Sustainability Assessment Tool for Pavements: Technical Development Report

A JOINT INITIATIVE BY WARRIP AND NACOE

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Acknowledgements

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Summary

The Sustainability Assessment Tool for Pavements (SAT4P) is a user-friendly lifecycle assessment (LCA) tool developed through a collaborative effort between the WARRIP and NACOE research programs for Main Roads Western Australia (Main Roads WA) and Queensland's Department of Transport and Main Roads (TMR). SAT4P enables the quantification of sustainability opportunities and environmental and economic impacts associated with new pavements and rehabilitation treatments, particularly those incorporating innovative materials and technologies.

SAT4P addresses limitations in existing LCA tools by providing enhanced capabilities for assessing material selection, design, and long-term maintenance strategies. It supports informed decision-making and promotes the adoption of innovation in pavement research and construction.

Designed to be available online, SAT4P allows users—including government agencies, consultants, and contractors—to calculate lifecycle greenhouse gas emissions and cost benefits. Its scope, processes, and outputs align with the Infrastructure Sustainability Council's IS rating framework, making it suitable for sustainability reporting and project assessments.

The anticipated benefits of SAT4P include:

- improved understanding of alternative pavement designs
- enhanced long-term investment decisions
- emissions reductions and cost savings
- reduced landfill and support for circular economy outcomes
- promotion of innovative pavements and recycling industries, including job creation.

SAT4P also aligns with strategic policy objectives of both state governments, including:

- reducing GHG emissions and waste
- supporting innovation and business growth in waste management and pavement construction
- delivering high-performance infrastructure within budget
- achieving economic sustainability through reduced lifecycle costs.

This technical report documents the development of SAT4P, detailing its structure, functionality, data requirements, calculations, and outputs. It is part of a suite of supporting documents, including the SAT4P User Manual.

Acronyms

Acronym	Definition
AADT	Average Annual Daily Traffic
AC	As-constructed
ATAP	Australian Transport Assessment and Planning
C&D	Construction and Demolition
CNG	Compressed Natural Gas
CO2eq	A standardised unit of measurement that converts the potential climate impact of all greenhouse gases into a single, comparable value based on the warming effect of carbon dioxide (CO_2) over 100 years. This may also be expressed as CO_2eq or combined with other units such /km, /m^2, t, etc.
EoL	End-Of-Life
EPD	Environmental Product Declaration
EV	Electric Vehicle
GHG	Greenhouse Gas
GJ	Gigajoule
IRI	International Roughness Index
ISC	Infrastructure Sustainability Council
IS	Infrastructure Sustainability
ITMM	Infrastructure and Transport Ministers' Meeting
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LPG	Liquefied Petroleum Gas
MVP	Minimum Viable Product
NMVOC	Non-methane Volatile Organic Compounds
PAH	Polycyclic Aromatic Hydrocarbons
PM2.5	Particulate Matter 2.5 microns
PM10	Particulate Matter 10 microns
PV	Present Value
RAP	Recycled Asphalt Pavement
RFP	Request for Proposal
SAT4P	Sustainability Assessment Tool for Pavements
Sox	Sulphur Oxides
TAGG	Transport Authorities Greenhouse Group
TMR	Queensland Department of Transport and Main Roads
WARRIP	Western Australia Road Research and Innovation Program

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1 Introduction

The Sustainability Assessment Tool for Pavements (SAT4P) is a life cycle assessment (LCA) tool with the ability to quantify the sustainability opportunities and environmental impacts of new pavements and pavement rehabilitation treatments, including those that use innovative materials and technologies. SAT4P addresses the limitations in existing LCA tools, and it provides the industry with an enhanced capability to inform decisions regarding material selection, design, construction (including existing pavement removal, if applicable) and long-term maintenance strategies over a pavement's life cycle. It also supports the adoption of innovations in pavement research and technologies.

SAT4P was developed as a joint WARRIP–NACOE project for both Main Roads Western Australia (Main Roads) and the Queensland Department of Transport and Main Roads (TMR). It enables Main Roads, TMR and their consultants and contractors to derive consistent and reliable lifecycle sustainability and economic comparative assessments of the designs for new pavements and pavement rehabilitation treatments, with a focus on innovative technologies.

