle Dog	Heavy Trucks	0.126	0.151	0.559
16. A-Double	Heavy Trucks	0.126	0.151	0.559

17. B Triple	Heavy Trucks	0.126	0.151	0.559
18. A B Combination	Heavy Trucks	0.126	0.151	0.559
19. A-Triple	Heavy Trucks	0.126	0.151	0.559
20. Double B-Double	Heavy Trucks	0.126	0.151	0.559
Total		100.00	100.00	100.00

Alternative tables were also derived to account for scenarios with a higher percentage of heavy vehicles and so that use phase modelling was in alignment with PLCC modelling. This was derived by assuming that passenger vehicles were directly displaced by heavy vehicles in terms of simplifying modelling assumptions. The distribution of vehicles is provided in Table C 12: for these categories (i.e. urban, rural and remote rural).

Table C 12: Vehicle use distributions – modelling assumptions for different roads – ABS data adjusted for more heavy vehicles

Vehicle type	Vehicle category	Urban – 5% HV AADT weighting (%)	Rural – 10% HV AADT weighting (%)	Rural – 15% HV AADT weighting (%)	Remote Rural – 20% HV AADT weighting (%)
01. Small Car	Passenger Car	23.593	16.699	15.032	13.365
02. Medium Car	Passenger Car	23.593	16.699	15.032	13.365
03. Large Car	Passenger Car	23.593	16.699	15.032	13.365
04. Courier Van-Utility	Light Commercial Vehicles	6.172	11.426	11.426	11.426
05. 4WD Mid-Size Petrol	Light Commercial Vehicles	6.172	11.426	11.426	11.426
06. Light Rigid	Light Commercial Vehicles	6.172	11.426	11.426	11.426
07. Medium Rigid	Medium Truck	2.325	2.450	2.450	2.450
08. Heavy Rigid	Medium Truck	2.325	2.450	2.450	2.450
09. Heavy Bus	Buses	1.058	0.726	0.726	0.726
10. Artic 4 Axle	Heavy Trucks	0.455	0.909	1.364	1.818
11. Artic 5 Axle	Heavy Trucks	0.455	0.909	1.364	1.818
12. Artic 6 Axle	Heavy Trucks	0.455	0.909	1.364	1.818
13. Rigid + 5 Axle Dog	Heavy Trucks	0.455	0.909	1.364	1.818
14. B-Double	Heavy Trucks	0.455	0.909	1.364	1.818
15. Twin steer + 5 Axle Dog	Heavy Trucks	0.455	0.909	1.364	1.818
16. A-Double	Heavy Trucks	0.455	0.909	1.364	1.818
17. B Triple	Heavy Trucks	0.455	0.909	1.364	1.818
18. A B Combination	Heavy Trucks	0.455	0.909	1.364	1.818
19. A-Triple	Heavy Trucks	0.455	0.909	1.364	1.818
20. Double B-Double	Heavy Trucks	0.455	0.909	1.364	1.818
Total		100.00	100.000	100.000	100.00

Total effective use phase emissions per km were calculated as a function of the weighted average of the AADT allocations by vehicle category multiplied by the road AADT.

C.4 TMR Survey

A survey was distributed to pavement asset managers in the 12 TMR districts to obtain and validate assumptions in the modelling of pavements over their life-cycle. The survey was distributed via survey monkey, as shown in Appendix C.4.1. The survey was distributed via TMR (the cover email is provided in Appendix E.1) to pavement asset managers on the 29th April 2019 and respondents were given until the 10th May 2019 to return the survey. The districts that responded included: Northern, Mackay/Whitsunday, South Coast region, Central West and Northwest. The results obtained from survey monkey are provided in Appendix C.4.2.

C.4.1 Survey Monkey

NACoE Project P106 'Assessing the Environmental Benefits of the NACoE Program' is currently being undertaken by ARRB in order to assess the environmental outcomes which can be achieved by using alternate pavement technologies.

Earlier NACoE research identified a number of pavement technologies as having significant potential benefits in greenhouse gas reduction. These technologies include: EME2, Reclaimed Asphalt Pavement (RAP), Crumb Rubber Modified Binders/Asphalt (CRMB/CRMA), Stabilisation Practices (including Foam Bitumen), and Non-Standard Granular Materials.

ARRB has invited you to complete the following survey. The results will help clarify and inform critical elements of the research and deliver accurate whole of life (construction, transport, maintenance, use and decommissioning) environmental costs of different innovative pavement types.

We request that you complete and submit one response by 10 May 2019.

OK

1. Please enter your information

Name	
Position	
District (current)	
Phone	
Email	

2. Of the pavement technologies being researched in this project, which do you have experience with using in your district? (Select all relevant technologies)

- | | |
|--|---|
| ☐ Crumb Rubber Modified Binders / Asphalt (CRMB / CRMA) | ☐ Stabilisation (Foam Bitumen) |
| ☐ Reclaimed Asphalt Pavement (RAP) | ☐ Stabilisation (Bitumen) |
| ☐ EME2 | ☐ Stabilisation (Lime) |
| ☐ Standard Granular Materials | ☐ Stabilisation (Cement) |
| ☐ Non-Standard Granular Materials | |

3. Surfacing Life: What is the expected service life (in years) of different Sprayed Seal surfacing?
(Select one for each type or if other, enter a response below)

	<7 years	7-8 years	9-12 years	12-16 years	>16 years
Single/Single (initial/reseal) Straight run and cutback binders	☒	☒	☒	☒	☒
Single/Single (initial/reseal) Polymer modified binders (PMB)	☐	☐	☐	☐	☐
Single/Single (initial/reseal) Crumb rubber modified binders (CRMB)	☒	☒	☒	☒	☒
Double/Double (initial/reseal) Straight run and cutback binders	☐	☐	☐	☐	☐
Double/Double (initial/reseal) Polymer modified binders (PMB)	☒	☒	☒	☒	☒
Double/Double (initial/reseal) Crumb rubber modified binders (CRMB)	☐	☐	☐	☐	☐
Other	☒	☒	☒	☒	☒

If other has been selected, please indicate the sprayed seal surface type:

4. Surfacing Life: What is the expected service life (in years) of different Asphalt Surfaces? (Select one for each type or if other, enter a response below)

	<10 years	10-13 years	14-17 years	17-20 years	>20 years
Dense graded asphalt	☒	☒	☒	☒	☒
Dense graded asphalt with RAP	☐	☐	☐	☐	☐
Open graded asphalt with PMB	☒	☒	☒	☒	☒
Open graded asphalt with CRMB	☐	☐	☐	☐	☐
Other	☒	☒	☒	☒	☒

If other has been selected, please indicate the asphalt surface type:

5. Haulage Distances: What is a typical haulage distance of binder to site? (Select one, enter any comment in 'Comments' where relevant)

Comment

6. Haulage Distances: What is a typical haulage distance of surfacing aggregate to site? (Select one, enter any comment in 'Comments' where relevant)

Comment

7. Haulage Distances: What is a typical haulage distance of asphalt to site? (Select one, enter any comment in 'Comments' where relevant)

Comment

8. Haulage Distances: What is a typical distance from a typical granular road base (type 3) material source to site? (Select one, enter any comment in 'Comments' where relevant)

Comment

9. Materials transportation: Which of the following vehicles are used to transport Bitumen or Binders?

- ☐ Light truck (3.5 – 16t average gross mass)
- ☐ Medium truck (16 – 28t average gross mass)
- ☐ Heavy truck (>28t average gross mass)

Other (please specify) / Comment (if applicable)

10. Materials transportation: Which of the following vehicles are used to transport Asphalt, Aggregate or Road Base products?

- ☐ Light truck (3.5 – 16t average gross mass)
- ☐ Medium truck (16 – 28t average gross mass)
- ☐ Heavy truck (>28t average gross mass)

Other (please specify) / Comment (if applicable)

11. Materials disposal: During construction/maintenance (including rehabilitation) - what percentage of excavated waste material from existing formations goes to disposal?

0% 50% 100%



12. Materials disposal: During construction/maintenance (including rehabilitation) - what are the typical haulage distances of excavated waste material from existing formations to disposal?

Comment

13. Use of marginal or non-standard materials: How often does your maintenance program use marginal materials?

In some cases, it may be preferable to use marginal or non-standard materials which can be sourced locally rather than hauling superior materials over long distances. Marginal, or non-standard granular materials are materials that may be sourced locally to avoid transporting superior (standard) materials over longer distances.

- ☐ Common practice (>50%) ☐ Rarely (<10%)
☐ Often (20-50%) ☐ Never
☐ Occasionally (10-20%)

If marginal materials are used, what is the general traffic design loading (design load refers to the load distribution, or combination of loads, for which a structure is designed) of the roads they are used on?

14. Do you have any other comments or feedback on these topics?

C.4.2 Survey Results

Five TMR districts (Northern, Mackay/Whitsunday, South Coast region, Central West and Northwest) responded to the survey. Survey results are presented in the following tables:

Table C 13: Pavement technologies used by the survey respondents (Question 2)

Pavement technology use by districts	Number of survey respondents
Crumb Rubber Modified Binders/Asphalt (CRMB/CRMA)	1
Reclaimed Asphalt Pavement (RAP)	3
High Modulus Asphalt (EME2)	1
Standard Granular Materials	6
Non-Standard Granular and Marginal Materials	3
Stabilisation (Foam Bitumen)	5
Stabilisation (Bitumen)	0
Stabilisation (Lime)	3
Stabilisation (Cement)	6

Table C 14: Expected service life of sprayed sealing (Question 3)

Expected service life	Number of Survey Respondents					
	Single/Single (initial/reseal) Straight run and cutback binders	Single/Single (initial/reseal) Polymer modified binders (PMB)	Single/Single (initial/reseal) Crumb rubber modified binders (CRMB)	Double/Double (initial/reseal) Straight run and cutback binders	Double/Double (initial/reseal) Polymer modified binders (PMB)	Double/Double (initial/reseal) Crumb rubber modified binders (CRMB)
< 7 years	3	0	0	2	0	0
7–8 years	2	3	1	1	1	0
9–12 years	2	4	1	3	5	2
12–16 years	0	0	0	0	0	0
> 16 years	0	0	0	0	0	0

Table C 15: Expected service life of asphalt (Question 4)

Expected service life	Number of survey respondents			
	Dense graded asphalt	Dense graded asphalt with RAP	Open graded asphalt with PMB	Open graded asphalt with CRMB
< 10 years	0	1	4	1
10–13 years	3	0	2	1
14–17 years	4	2	0	0
17–20 years	0	0	0	0
> 20 years	0	0	0	0

Table C 16: Typical haulage distances (Question 5, 6, 7, 8, and 12)

Haulage distance	Number of survey respondents
------------------	------------------------------

	Binder	Surfacing aggregate	Asphalt	Typical granular road base (type 3)	Excavated waste material
Less than 10 km	0	0	0	0	1
10–30 km	0	1	3	1	3
30–50 km	1	1	0	2	1
50–70 km	0	1	1	1	1
70–100 km	1	0	0	1	0
100 km+	4	3	2	1	0

Table C 17: Materials transportation (Question 9 and 10)

Type of vehicle used	Number of survey respondents	
	Bitumen and binders	Asphalt, aggregate or road base products
Light truck (3.5–16 t average gross mass)	0	0
Medium truck (16–28 t average gross mass)	2	2
Heavy truck (> 28 t average gross mass)	5	5

Table C 18: Excavated waste material (Question 11)

Percentage of excavated waste material from existing formations going to disposal	Number of survey respondents
0–10%	2
10–20%	0
20–30%	1
30–40%	0
40–50%	0
50–60%	0
60–70%	0
70–80%	0
80–90%	2
90–100%	0

Table C 19: Use of marginal materials (Question 13)

Use of marginal materials in maintenance program	Number of survey respondents
Never	1
Rarely (< 10%)	2
Occasionally (10–20%)	1
Often (20–50%)	0
Common practice (> 50%)	1

C.5 TMR Workshop

On 23 May 2019, ARRB facilitated a workshop at the Mary Street TMR offices in Brisbane. In this workshop, ARRB sought input from TMR practitioners to validate the modelling assumptions and results for the GHG emissions component of the project.