The development of SAT4P has progressed through a staged pathway, including the following phases:

1. A foundational tool was developed in an earlier NACOE project (described in Section 2.3).
2. An Excel-based 'proof-of-concept' or minimum viable product (MVP) tool was developed and contains the core functions needed by Main Roads and TMR. However, it has not yet reached full development maturity in terms of extended capability. A design and user-friendly interface was developed in 2020–21.
3. An enhanced Excel-based SAT4P with additional sustainability outputs and economic indicators was developed from the MVP.
4. Finally, a web-based tool with enhanced user-interface, superior output visualisations and -user authentication and access controls was developed.

The development also involved rigorous user testing, an independent peer review and quality assurance processes to achieve a comprehensive, reliable and fit-for-purpose assessment package.

This technical report describes the SAT4P development pathway, its structure and operation, and its critical data. It was preceded by interim development documents that were produced in October 2020, December 2020, March 2021, June 2021 and August 2021.

The final SAT4P has been designed to be publicly accessible to enable Main Roads, TMR and their industry partners to undertake sustainability and economic assessments of pavement options and to make more informed decisions about material selections for projects.

2 Background

2.1 WARRIP–NACOE Partnership

The SAT4P project was initiated under the WARRIP research program in November 2019. An equivalent NACOE project commenced in February 2020. During February and March 2020, the WARRIP and NACOE project teams discussed project similarities, including the alignment of final deliverables. In March 2020, the WARRIP and NACOE project teams agreed to collaborate on the development of the tool, and a joint project plan was signed by the National Transport Research Organisation (NTRO) (operating as the Australian Road Research Board (ARRB) at the time), Main Roads and TMR project sponsors and the respective WARRIP and NACOE Agreement Managers in April 2020.

The purpose of the collaboration was to realise:

1. a consistent end-product and comparable tool outcomes
   The end-product supports a single source of information, providing consistency and reliability for road agencies and industry Australia-wide. It also minimises ongoing product maintenance costs.
2. efficiencies in project delivery.
   These efficiencies have been reinvested into additional project (data and software) enhancements.

2.2 Strategic Linkages

The implementation of SAT4P is strategically linked to the Queensland and Western Australian governments and departmental policy objectives. Its targets include:

- reducing greenhouse gas (GHG) emissions
- meeting waste reduction and recycling targets
- supporting innovation and business growth, especially in the waste management and pavement construction industries
- delivering high-performing road infrastructure within budget constraints
- achieving economic sustainability goals through a reduction in lifecycle costs.

The tool's scope, processes and outputs are also aligned with the Infrastructure Sustainability Council's (ISC's) Infrastructure Sustainability (IS) rating process and requirements.

2.3 Earlier Work

2.3.1 User Requirement Review and Model Scoping (Sustainability Assessment Tool)

Under the first stage of this project, individual state-based user requirements were reviewed and model scoping papers for both Main Roads (Hall 2020) and TMR (Hall et al. 2020) were prepared. These papers provided Main Roads and TMR with a clear project scope that aligned with their policy and practical needs and provided confidence that the objectives were achievable and the data required to run the model was available. Specifically, the papers included:

- the review of user requirements, including policy and stakeholder needs and their alignment with ISC's IS ratings requirements
- the proposed model scope and key outputs
- input data requirements and an outline of reference datasheets
- an assessment of Main Roads' and TMR's internal capabilities to produce essential customisable input data.

It was concluded that the proposed model scope would meet a number of Main Roads' and TMR's operational and policy needs and that both agencies had ready access to the essential data and internal expertise needed to run the proposed tool. It was therefore recommended that Main Roads and TMR agree to pursue the joint development of an Excel-based SAT4P. The tool would be based on an MVP approach – one that met both Main Roads' and TMR's core assessment needs and allowed for further testing and enhancements.

In accordance with the joint WARRIP–NACOE project agreement and following the completion of individual state-based user requirements reviews, the remainder of the project was delivered collaboratively, as far as practicable and subject to continued agreement by all parties.

The NACOE user requirements review and model scoping study assessed existing LCA tools and databases. It was found that while there is a broad range of LCA tools and databases available for road infrastructure assessments, none fully catered for all the user requirements. The key areas where the proposed SAT4P stood out against comparable LCA tools were:

- allowance for detailed and innovative pavement designs
- flexibility to enter user-defined assessment and process parameters to refine the results
- inclusion of the use phase in the pavement's lifecycle
- incorporation of Australian and Queensland reference data
- concurrent evaluation of economic and sustainability outcomes (including recycling and waste outputs).

2.3.2 Foundational Lifecycle Greenhouse Gas Tool

In August 2019, the NACOE research program delivered an innovative pavement LCA research project titled 'Assessing the Potential Greenhouse Gas Emissions (GHG) Reductions and Sustainability Benefits of Innovative Pavements Solutions' (NACOE P106). NACOE P106 quanitified the lifecycle GHG and waste reduction benefits from the use of innovative pavement technologies compared to traditional pavement technologies and designs. It also identified a range of sustainability benefits (such as reduced material quantities used and disposed of, climate resilience performance, and road alignment outcomes) from the use of these technologies over the pavement lifecycle.

To assist in the delivery of the research outcomes, an Excel-based tool was developed based on comparable Australian and international models and emissions factors. Compared with existing methods used in Australia, the model was unique as it:

- allowed more flexibility in pavement designs, not limited by drop-down menus; this allowed for the evaluation of new and innovative pavement designs
- enabled differences in pavement performance to be accounted for
- allowed the resilience of pavements to extreme weather events and lifecycle savings to be assessed
- allowed vehicle emissions from pavement design and alignment decisions to be evaluated
- enabled pavement performance, sustainability and costs over the pavement lifecycle to be evaluated
- informed smarter procurement decision-making.

The model was a partial LCA model in the sense that it provided a comparative assessment of lifecycle elements that were expected to be different for the base and alternative cases assessed. For example, manufacturing processes were not addressed, as this was not expected to result in significant differences between the compared pavements.

The SAT4P project significantly adapted and enhanced the foundational NACOE P106 lifecycle modelling tool. It expanded the foundational tool's scope, modelling capabilities, datasets and user interfaces. Compared with the NACOE P106 tool, SAT4P:

- is more comprehensive, because it includes a full LCA of every relevant lifecycle phase
- is more flexible in terms of the assessment parameters and extended reportable metrics
- is user-friendly, in that it provides an enhanced online user interface with embedded assessment tips and guidance
- contains pre-populated reference data, including research data used in the P106 project, as well as new research (see Section 8 for details).

3 Purpose, Objectives and Deliverables

3.1 Overall Project Purpose

The overall purpose of the project was to enable Main Roads, TMR and their industry partners to consistently and reliably quantify and compare the lifecycle sustainability and economic opportunities and impacts of innovative pavements. SAT4P, therefore, contributes to:

- an improved capability to assess sustainability opportunities and impacts of the designs of new pavements and pavement rehabilitation treatments, including those that use innovative technologies (see Section 2.3 on how SAT4P improves existing tools)
- a better understanding of the opportunities and impacts of alternative pavement designs, leading to improved long-term investment decision-making and the adoption of innovative pavements
- reductions in emissions, including GHGs and other air-borne pollutants
- reductions in energy and water use
- cost savings
- reduced landfill and the promotion of circular economy outcomes
- the promotion of innovative pavement and recycling industries (including job creation)
- ISC project assessments.

3.2 Project Objectives

The objective of this project was to develop a tool capable of assessing pavement innovations that will help inform Main Roads, TMR and other users when making decisions regarding pavement design and material selection, and long-term maintenance strategies over the pavement lifecycle. It was also developed to provide data suitable for annual reporting or sustainability reporting.

By specifying the physical assessment boundaries, SAT4P's output units are flexible and can report on a unit basis (such as m^2 or lane-kilometre) or project basis. Technology-based assessment outputs use a common unit basis to show the difference between the base and alternative cases and enable trend comparisons over time and against policy targets. Project-based assessment outputs are expected to help inform pavement design and material selection decisions for request for proposal (RFP) documents, issue for construction (IFC) designs and as-constructed (AC) evaluations.

SAT4P is intended to be used to evaluate pavement options, either in Western Australia or Queensland, with a focus on designs for new pavements and rehabilitation treatments that incorporate innovative pavement materials/technologies and processes.

The SAT4P includes:

- a flexible, web-based tool with the ability to compare base case and alternative case (i.e. innovative) pavement design options
- comparative lifecycle outputs, including:
  - GHG emissions (tCO_2eq)
  - other air pollutants, including nitrous oxides (NOx), sulphur oxides (SOx), non-methane volatile organic compounds (NMVOC), particulate matter (PM2.5 and PM10) and polycyclic aromatic hydrocarbons (PAHs)
  - material use and waste, reuse and recycling quantities (tonnes)
  - total energy usage (GJ) and by fuel source (diesel, petrol, gas and electricity)
  - total freshwater use (m^3)
  - EnviroPoints – environmental impact measures used in the ISC IS Materials Calculator
  - economic costs, as lifecycle costs expressed in present value (PV) terms, and sensitivity analyses around carbon values and discount rates.