Workshop attendees included the ARRB and TMR project teams and members of the E&T, PIP and TSAM teams in TMR.

The workshop consisted of the following activities:

- introduction and overview of NACoE Program;
- workshop purpose, project objectives, scope and activities;
- life-cycle analysis and modelling approach;
- design summary and example results;
- preliminary results and conclusions;
- review and validation of modelling and key assumptions;
- recommendations for integrating findings into TMR.

Workshop attendees provided advice on modelling sections of this project (including assumptions and scenarios) and on ways to integrate the findings into TMR practice. Modelling advice included:

- Ensure that haulage distances are confirmed with the districts (this was done by the survey).
- Clearly identify key research outcomes in the final report, including that the greatest environmental savings will be from use phase emission reductions, reduction of waste to landfill, etc.
- Highlight additional benefits that align with broader government objectives, such as waste deferral, job creation.
- Note that durability would be a major selling point for NACoE pavement technologies; however, long-term performance evidence is not currently available.
- Consider which pavement technologies are suitable for recycling at the end of their operating lives (i.e. consider circular economy impacts).

Advice on integrating the findings included:

- Develop a short, accessible summary document to capture the research findings aimed at a broad, time-poor audience forming a cheat sheet for emissions reductions. Include infographics.
- Provide ISCA an overview of this research to assist with the further development of the ISCA metrics.
- Share project findings with both TMR and ISCA via a webinar published on the NACoE website.
- Recommend possible changes to the non-price-related selection criteria for designing pavements in TMR. Bids on big projects to include traditional and alternative options.
- Encourage improvement to environmental reporting, including materials haulage, to assist with data collection for further studies.

C.6 Cost Benefit Analysis Model

The purpose of the CBA model was to assess the GHG costs and benefits of each of the respective pavement technologies compared to typical base case pavements. The key CBA assumptions include:

- appraisal in real terms rather than nominal terms
- base case real discount rate of 7% and sensitivity analysis at 4% and 10% real discount rate
- evaluation period of 40 years (consistent with similar international examples)
- asset residual value proportional to the IRI in year 40 compared to a terminal IRI value
- all extraction and processing emissions and construction emissions and costs occur in year 0
- during maintenance and disposal phases the emissions and costs occur in the year of maintenance
- the absence of any further policy interventions or major technological changes e.g. changes in travel behaviour, fuel emissions standards etc.

The CBA model used was consistent with the methodologies used by TMR in Queensland.

C.6.1 Metrics Calculated

Outputs from the CBA include a calculation of Net Present Values (NPVs) for each NACoE pavement technology as measured against comparable traditional pavements. The results include NPVs based on:

- economic and environmental costs and benefits
- environmental benefits (i.e. GHG savings) only.

Results were subjected to a sensitivity analysis on the discount rate and the carbon price (Appendix E.8).

C.6.2 Benefits

Life-cycle benefits of the NACoE pavements include reduced environmental externalities in terms of greenhouse gases, measured as carbon dioxide equivalent (CO₂-e). An environmental benefit occurs where the life-cycle GHG emissions from the NACoE pavement technology is less than those from the comparable base case pavement. This represents a GHG (or carbon) saving.

This benefit can be monetised (in dollar terms) by applying a price on the tonnes of carbon saved. This can be referred to as emissions cost savings.

Over the 40-year assessment period, emissions cost savings are presented as discounted net present values⁵.

This research did not specifically assess other potential externality benefits including reduced fuel use, noise and water and other air pollutants, and notes that further research could be done to assess these. Additionally, RUCs were not included in the CBA modelling scope; however, there is an expectation that if NACoE pavements deliver improved pavement performance (as they are designed to do), there will be RUC savings.

⁵ Discounting determines present value (in today's dollars) of costs or savings that will be realised in the future.

C.6.3 Price of Carbon

The carbon price used in the CBA Model is based on the medium (or central) price estimate (AUD\$/tonne CO₂-e) as presented in the unpublished ATAP Guidance Document for Valuing Carbon Emissions (ATAP 2019). The ATAP guidance document derives high, medium and low carbon price estimates based on a range of Australian and comparable international values and methods for deriving social cost of carbon methods (methods include the damage cost avoided approach, market prices of carbon and abatement cost methods), noting the inherent levels of uncertainty in these values and methods.

Table C 20 presents the ATAP carbon price estimates (in 2017 dollars) and the adjusted prices for December 2018 (adjusted using the ABS's CPI inflation calculator).

Table C 20: Carbon price (AUD \$/tonne CO₂-e)

Carbon (AUD \$/tonne CO ₂ -e)	Low	Medium	High
2017	\$12	\$30	\$48
2018	\$12.22	\$30.57	\$48.91
Estimate source	Australian Government's 'Emissions Reduction Fund' (ERF) approach.	Department of Treasury, who nominally set the tax.	Australianised adaptation of carbon value estimated using a mitigation cost.

Factors that may affect future carbon prices include strictness of emission standards (upwards pressure on the carbon price) and user behaviour such as changes in vehicle technology, fuel type use of public transport and active travel (downwards pressure on the carbon price). It is possible that both price pressures work together. As such, the modelling has assumed that the carbon price remains constant for the duration of the assessment.

The modelling undertook a sensitivity analysis to explore the range of carbon prices from low, medium and high. Results are presented in Appendix E.8.

C.6.4 Costs

The CBA Model includes the following life-cycle costs:

- pavement construction costs and residual asset value;
- pavement maintenance cost;
- materials haulage costs;
- materials disposal costs.

The modelling excluded costs that are common to both the base cases and the NACoE technology alternative cases. The excluded common costs included: land clearing, land acquisition, project construction and design contingencies, project management and other professional services, etc. Routine annual pavement maintenance costs were also excluded as they are assumed similar across comparable pavements.

Costs may be variable between locations reflecting site specific factors. Cost estimates were informed by and benchmarked against a range of sources as outlined in Appendix A.9.

Modelled cost assumptions – construction and maintenance

Previous work by ARRB (Roper & Toole 2014) derived an equation (Equation A7) that estimates typical rehabilitation costs based on the modified structural number, SNC.

$$\text{Pavement construction cost} = 10.129 * e^{0.3459 \text{ SNC}} \quad \text{A7}$$

Initial construction costs were assumed as equivalent to rehabilitation costs, because rehabilitation involves the replacement of the entire pavement. This study is only concerned with pavement cost components and does not include other road construction elements such as earthworks, bridges, lighting and signalling, etc.

Table C 21 summarises the construction and maintenance costs used in the CBA Model. Construction costs were based on the initial construction scope and calculated using Equation A7. Maintenance costs were based on specified maintenance scope modelled and ARRB estimates developed in 2014 (Roper & Toole 2014). Crumb rubber was considered as a modified binder surface.

All costs are expressed in December 2018 dollars.

Table C 21: Model assumptions – construction and maintenance costs Dec 2018 values

ID	SNC	Construction costs		Resurfacing costs		Surface designs – used to select cost information
		(\$/sq. m)	(\$/lane-km)	(\$/sq. m)	(\$/lane-km)	
U1	10.40	\$398.34	\$1 394 197	\$30.17	\$105 585	50 mm dense graded asphalt w/out modified binder
U2	8.40	\$199.44	\$698 039	\$33.40	\$116 898	50 mm dense graded asphalt w/modified binder
U3	–	\$20.04	\$70 139	\$20.04	\$70 139	30 mm open graded asphalt w/modified binder
R1	–	\$9.70	\$33 938	\$9.70	\$33 938	Modified single seal
R2	–	\$19.39	\$67 876	\$19.39	\$67 876	Modified double seal
R3	4.70	\$55.46	\$194 114	\$19.39	\$67 876	Modified double seal
R4	8.40	\$199.44	\$698 039	\$33.40	\$116 898	50 mm dense graded asphalt w/modified binder
R5B	4.50	\$51.75	\$181 139	\$19.39	\$67 876	Modified double seal
R5A	4.20	\$46.65	\$163 285	\$19.39	\$67 876	Modified double seal
R6A	4.20	\$46.65	\$163 285	\$19.39	\$67 876	Modified double seal
R7A	4.20	\$46.65	\$163 285	\$19.39	\$67 876	Modified double seal

Costs presented in Table C 21 were verified against comparable benchmark data and are considered representative for Australia and sufficiently accurate for modelling purposes.

Residual asset value

Residual asset value was determined based on the remaining asset performance. The residual value of pavement assets which were replaced during the project life was determined as follows:

- Calculating the proportionate loss in the value of the pavement and surfacing components from the time of replacement to the end of the analysis period (40 years) based on a common initial roughness and a common terminal roughness for the pavement structural layers above subgrade.
- Determining the financial value of both components at the end of the analysis period.

- Entering the residual value as a negative capital cost in the economic analysis in the final year of analysis (year 40) in the construction cost line item.

For the purposes of modelling, the IRI value, which initiates rehabilitation, for all pavements was assumed to be 4.2. Note that different regions may have different levels that trigger maintenance and/or rehabilitation treatments.

Disposal costs

Disposal costs are both project and site-specific. To inform a single assumed disposal cost value, a range of benchmark costs were assessed. These benchmark costs are provided in Appendix A.9 as considerations, however, they were not used.

The below table presents assumptions used in the modelling.

Table C 22: Model assumptions for disposal costs

Model assumption	Cost value	Source of data
Disposal cost – urban	\$100/tonne	(GCCC 2018)
Disposal cost – rural	\$120/tonne commercial waste	(MRC 2019)

Source: GCCC (2018) & MRC (2019).

The cost benefit analysis did not account for costs savings from land-fill diversion of recycled materials used in production of crumb rubber and RAP.

From 1 July 2019, a levy zone will also be applicable for most of Queensland's disposal of commercial waste (Queensland Government 2019b). The levy is intended to reduce the amount of waste generated, grow the resource recovery and recycling industry and create new jobs. For Construction and Demolition (C&D) waste the applicable levy is \$75/tonne (Queensland Government 2019b). The waste levy for all classifications is proposed to increase by \$5 on 1 July each year (Queensland Government 2019b). The levy is applicable for most of the East coast of Queensland. Many of the marginal materials used are applicable in Western Queensland and thus the levy was not modelled for marginal materials.

Modelling assumes a constant disposal fee plus annual and escalating levy annually.

Tyres are considered a category 2 waste and subject to a category 2 levy. The disposal cost of tyres is provided for information only but was not used to quantify co-benefits of diversions of tyres away from landfill.

Haulage costs

Haulage costs were based on information sourced and provided by TMR on 20 June 2019. A haulage cost of 30c per tonne.km was assumed in the model. This is indicative of RoadTek Cairns, haulage rates.

APPENDIX D DETAILED RESULTS

Table D 1 provides detailed results for each of the technologies evaluated.

Table D 1: Emissions modelling results – total emissions [tonnes CO₂-e/lane.km – 40 years] (U1B, U1A, U2B, U2A, U3B, U3A)

Life-cycle Stage	Pavement No.	U1B	U1A	U2B	U2A	U3B	U3A
	Pavement Name	U1B: Dense graded asphalt	U1A: EME2 high modulus asphalt	U2B: Dense graded asphalt without RAP	U2A: Dense graded asphalt with RAP	U3B: Surfacing – Open graded asphalt with A15E binder	U3A: Surfacing – OGA with crumb rubber modified binder
Extraction and Production	Embodied Energy – Construction	112.37	108.73	94.60	89.30	7.76	7.92
	Embodied Energy – Maintenance	34.58	34.58	34.74	32.66	15.52	15.84
Construction	Construction – Equipment Emissions	22.36	20.76	22.36	22.36	3.19	3.19
	Construction – Haulage Emissions	27.17	24.56	8.07	8.07	0.40	0.40
Use Phase	Use Phase – Vehicles	244 084.66	244 084.66	49 388.68	49 388.68	56 799.66	56 799.66
Maintenance	Maintenance – Equipment Emissions	6.39	6.39	6.39	6.39	6.39	6.39
	Maintenance – Haulage Emissions	4.40	4.40	1.47	1.47	0.79	0.79
End-of-Life	End-of-Life	–	–	–	–	–	–
	Material Haulage – to Landfill	2.20	2.20	1.47	0.29	0.16	0.16
Total Life-cycle Emissions		244 294.13	244 286.29	49 557.77	49 549.22	56 833.87	56 834.35

Table D 2: Emissions modelling results – total emissions [tonnes CO₂-e/lane.km – 40 years] (R1B, R1A, R2B, R2A, R3B, R3A)

Life-cycle Stage	Pavement No.	R1B	R1A	R2B	R2A	R3B	R3A
	Pavement Name	R1B: Sprayed seal base case (lower traffic)	R1A: Sprayed seal alt case CRM binder (lower traffic)	R2B: Sprayed seal base case (higher traffic)	R2A: Sprayed seal alt case CRM binder (higher traffic)	R3B: CTB Base Case (low/med traffic)	R3A: FBS Alt Case (low/med traffic)
Extraction and Production	Embodied Energy – Construction	4.05	3.77	6.17	5.53	73.12	81.44
	Embodied Energy – Maintenance	12.16	11.32	18.52	13.28	18.46	18.46
Construction	Construction – Equipment Emissions	1.16	1.16	2.32	2.32	19.16	19.16
	Construction – Haulage Emissions	0.63	0.62	0.77	0.77	3.74	3.42
Use	Use Phase – Vehicles	2 780.46	2 780.46	83 286.29	83 286.29	2 197.54	2 197.54
Maintenance	Maintenance – Equipment Emissions	3.47	3.47	6.95	6.95	6.95	6.95
	Maintenance – Haulage Emissions	1.89	1.87	2.31	1.84	2.31	2.31
End-of-Life	End-of-Life	–	–	–	–	–	–
	Material Haulage – to Landfill	–	–	–	–	–	–
Total Life-cycle Emissions		2 803.83	2 802.67	83 323.32	83 316.96	2 321.28	2 329.28

Table D 3: Emissions modelling results – total emissions [tonnes CO₂-e/lane.km – 40 years] (R4B, R4A, R5(6&7)B, R5A, R6A, R7A)

Life-cycle Stage	Pavement No.	R4B	R4A	5,6,7B	R5A	R6A	R7A
	Pavement Name	R4B: CTB Base Case (high traffic)	R4A: FBS Alt Case (high traffic)	R5B: Marginal Materials – Base Case	R5A: Marginal Materials – ridge gravel	R5A: Marginal Materials – MGB Poorly drained Wet	R5A: Marginal Materials – SGB Poorly drained Wet
Extraction and Production	Embodied Energy – Construction	124.30	118.40	12.03	6.15	24.61	11.32
	Embodied Energy – Maintenance	27.11	27.11	18.46	18.46	–	11.32
Construction	Construction – Equipment Emissions	25.55	23.96	8.60	8.60	34.40	17.20
	Construction – Haulage Emissions	13.75	10.21	9.25	2.47	9.87	4.93
Use	Use Phase – Vehicles	83 270.74	83 270.74	2 613.63	2 617.04	2 620.41	2 607.18
Maintenance	Maintenance – Equipment Emissions	6.39	6.39	6.95	6.95	–	4.63
	Maintenance – Haulage Emissions	5.87	5.87	2.31	2.31	–	1.54
End-of-Life	End-of-Life	–	–	–	–	–	–
	Material Haulage – to Landfill	0.73	0.73	–	–	–	–
Total Life-cycle Emissions		83 474.44	83 463.40	2 671.23	2 661.97	2 689.28	2 658.13

Table D 4: Emissions modelling results – emissions savings [tonnes CO₂-e/lane.km – 40 years] NACoE technologies U1 to R7

Life-cycle Stage	CBA Scenario	U1	U2	U3	R1	R2	R3	R4	R5	R6	R7
	Pavement Name	U1A: EME2 high modulus asphalt	U2A: Dense graded asphalt with RAP	U3A: Surfacing – OGA with crumb rubber modified binder	R1A: Sprayed seal alt case CRM binder (lower traffic)	R2A: Sprayed seal alt case CRM binder (higher traffic)	R3A: FBS alt case (low/med traffic)	R4A: FBS alt case (high traffic)	R5A: Marginal materials – ridge gravel	R5A: Marginal materials – MGB poorly drained wet	R5A: Marginal materials – SGB poorly drained wet
Extraction and Production		-3.64	-7.37	0.48	-1.13	-5.87	8.32	-5.90	-5.88	-5.88	-7.84
Road Equipment		-1.60	–	–	–	–	–	-1.60	–	18.85	6.28
Use – Vehicles		–	–	–	–	–	–	–	3.40	6.78	-6.46
End-of-Life		–	–	–	–	–	–	–	–	–	–
Total Materials Haulage		-2.60	-1.17	–	-0.02	-0.48	-0.32	-3.54	-6.78	-1.70	-5.09
TOTAL		-7.84	-8.55	0.48	-1.16	-6.36	8.00	-11.04	-9.26	18.05	-13.10

Table D 5: Cost benefit analysis results [\$ /lane.km – 40 years]

Financial Ratio	CBA Scenario	U1	U2	U3	R1	R2	R3	R4	R5	R6	R7
	Pavement Name	U1A: EME2 high modulus asphalt	U2A: Dense graded asphalt with RAP	U3A: Surfacing – OGA with crumb rubber modified binder	R1A: Sprayed seal alt case CRM binder (lower traffic)	R2A: Sprayed seal alt case CRM binder (higher traffic)	R3A: FBS alt case (low/med traffic)	R4A: FBS alt case (high traffic)	R5A: Marginal materials – ridge gravel	R5A: Marginal materials – MGB poorly drained wet	R5A: Marginal materials – SGB poorly drained wet
Total NPV	4%	3 849	77 601	-9	77	951	6 974	21 635	46 430.58	-68 947.00	6 412.00
	7%	3 849	41 919	-7	59	570	6 974	21 635	46 448.32	-16 323.19	26 197.59
	10%	3 849	24 050	-6	49	371	6 974	21 635	46 456.21	9 384.88	36 016.23
Marginal BCR	4%	-0	-0	N/A	-0	-0	0	-0	-0.01	-0.00	-0.05
	7%	-0	-0	N/A	-0	-0	0	-0	-0.01	0.01	-0.01
	10%	-0	-0	N/A	-0	-0	0	-0	-0.01	-0.02	-0.01

Financial Ratio	CBA Scenario	U1	U2	U3	R1	R2	R3	R4	R5	R6	R7
	Pavement Name	U1A: EME2 high modulus asphalt	U2A: Dense graded asphalt with RAP	U3A: Surfacing – OGA with crumb rubber modified binder	R1A: Sprayed seal alt case CRM binder (lower traffic)	R2A: Sprayed seal alt case CRM binder (higher traffic)	R3A: FBS alt case (low/med traffic)	R4A: FBS alt case (high traffic)	R5A: Marginal materials – ridge gravel	R5A: Marginal materials – MGB poorly drained wet	R5A: Marginal materials – SGB poorly drained wet
NPV Carbon	4%	240	203	–9	20	93	–245	337	352.18	–56.77	307.21
	7%	240	184	–7	15	62	–245	337	369.93	101.42	319.72
	10%	240	175	–6	13	46	–245	337	377.82	190.94	340.60

APPENDIX E SENSITIVITY AND SCENARIO ANALYSIS

Scenario and sensitivity analysis was done for:

- AA: Embodied Carbon – Crumb Rubber Haulage Distances Sensitivity (Appendix E.1);
- BB: Use Phase Emissions – Roughness and Speed Scenarios (Appendix E.2);
- CC: Use Phase Emissions – Curvature and Elevation Scenarios (Appendix E.3);
- DD: Use Phase Vehicle Operating Costs – Roughness and Speed Scenarios (Appendix E.4);
- EE: Whole-of-Life Resilience – Flooding Scenarios for Foam Bitumen Stabilisation (Appendix E.5);
- FF: Use Phase Emissions – Electric Vehicles Uptake Scenario (Appendix E.6);
- GG: Haulage Distances – Base Case vs Local Marginal Materials (Appendix E.7); and
- HH: Cost Benefit Analysis – Carbon Price and Discount Rates (Appendix E.8).

The following sections discuss the key assumptions, modelling and results for these sensitivity and scenario analyses.

E.1 AA: Embodied Carbon Crumb Rubber Haulage Sensitivity

E.1.1 Context

Technologies such as crumb rubber or other recycled materials have the potential to reduce the GHG footprint through the use of low embodied carbon of the materials compared to the extraction of virgin materials. This is particularly the case if their manufacture processes are powered by renewable electricity. It also allows for the incorporation of a waste stream in the road construction and saving raw materials from disposal in landfill. The crumb rubber embodied carbon factor estimate did not incorporate haulage into the embodied carbon value.

Indicative haulage distances were derived based on TMR registers of approved suppliers and Google maps of known quarries as well as TMR survey results (Appendix C.4). In rural areas in particular, large haulage distances may result in the haulage emissions outweighing potential savings from the embodied carbon of materials. In rural areas haulage distances may easily be greater than 25 km and in some cases hundreds of kilometres. Similarly, the cost of haulage of recycled materials over long distances may result in low carbon pavement technology or recycle pavement material options being uncompetitive or cost prohibitive compared to traditional pavements.

E.1.2 Sensitivity Analysis

It is assumed that in an urban context, virgin and recycled materials may be sourced relatively closely to the construction site. Thus, a sensitivity analysis was done on the haulage distances of rural pavement technology options. Crumb rubber technologies were evaluated.

The embodied energy savings from the use of crumb rubber were used to calculate the equivalent haulage distance of the rubber component where the embodied carbon savings equalled zero.

E.1.3 Results

Table E 1 summarises the results from the initial modelling for the crumb rubber (CR) technologies.

Table E 1: Summary of results – sensitivity analysis AA

Design	U3	R1	R2
NACoE alternative technology	U3A Crumb rubber – rural	R1A. Single/Single reseal (HSS1) with crumb rubber modified binder	R2A. Double/Double reseal (HSS2) with crumb rubber modified binder, Unbound granular base.
Base case technology	U3B: Open graded asphalt with A15E binder	R1B: Polymer modified binder reseal, Unbound granular base	R2B: Polymer modified binder reseal, Unbound granular base.
Road type	Urban road	Rural main road – lower traffic	Rural main road – higher traffic
Embodied carbon savings – surface layer (tonnes CO ₂ -e/ lane.km)	-0.16	0.28	0.64
Mass crumb rubber – surface layer (tonnes CR per lane.km)	2.38	1.17	1.75
Additional haulage distance where benefit offset (km)	N/A	3360.2	5055.0

Assuming transport produces 0.000072088 tonnes CO₂-e per tonne-km (ISCA 2019c), the savings in embodied carbon may be offset from the additional haulage cost of crumb rubber between 3360 km and 5055 km haulage distance. It is possible to haul tyres for processing and/or crumb rubber over long distances to construction sites and still achieve a net embodied carbon reduction (tonnes CO₂-e) compared to a traditional pavement.

E.1.4 Removing Car Tyres from Landfill Co-benefit

It is difficult to undertake a direct calculation as to the actual number of tyres recycled through use in rubberised binders, as a range of tyre types are processed at shredding and crumbing facilities for various uses, only one of which is for incorporation into binders. Tyre Stewardship Australia has adopted a metric known as the Equivalent Passenger Unit (EPU), which represents an ‘average’ passenger car tyre with a standardised weight of 8 kg at end-of-life (Tyre Stewardship Australia n.d.).

Roughly 70%, or 5.6 kg, of an EPU is rubber and carbon black, and the approximate weight of rubber and carbon black used in a litre of CRM binder is known. It is therefore possible to use binder spray rates for sprayed seals and binder content in asphalt layers to estimate the weight of rubber and carbon black in a lane-km of pavement.

The final NACoE report under project P31/P32 included a calculation of the potential use of crumb rubber in sprayed seals in asphalt in Queensland. Two seal designs were done with low and high traffic scenarios, with 3.5 m lanes and using typical binder spray rates. Allocating the low and high seal designs across the network in a 2/3rd and 1/3rd ratio, an average crumb rubber use was calculated at 146 EPUs/lane-km. TMR’s annual sealing program is typically 3500–4500 lane-km per year, so if all of that length was to shift to using rubberised seals then up to 657 000 EPUs could be recycled into sprayed seals across the TMR network each year.

A similar calculation was made for asphalt surfacing, with higher estimates per lane-km given the greater thickness of these layers. The NACoE report noted that up to 1300 EPUs/lane-km could be used in rubberised asphalt layers using CRM open-graded mixes or CRM asphalt with the dry process. To date, applications for crumb rubber in asphalt have focused on high-performance

surfacing using the wet process, which utilises fewer EPU's but is intended to provide the greatest performance enhancement. However, in the future there is potential to adopt a mix of different rubberised asphalt mixes for various layers and this may help to maximise recycling of rubber. Were the approximately 455 lane-km of resurfaced asphalt each year to incorporate higher percentages of rubber, this would equate to another 588 000 EPU's.

Combined, there is scope for approximately 1.2 million EPU's worth of crumb rubber to be utilised each year across Queensland, although the technology, material supply and expertise to scale up to these amounts would take several years to reach maximum potential. The local road sealing and resurfacing program across Queensland would further enhance the total usage of rubber in roads.

In 2013–14, around 11.4 million EPU's worth of tyres reached end-of-life condition in Queensland, with licensed landfills accounting for around 2 million EPU's worth (Mountjoy, Hasthanayake & Freeman 2015). It is further understood that a significant number of tyres are illegally dumped or are sent overseas for re-treading or energy recovery. It should be noted that the source of tyres for use in crumb rubber is presently focused on truck tyres due to the favourable blend of material in the composition of the tyre.

Utilising 1.2 million EPU's worth of crumb rubber in asphalt and spray seals each year would offset 60% of the total landfill stream for tyres, and although this usage is presently far above current rates, ongoing investment in research into CRM binders will allow Queensland to maximise the potential recycling of this significant waste stream.

E.2 BB: Use Phase Emissions –Roughness and Speed Scenarios

E.2.1 Context

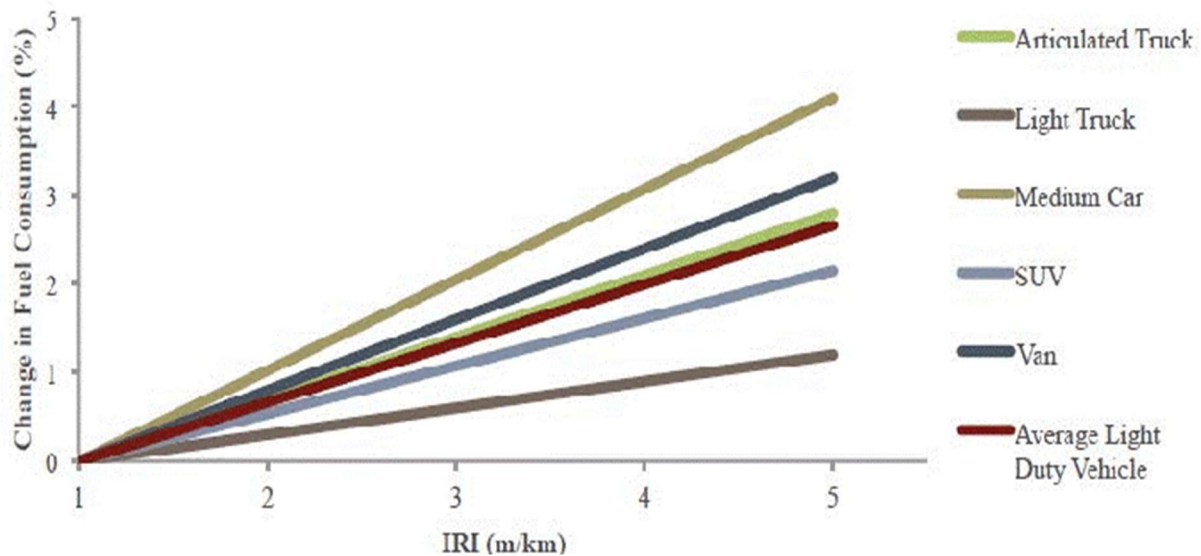
Road transportation vehicles emit a high quantity of GHGs, over 97% of their total life-cycle emissions. Consequently, there is potential to reduce road vehicle emissions through road engineering practices (Zhang 2015).

The surface of a road pavement affects the speed at which a vehicle can travel. Higher road roughness and high travelling speed are both associated with higher vehicle emissions. However, both these two aspects are affected by road maintenance works. A well-maintained road reduces road roughness, although this can cause an increase in traffic speed if a speed limit is not imposed. Poor road maintenance will lead to higher vehicle emissions over time. However, travelling speeds will be lower and the amount of vehicle emissions from poor maintenance will be larger when roughness is high. Considering these effects, Zhang (2015) concluded that a reasonable level of maintenance is the best method for controlling vehicle emissions.

Shahare et al. (2017) undertook a study of the effects of road deterioration on vehicle emissions. This study showed that vehicle emission values can be reduced by almost 10% when a road is properly maintained. The study also found that on roads where the speed limit is 60 km/h or less, the IRI is directly proportional to the emissions the vehicle produces, due to higher fuel consumption. This concurs with Zhang's (2015) study which showed that speed and roughness were the two major factors in fuel consumption.

Figure E 1 provides a description of the effects of road roughness (in IRI) on the fuel consumption of a vehicle by vehicle type. As can be seen from Figure E 1, the results concur with Zhang (2015) & Shahare et al. (2017) in that emissions increase with road roughness. However, this graph also shows that as the size of the vehicle increases, so does the effect of road roughness on fuel consumption.

Figure E 1: Effects of road roughness on fuel consumption



Source: Zaabar & Chatti (2010; cited in Li, Qiao & Yu 2017).

E.2.2 Sensitivity Analysis

A sensitivity analysis was done using the fuel model to explore the relationship between roughness and speed and estimated GHG emissions.

The highest emissions savings from improvements in roughness are potentially realised on the highest design AADT roads. From the designs evaluated, the highest AADT design was associated with high modulus asphalt (EME2). A typical urban motorway in South-East Queensland has 37 500 AADT.

For the purpose of a sensitivity analysis the following assumptions are made:

- a low curvature, flat urban road;
- a design traffic of 37 500 AADT, indicating a high traffic typical urban motorway in South East Queensland (relatively high);
- the AADT vehicle distribution weighting of an 'Other Urban' road as according to the ABS vehicle distributions;
- 0.75 of GMV;
- a road width of 8.5 m (standard regression equation assumption).

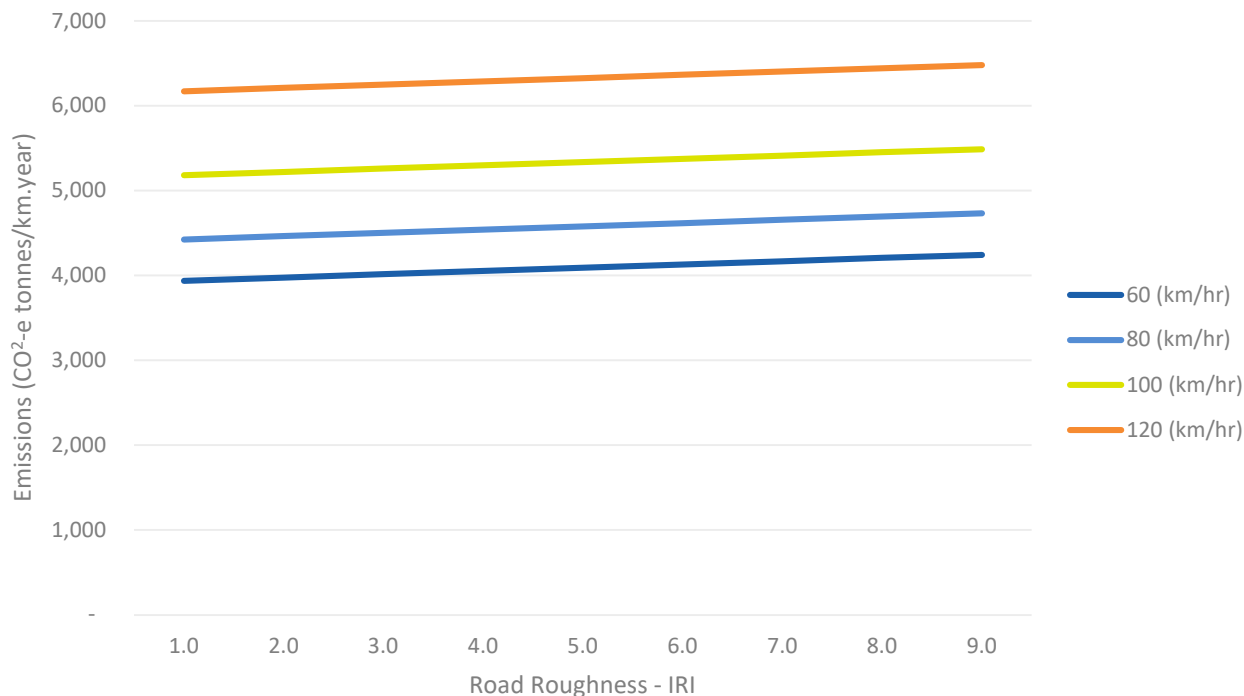
It should be noted that a limitation of the regression equation model is that the model is not dynamic and thus there is an inability to adjust the free flow speed in response to the roughness deterioration. Several free flowing speed levels were therefore simulated:

- 60 km/hour
- 80 km/hour
- 100 km/hour
- 120 km/hour.

It should be noted that different districts may have different asset maintenance initiation triggers for different roads. A range of roughness factors were explored from 1 to 9 – to determine their relative contributions to emissions.

E.2.3 Results

Figure E 2: Emissions at different roughness and speed levels(km/hr), other urban area distribution, AADT = 37 500 urban road



The above chart provides roughness (x-axis) vs road speed (y-axis). As can be seen, the posted speed on the road network has a more significant impact on emissions compared to road roughness. At higher speeds, a marginal increase in free flowing traffic speeds results in higher marginal increase in emissions. The posted speed on the road may have the potential to reduce GHG limits, subject to the safety and economic efficiency costs in doing so. This would particularly be beneficial where roads have the highest percentage of heavy vehicles and high design traffic AADT per lane-km.

In terms of road maintenance, newly constructed roads may be typically constructed to 1.8 IRI. A resurfacing intervention may be at 4.2 IRI. At an assumed 37 500 AADT and a free flowing speed of 100 km/hour, the difference between the emissions at 1.8 IRI and 4.2 IRI may be approximately 64.9 tonnes CO₂-e/year. This is significant compared to emissions associated with U1 maintenance, haulage and embodied carbon from a 50 mm asphalt resurfacing which is approximately 25 tonnes CO₂-e per lane-km per maintenance cycle. At lower AADT per lane.km levels, the effects would be less pronounced and the trade-offs less significant.

E.3 CC: Use Phase – Curvature and Rise/Fall Sensitivity Analysis

E.3.1 Context

The modelling for the use phase emissions assumed a flat and low curvature road. It is likely that the majority of Queensland roads operate under free flowing and low curvature and flat alignment situations. Other factors that affect fuel emissions, and thus also vehicle operating costs, include, but are not limited to, road elevation and road curvature.

The ATAP PV2 guide provides a range of regression model coefficients for various elevation and road curvature scenarios.

E.3.2 Sensitivity Analysis

A sensitivity analysis was done looking at a range of curvature and elevation scenarios. The following parameters were assumed in the model including:

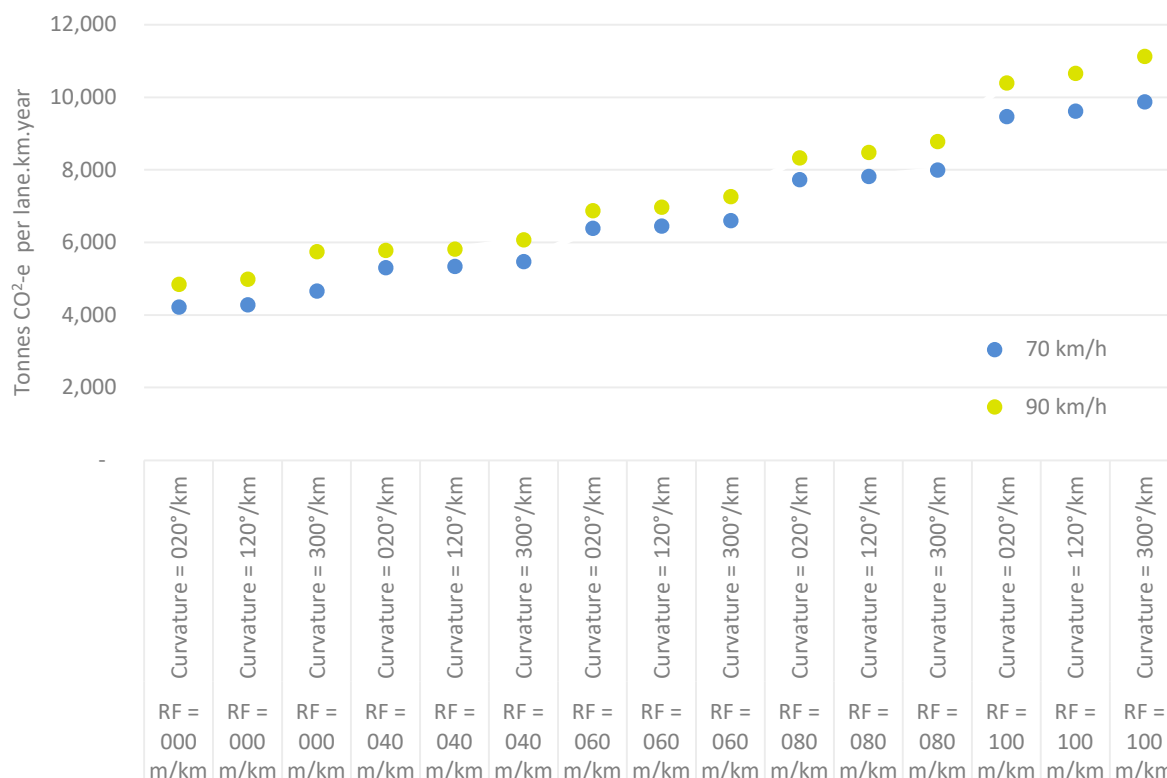
- A roughness of 3 IRI as an average indication of a good performing road surface.
- A design traffic of 37 500 AADT, indicating a high traffic typical urban motorway in South East Queensland (relatively high).
- Fuel type and emissions as per Section 7.3.
- The AADT vehicle distribution weighting of 'Urban with 5% HV' road as according to the vehicle distributions.
- A constant road speed of 90 km/hour and 70 km/hr (note that under high curvature scenarios the design road speeds may in reality drop for safety reasons).
- 0.75 of GMV.
- A road width of 8.5 m (standard regression equation assumption and not a regression equation input). Note that according to ATAP PV2 Table 30, narrower road widths (4.5 m) reduced emissions estimates by a maximum of 22% on flat low curvature roads across vehicle classes due to speed effects. Only marginal differences are seen between road widths in high gradient and high curvature road scenarios. It is assumed that this assumption is suitable for the purposes of this analysis.
- Curvature options ($^{\circ}$ /km): 20 $^{\circ}$ /km; 120 $^{\circ}$ /km; and 300 $^{\circ}$ /km;
- Elevation options RF (m/km): 0; 40; 60; 80; and 100.

E.3.3 Results

Figure E 3 shows a sensitivity of road emissions over a range of curvature and elevation combinations at assumed 70 km/hr and 90 km/hr constant speeds. The elevation has a more significant influence on fuel emissions compared to road curvature. The elevation and curvature have a more significant effect compared to the posted speed. It should be noted that at higher rise/fall and curvatures, speeds may in reality drop for safety or due to engine power limits. It also excludes emissions associated with congestion or lower speeds.

Significant emissions savings could be realised for higher traffic roads. When designing a road alignment for high traffic, a flatter and lower curvature road alignment option could significantly reduce GHG emissions and vehicle operating costs. This, however, would need to be evaluated and compared to the emissions associated with cut and fill during construction. There may also be other factors that constrain the alignment of greenfield or brownfield road corridor, including the vegetation clearing, which would in effect increase the effective road carbon footprint.

Figure E 3: Use phase annual emissions for different curvature and elevation scenarios at constant speeds



E.4 DD: Use Phase Vehicle Operating Costs

E.4.1 Context

RUCs are a key consideration when modelling traffic behaviour and road interventions. It should be noted that RUCs were excluded from the cost benefit analysis scope. Maintenance interventions affecting roughness and free flowing speed have the potential to impact RUCs.

E.4.2 Scenario Analysis

In a similar manner to the fuel consumption model, Table 26 of the ATAP PV guidelines provides coefficients for an uninterrupted (free flow) speed road. Similar inputs include vehicle speed (V), roughness (IRI) and gross vehicle mass (GVM) inputs. A 75% payload is assumed in the regression equation for vehicles. The RUC incorporate costs including fuel, oil, tyres, repairs and maintenance and new vehicles (depreciation).

The following regression equation was adopted:

$$VOC = BaseRUC * (k_1 + \frac{k_2}{V} + k_3 * V^2 + k_4 * IRI + k_5 * IRI^2 + k_6 * GVM) \quad A8$$

where

RUC = road user costs in \$/lane-km

V = vehicle speed in km/h

IRI = International Roughness Index in m/km

GVM = gross vehicle mass in tonnes

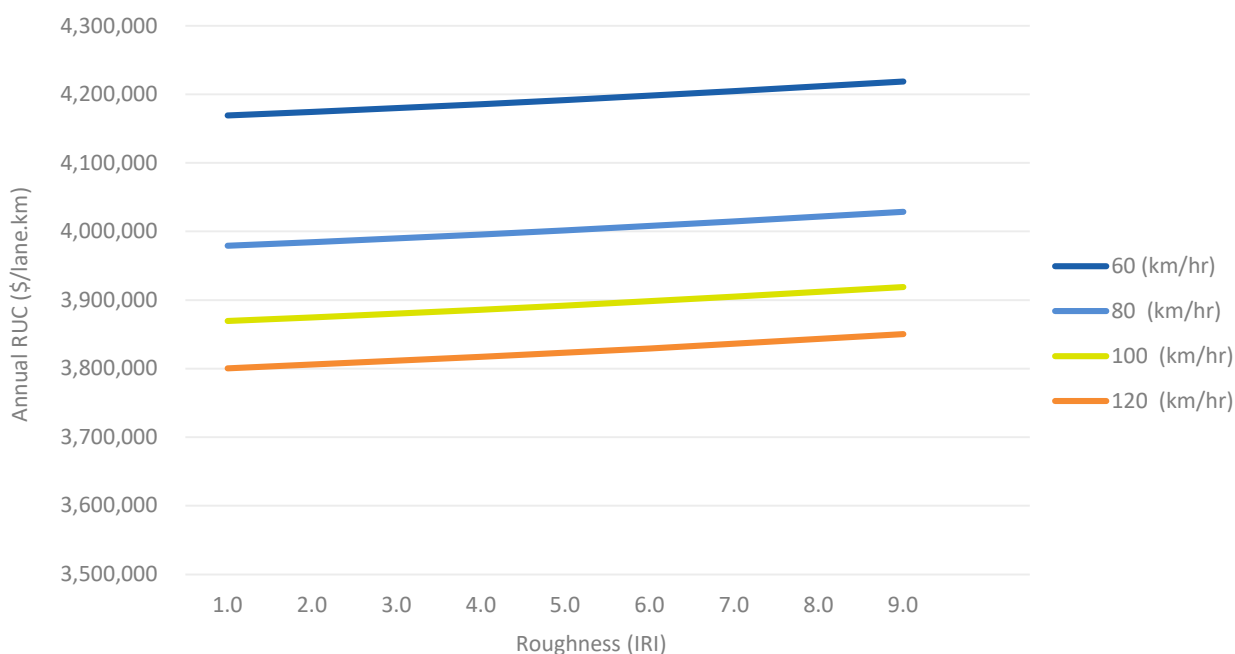
k_1 to k_5 = model coefficients

IRI and GVM assumptions were the same as the above section. It assumes business as usual in terms of vehicle fuels (petrol and diesel) over the life-cycle. A 37 500 AADT urban road was assumed as indicative of the upper end of roughness speed effects.

E.4.3 Results

Figure E 4 compares the RUC for different roughness and speed combinations for a 37 500 AADT per lane road.

Figure E 4: Annual RUC for different roughness and speed levels – flat low curve road, AADT = 37 500



The modelling results suggest that posted speed is a more significant factor compared to road roughness. In terms of roughness, both RUCs and emissions increase linearly with deteriorating roughness. In terms of speed, RUC has an opposite relationship to the fuel emissions per km. A higher speed results in a lower RUC per km, but higher GHG emissions per km. It may be possible to derive an optimal posted speed level when incorporating the cost of carbon into RUCs.

E.5 EE: Pavement Stabilisation – Flood Event Scenarios

E.5.1 Context

Pavement performance of rural road designs may be subject to stresses from locational differences (e.g. low-lying flood prone pavements). Foam bitumen stabilisation is expected to have improved flooding resilience compared to traditional cement stabilised pavements. Improved flood resilience has the potential to achieve GHG savings over the pavement life-cycle.

E.5.2 Scenario Analysis

A scenario analysis was done to evaluate the potential impact of the varying resilience of pavements to flood or pavement inundation shocks. Shocks were introduced in year 10 and in year 30 of the analysis. This resulted in a partial rehabilitation of the pavement. This was done on pavement designs R3 and R4 that are indicative of low/medium and higher traffic designs on rural roads.

Table E 2 highlights the key rehabilitation assumptions made in the scenario analysis.

Table E 2: Scenario Assumptions – Flood Events Scenario EE

	R3B EE: CTB base case (low/med traffic)	R3A EE: FBS alt case (low/med traffic)	R4B EE: CTB base case (high traffic)	R4A EE: FBS alt case (high traffic)
Scope of maintenance	20% of road – major rehabilitation	5% of road – major rehabilitation	20% of road – major rehabilitation	5% of road – major rehabilitation

Modelling assumptions included that following a flooding rehabilitation brings back the IRI to the newly constructed values. Maintenance frequencies were also reset. AADT trends and growth at 2.5% remained.

Vehicle diversions and potential congestion costs associated with a flood event during the use phase were excluded in the calculation of GHGs. It would, however, serve to increase use phase emissions for the low resilience un-stabilised pavements particularly where the network is vulnerable (limited route redundancy), and thus, diversion routes may involve quite long distances.

E.5.3 Results

Figure E 5: Flood scenario results – net emissions (tonnes CO₂-e/lane.km, 40 years) R3 and R4 comparisons

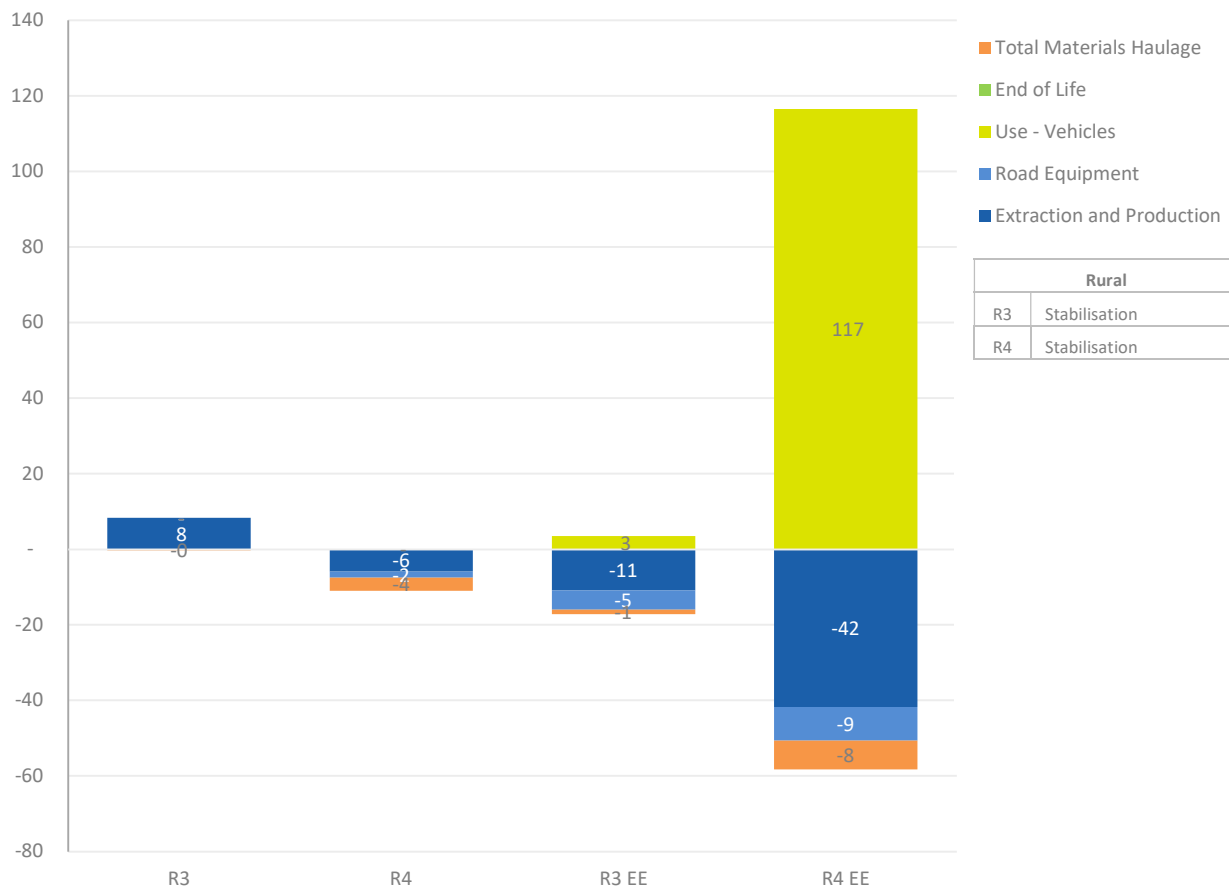


Figure E 5 compares the net emission savings from the use of a foam bitumen stabilised (FBS) layer compared to traditional cement stabilisation. R3 and R4 are the typical pavements, assuming no flood shocks. R3 EE and R44 EE are the pavement scenarios over a whole life-cycle of 40 years with flood shocks. A negative value is indicative of an emission decrease in FBS pavements compared to the base case, while a positive value is a net emissions increase.

Under R3 and R4, it is assumed that the construction and maintenance emissions and road roughness performance are equivalent and thus the key differences are in the embodied carbon of the materials, construction and haulage. For R3, the FBS pavement has more bitumen and lime and is more energy intensive than the cement. Thus, the use of FBS alternative technology compared to traditional technologies results in emissions increases.

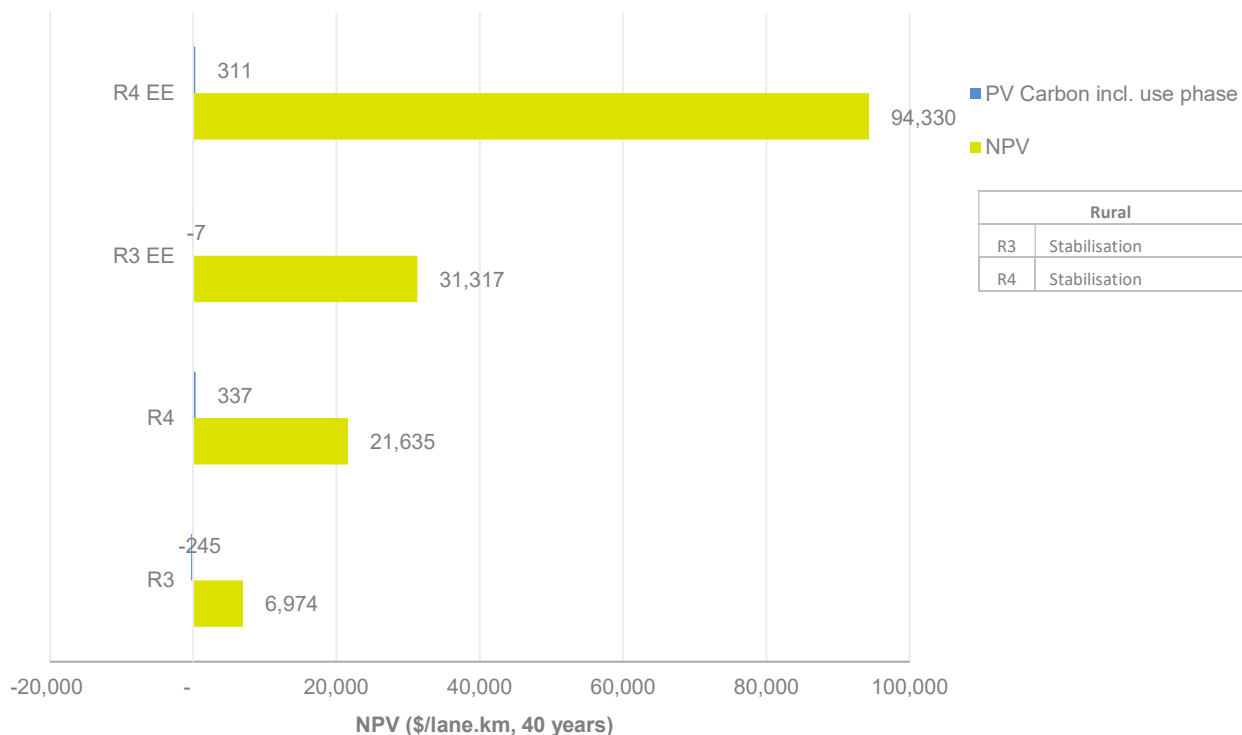
Under R4 the use of FBS is assumed to result in a stiffer base layer requiring less asphalt surfacing. This results in both emissions savings from materials haulage and embodied carbon compared to traditional concrete base stabilisation.

Under R3 EE, a flood scenario shocks the improved resilience of the FBS, and savings in rehabilitation outweighs the embodied carbon differences. There are minor differences in the use phase emissions due to the low traffic levels. The marginally higher use phase emissions are associated with longer intervals between maintenance on FBS roads versus newly constructed cement stabilised roads.

Under R4 EE there are significant savings due to avoided rehabilitation of the FBS sections. This results in reductions in total GHGs from less use of embodied carbon materials, haulage of materials and rehabilitation equipment emissions. At the assumed traffic level, however, there is a more significant increase in use phase emissions compared to the CTB base case. This is because the CTB undergoes rehabilitation which resets and reduces the surface roughness compared to the resilient FBS sections which continue to deteriorate resulting in a use phase emissions effect. The increase in use phase emissions far outweigh any embodied carbon or haulage emissions savings from the increased pavement resilience.

Figure E 6 compares the NPV of just the carbon cost and the total NPV for a scenario with (EE) and without a flood event. The NPV of carbon is only a small component of the total NPV. This is the case for both the with and without flood shock and rehabilitation scenarios. This reflects the sensitivity of the NPV to haulage distances and haulage tonnages, with the cost of carbon being a small overall component of the total NPV.

Figure E 6: Flood scenario results – NPV (\$/lane.km, 40 years) R3 and R4 comparisons



The total NPV of EE scenarios, therefore, also reflect rehabilitation cost savings associated with the more resilient FBS pavement where the avoided rehabilitation costs are a significant component. Between R4 and R4 EE, the NPV of carbon is similar including the use phase. This is due to the construction emissions carbon cost savings being weighted more than future use phase emissions increases over the assessment period.

E.6 FF: Use Phase Emissions – Electric Vehicles Uptake Scenario

E.6.1 Context

Queensland Transport system is rapidly evolving, suggesting that further changes are on the horizon. The CSIRO and Data 61 recently completed a study forecasting Queensland travel demand and transport system characteristic to 2048.

Figure 3.4 provides an overview of the forecasted breakdown of the Queensland fleet. As can be seen in both scenarios, the portion of electric vehicles increases greatly and is the dominant fuel type in the fleet. For a detailed overview of Electric Vehicles projections for Queensland refer to Section 3.4.1.

E.6.2 Sensitivity Analysis

A sensitivity analysis was done to evaluate the potential impacts from the uptake of electric vehicles over time. The scenario analysis was applied across each of the pavement technologies and just for the use phase emissions of road vehicles.

The following assumptions were made:

- No new vehicle emission standards for new petrol and diesel cars – business as usual.
- Electric vehicle uptake on average across all vehicle types.
- 0% renewable powered (e.g. electric) vehicles in 2020, 54% by 2048 with linear average growth. This is an estimated 77% of the fleet renewable by 2060 or an approximate 1.93% increase per year.
- Electric vehicles are 100% powered by renewable sources.

This was done in the GHG summary workbook with the use of a multiplier for each year.

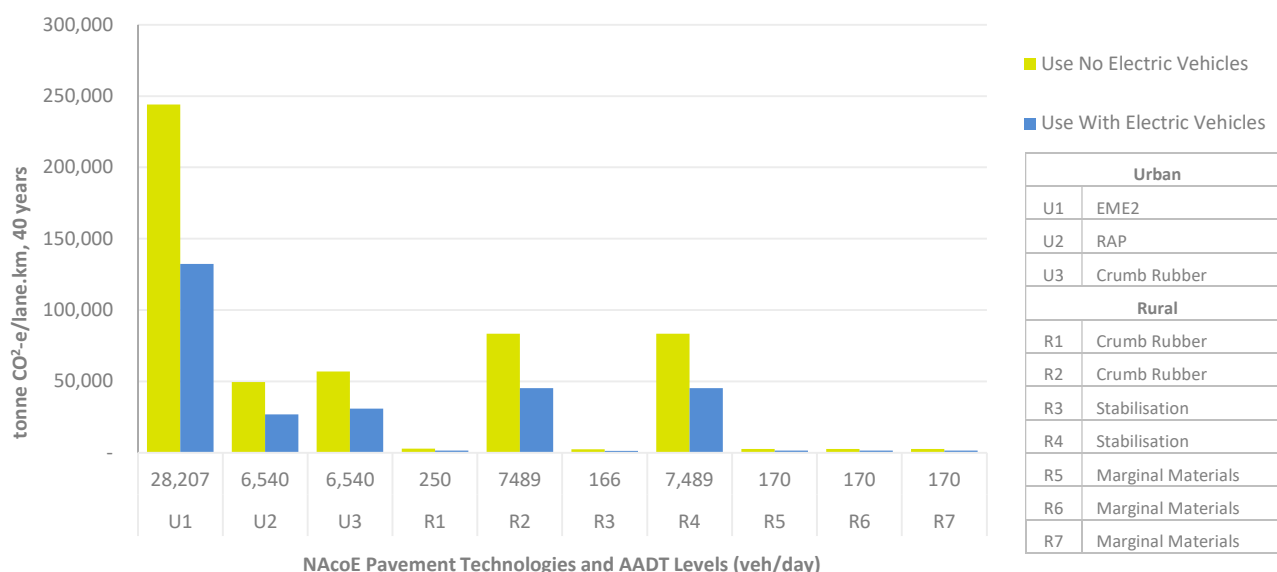
E.6.3 Results

Figure E 7 provides the results for the different traffic scenarios and the use of electric vehicles.

Due to the assumption in the base case vs the alternative case performing similarly, the use phase emissions effects between the NACoE technologies and base case technologies are equivalent except in the case of marginal materials (R5, R6 and R7). Marginal materials, however, have low AADT levels and thus the potential for emissions savings in rural areas are low.

Over all the scenarios, a 45.9% reduction in fuel emissions was realised over 40 years. This is a substantial reduction vs possible savings from pavement technologies through pavement design and construction. The highest benefits may be realised on high traffic roads. Even at low traffic rural roads there is potential for the emissions savings to be far higher than savings in other road life-cycle phases when evaluated over a 40-year period.

Figure E 7: Use phase total emissions (tonne CO₂-e/lane.km, 40 years) – technology comparisons



E.7 GG: Haulage Distances – Base Case vs Local Marginal Materials

E.7.1 Context

In rural areas, the haulage of virgin materials may be cost-prohibitive over long distances. Regions have the option of using lower quality marginal materials for the construction of low traffic urban roads. Marginal materials typically have an embodied carbon value of zero as it is sourced locally as a material with minimal processing. Different materials perform differently over different load conditions and under saturation conditions (Appendix D). The relative performance may therefore be location-specific. It is possible that the cost savings and emissions savings from the use of granular materials are traded off through the sub-optimal performance resulting in more frequent maintenance cycles and more rapid surface deterioration i.e. roughness and rutting.

E.7.2 Sensitivity Analysis

Three marginal materials were explored with NACoE technologies 5A, 6A and 7A. The base case traditional technologies remained common between the three marginal material scenarios.

Sensitivity analyses were done on the haulage distances i.e. 20 km; 100 km; and 200 km for the base case, pavement base layer. The haulage of marginal materials in the base were assumed constant at 20 km. The haulage of the spray seals for the alternative technologies were assumed to vary with the base case i.e. 20 km, 100 km and 200 km.

For the NPV component, consistent with the initial results, a discount rate of 7% and a mid-range cost of carbon of \$30.57 is used.

E.7.3 Results

Figure E 8 – Figure E 11 present the total emissions excluding use phase emissions for marginal materials and the base case. For each technology, as expected, the extraction and production and the road equipment associated with construction and maintenance remain constant while the total haulage emissions change. The base case scenario shows the largest sensitivity in transport haulage emissions due to the haulage of surfacing and base materials. The transport emissions changes associated with marginal materials 5A, 6A and 7A are due to the increased haulage distances of the surfacing layer associated with the D/D seal. The embodied energy of the materials remains the largest per cent of total emissions (excluding use phase). With a haulage distance of 200 km, the emissions associated with the haulage of materials in the base case exceeds road equipment emissions associated with construction and maintenance.

Figure E 8: Marginal materials base case – total emissions (excl. use phase) (tonnes CO₂-e/lane.km, 40 years) – 20 km, 100 km, 200 km sensitivity



Figure E 9: Marginal materials 5A – total emissions (excl. use phase) (tonnes CO₂-e/lane.km, 40 years) – 20 km, 100 km, 200 km sensitivity

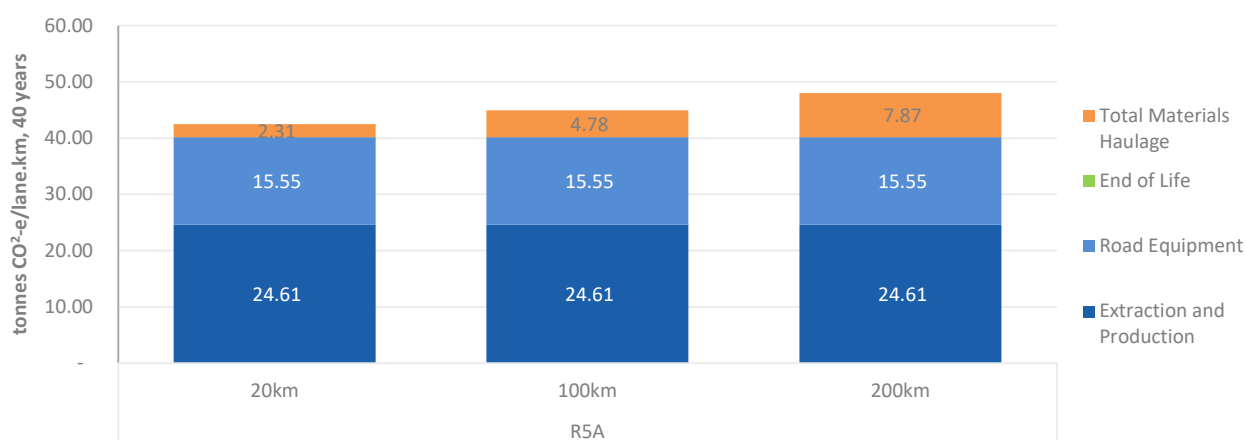


Figure E 10: Marginal materials 6A – total emissions (excl. use phase) (tonnes CO₂-e/lane.km, 40 years) – 20 km, 100 km, 200 km sensitivity

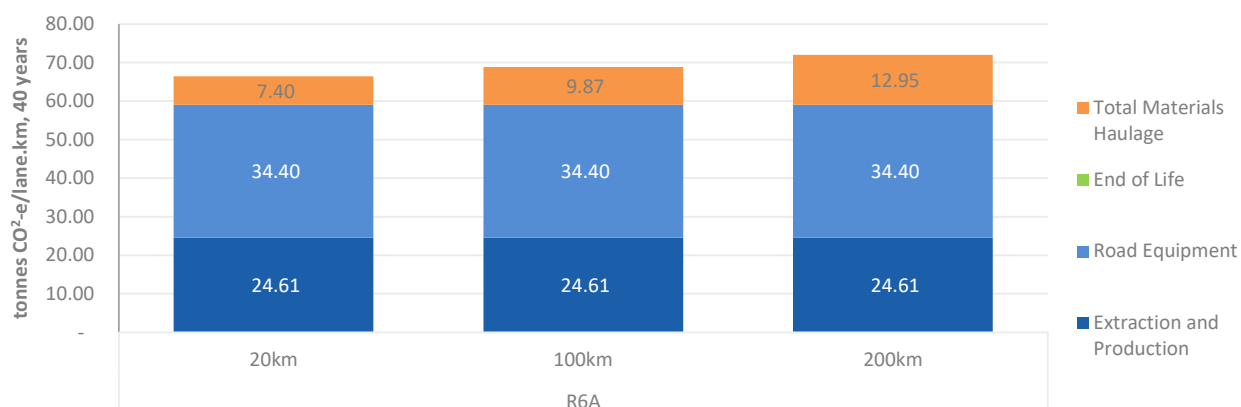


Figure E 11: Marginal materials 7A – total emissions (excl. use phase) (tonnes CO₂-e/lane.km, 40 years) – 20 km, 100 km, 200 km sensitivity

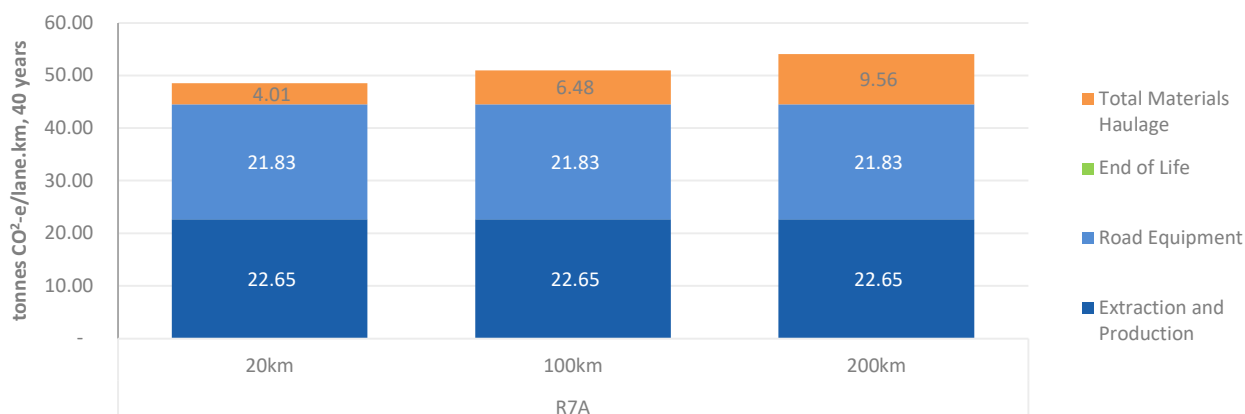
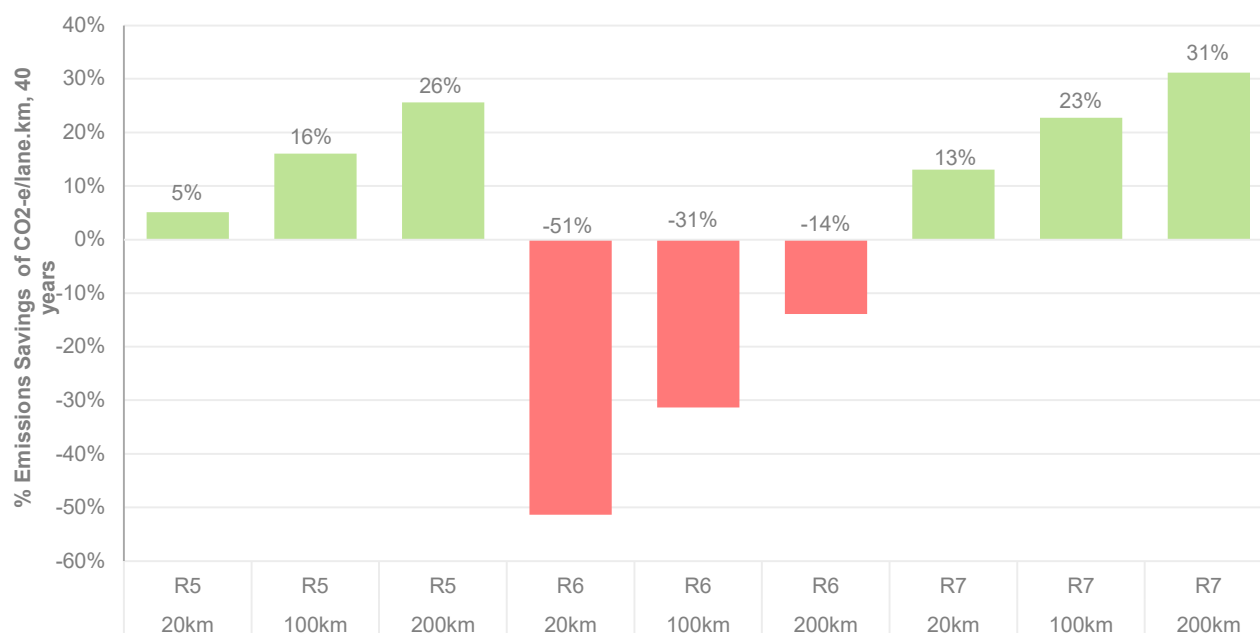


Figure E 12 provides a comparison of emissions savings of technologies 5A, 6A and 7A compared to the base case for total emissions, excluding use phase emissions. The percentage of emissions savings is sensitive to the haulage distances. At 20 km the base case and the alternative case haulage distances are equivalent. The differences in savings reflect the frequency of rehabilitation associated with the marginal materials pavements compared to the base case and associated embodied carbon differences. Technology 5A performs similar to the base case, 6A is reconstructed every 13 years and R7 is reconstructed every 24 years. For 6A at haulage distances of greater than 315 km in the base case, there is potential net GHG savings over the 40-year assessment period.

Figure E 12: Pec cent of emissions savings vs base case technology (CO₂-e/lane.km, 40 years) of marginal materials (excl. use phase) – 20 km, 100 km, 200 km sensitivity

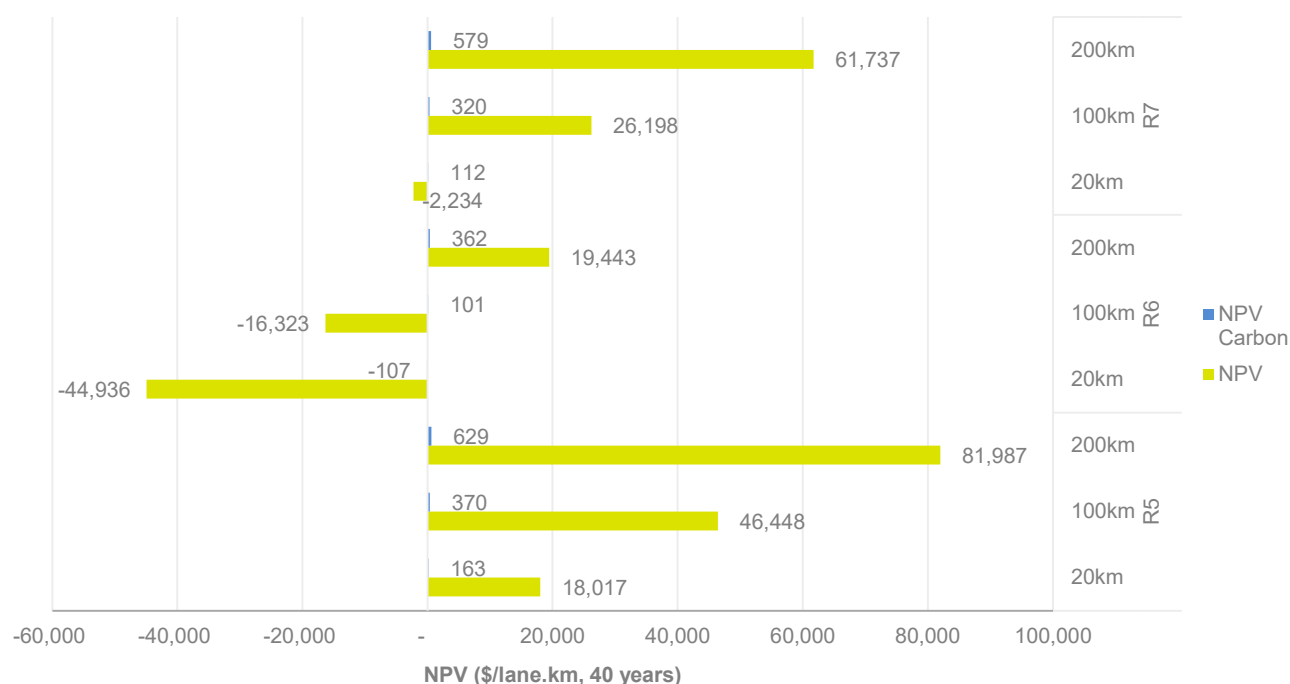


Notes:

- Green indicates an emissions reduction achieved i.e. GHG reductions.
- Red indicates an increase in emissions.

Figure E 13 shows the total NPV of marginal materials including use phase emissions. Both the total NPV and the NPV of the cost of carbon are presented at 20 km, 100 km and 200 km haulage distances for the base case, base layer and surfacing layers for all technologies, respectively.

Figure E 13: NPV of marginal materials (incl. use phase) – 20 km, 100 km, 200 km sensitivity – NPV (\$/lane.km, 40 years) – sensitivity analysis for 5A, 6A and 7A



For all scenarios, the NPV of carbon is a small component of the total NPV. This means that the carbon cost is not a significant factor affecting decision making. R5A, R6A and R7A are sensitive

to haulage distances. R5A had a positive NPV and carbon NPV for 20 km, 100 km and 200 km haulage distances. R6A had a negative NPV for all scenarios due to the frequency of rehabilitation associated with the poor performance of saturated marginal material and the associated costs of rehabilitation. For R6A at 20 km, the NPV of carbon was negative, but becomes positive improving with increased haulage distances. For R7A at 20 km, the NPV is negative, but it is positive at 100 km and 200 km haulage distances. For R7A, the NPV of carbon is positive in all instances.

Overall it shows that the total NPV performance of marginal materials is more sensitive to the relative performance of the pavement compared to the base case mainly due to the costs and frequency of rehabilitation. Haulage distances of materials then provide a secondary effect.

E.8 HH: Cost Benefit Analysis – Carbon Price and Discount Rates

E.8.1 Context

In the results section, a 7% real discount rate and a \$30.57 per tonne CO₂-e mid-range cost of carbon was assumed. The discount rate and the cost of carbon assumed have the potential to change the total NPV results and are subject to the scope of construction, maintenance and use phase activities. Typically, TMR undertakes sensitivity analysis at a 4% and 10% discount rate. The cost of carbon may be lower or higher.

E.8.2 Sensitivity Analysis

A sensitivity analysis was done to explore the impact of both the cost of carbon and the real discount rate on the results. The real discount rates used were: 4%, 7% and 10%. The carbon prices used were: \$12.22, \$30.57 and \$48.91 per tonne CO₂-e.

E.8.3 Results

Figure E 14 presents the results of a sensitivity analysis of the real discount rate on the total NPV. The NPV is sensitive to haulage and disposal tonnages, distances and costs. U1, U3, R1 and R2 NPVs are very low due to marginal, if any, differences in haulage tonnage and disposal between the base case and alternative case. A higher real discount rate has the effect of putting a higher weighting on construction phase effects vs future maintenance and use phase effects when calculating the NPV. U2 with the use of RAP, for example, assumes a higher percentage of the asphalt surfacing goes to landfill in the base case compared to the alternative case. R3 and R4 are similar regardless of the real discount rate, as the savings are realised in the construction phase in year zero, which is undiscounted. Marginal materials R5, R6 and R7 are sensitive to rehabilitation frequencies. R7 is a positive NPV at 7% and 10% real discount rates.

Figure E 14: NPV of NACoE technologies (incl. use phase) – 4%, 7% and 10% sensitivity (\$/lane.km)

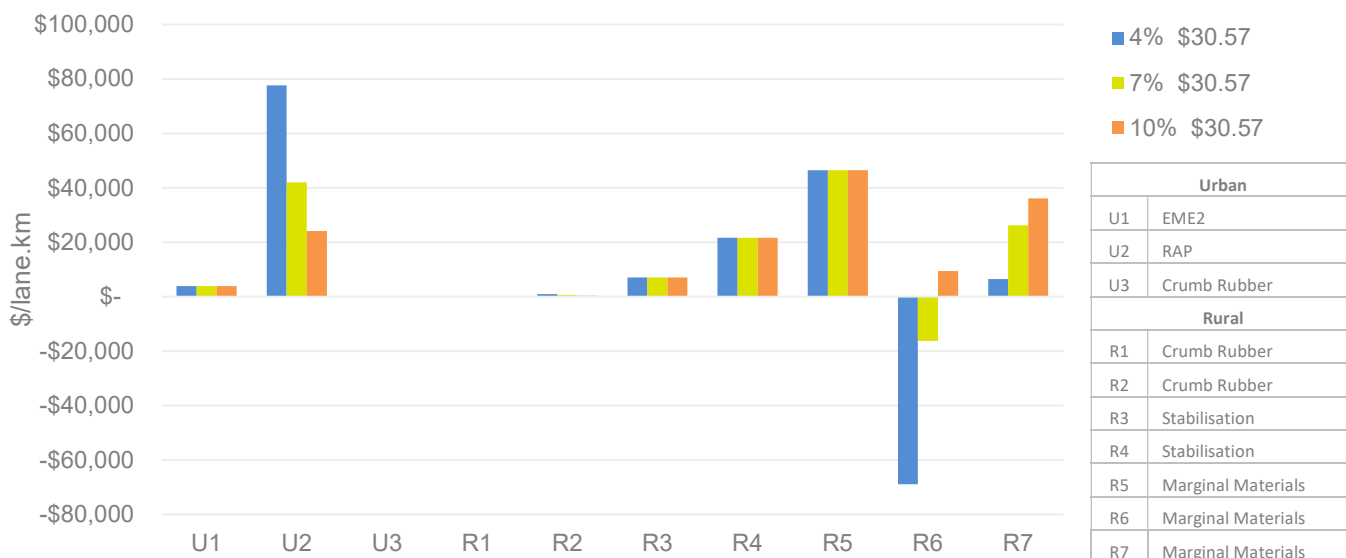


Figure E 15 presents the results of a sensitivity analysis of the carbon price (\$/tonne CO₂-e) on the total NPV per lane-km. All the technology scenario results are similar regardless of the carbon price, where the construction and maintenance costs are a larger influencing factor. This is expected, as the cost of carbon is relatively low compared to construction and maintenance costs.

Figure E 15: Total NPV of NACoE technologies (incl. use phase) – \$12.22, \$30.57 and \$48.91 carbon price (\$/lane.km)

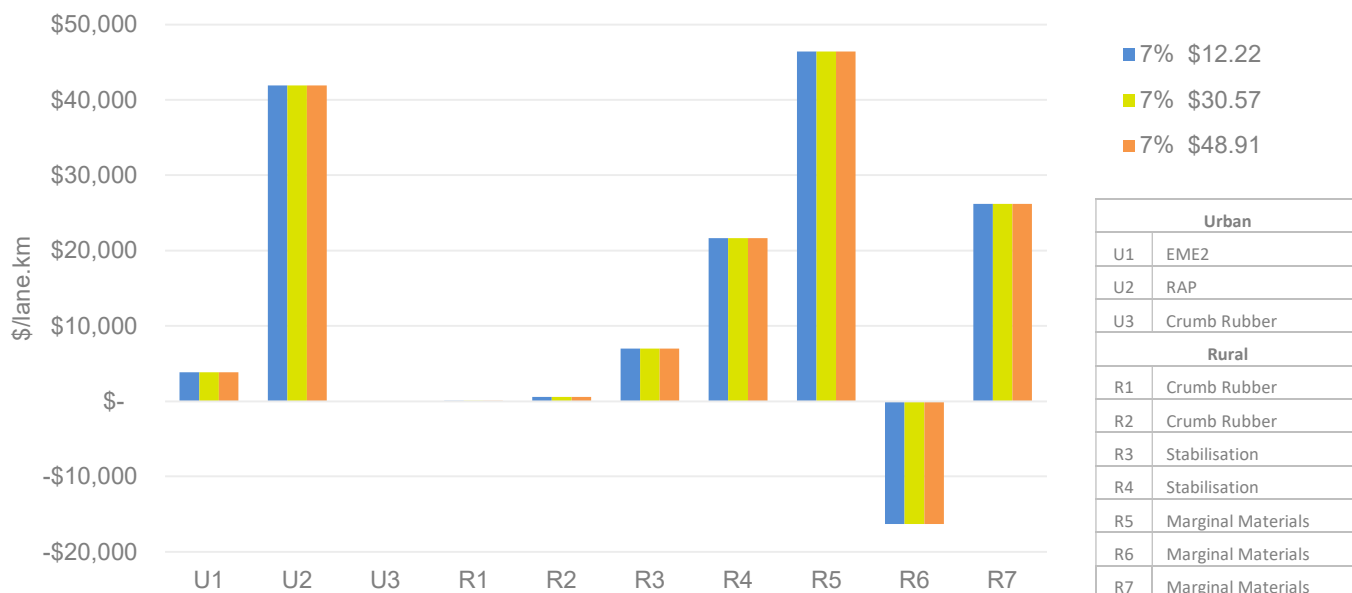


Figure E 16 presents discounted carbon savings for the different technologies in \$ per lane-km. Where the cost of carbon remains constant, the NPV is a reflection of all the benefits or costs being realised during construction. For example, with U1, R3 and R4, the carbon savings are in the base layers rather than surfacing layers. U3, R1 and R2 involve resurfacing using crumb rubber. U3 remains a carbon cost. Marginal materials R5, R6 and R7 are also sensitive to rehabilitation frequencies. At a 4% real discount rate, the R6 future emissions increase from rehabilitation to outweigh the construction and haulage emissions savings resulting in a negative NPV or a net

carbon cost over 40 years. At the assumed carbon price, all sensitivity options are within a plus or minus \$400/lane-km carbon benefit or cost over 40 years.

Figure E 16: NPV of carbon, NACoE technologies (incl. use phase) – (\$/lane-km) – 4%, 7% and 10% discount rate