- state-based reference data (e.g. pavement materials and product libraries, emissions and consumption factors, waste levies, road categories, and road surface deterioration profiles (where available)) to minimise user data requirements and facilitate the generation of consistent and reliable results.

3.3 Deliverables

The progressive SAT4P deliverables included the following:

- A short summary report on the consultation with Main Roads and TMR regarding the development and testing of the proof-of-concept tool, prioritised enhancement options, user interface delivery options, hosting and licensing arrangements was delivered in December 2020.
- A feasibility study into a range of model enhancements, including the functionality to optimise outputs and the inclusion of additional model outputs, i.e. other air-borne pollutants, EnviroPoints, energy and water use was delivered in February 2021.
- A proof-of-concept sustainability assessment tool built in an Excel platform with linked state-based reference data and a range of sustainability and economic output measures (as identified in Section 3 and detailed in Section 5.2) was delivered in March 2021.
- A report detailing the expert peer review that examined the completeness and robustness of SAT4P and model enhancements (outcomes are discussed in Section 4.4.2) was delivered in April 2021.
- A user-friendly SAT4P using a web-based platform and including a user manual for the model was delivered in September 2021.
- A technical report on the development and operation of the SAT4P was delivered in June 2021 and updated in June 2024.

This report is an update to the earlier technical report (June 2021). It includes updates of the report’s content, reflecting a further 3 years of SAT4P introduction of web services (online hosting and helpdesk), software testing, development, quality assurance and refinements.

4 SAT4P Assessment Scope

LCAs require a clear definition of the project assessment scope. SAT4P's lifecycle scope includes cradle-to-grave lifecycle phases and assessment-specific scope boundaries, such as the assessment period and the physical asset boundaries.

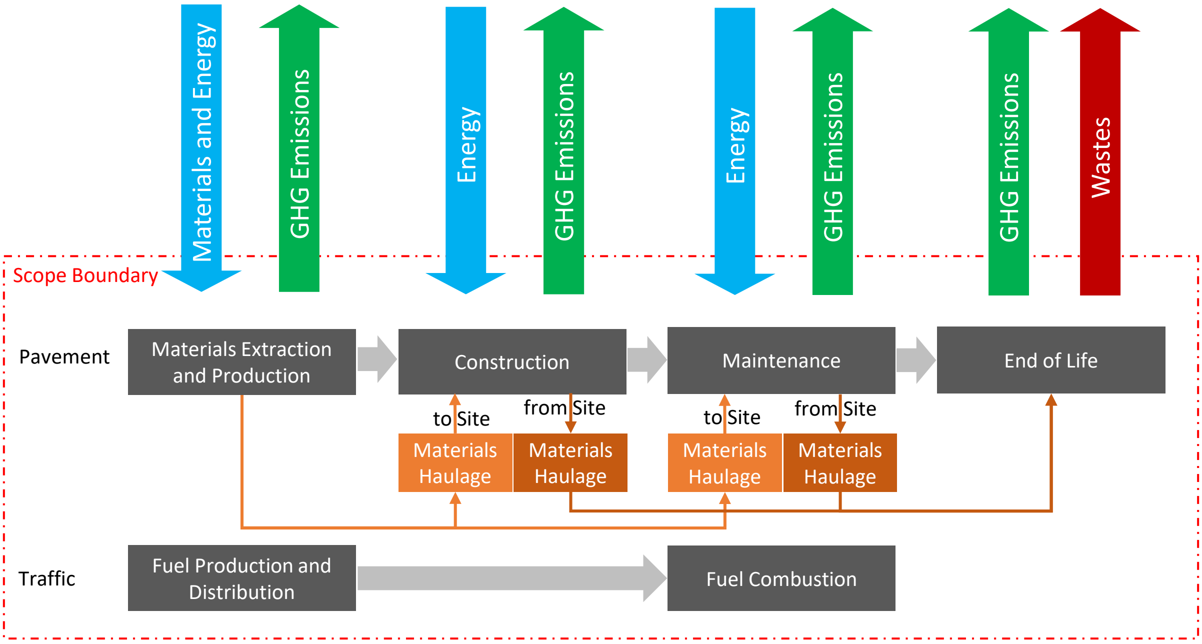
4.1 Lifecycle Assessment Scope

The SAT4P's LCA scope consists of 6 interlinked phases:

- extraction and production – embodied energy contained in the pavement materials from extraction and production (i.e. 'cradle to gate')
- construction – the energy used during the initial construction of pavements, including their manufacture and laying and use of construction vehicles and machinery
  The construction phase can also include pre-construction removal of existing materials.
- maintenance – use of construction vehicles, machinery and energy while delivering maintenance treatments
- End of life (EoL) – disposal[1], recycling or reuse of end-of-life materials
- transportation/materials haulage – use of heavy haulage vehicles in transporting materials to the project site for construction and maintenance, or from the project site to EoL disposal
- use (traffic) – on-road emissions from vehicles using the road.

The pavement LCA phases are outlined in Figure 4.1.

Figure 4.1: Pavement LCA diagram



4.1.1 Alignment with Environmental Product Declarations

An Environmental Product Declaration (EPD) is defined by ISO 14025:2006 as a declaration that 'quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the

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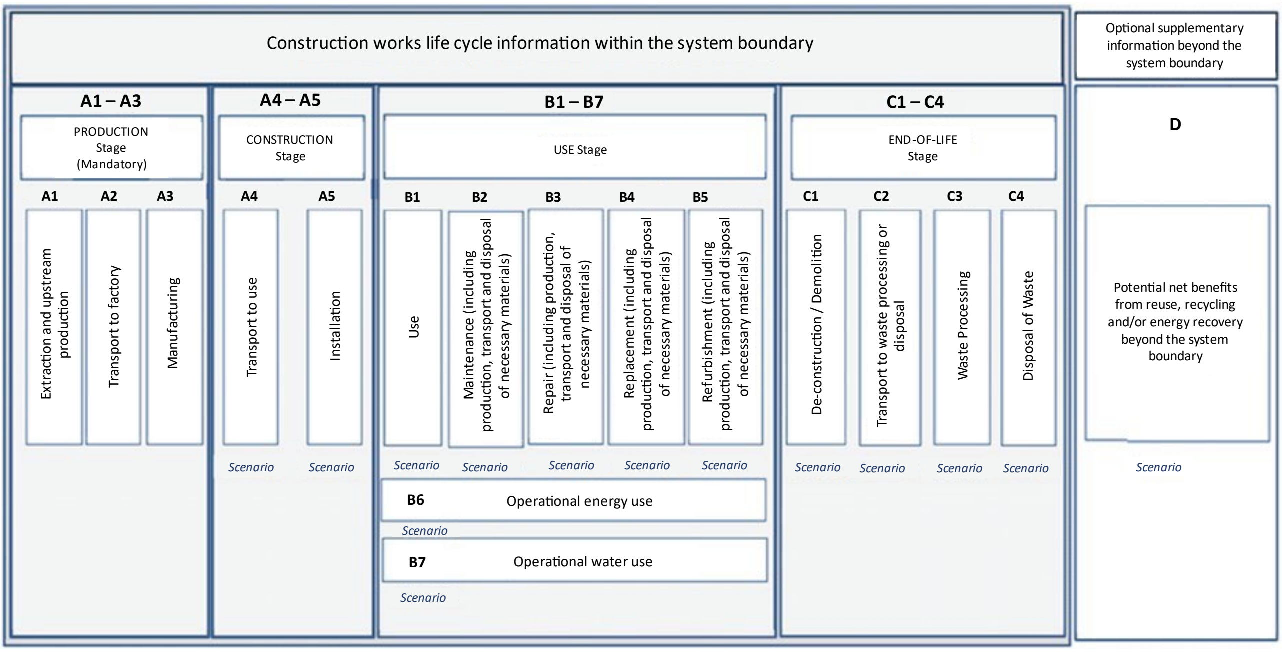
[1] While end-of-life disposal of pavements into landfill is rare (or perhaps even non-existent), it is important to include this phase in the lifecycle to demonstrate completeness and allow flexibility if needed (e.g. distressed roads that cannot be reused due to contamination, or inclusion of recycled content that has not yet been approved for reuse). Additionally, alignment with the IS ratings process requires the inclusion of end of life in the LCA.

same function' (2006a). The EPD methodology is based on the LCA tool that follows ISO series 14040:2006 (2006b) and the life cycle stages (modules) of construction works defined in ISO 21930:2017 (2017) and shown in Figure 4.2.

The European Committee for Standardization (2019) has published EN 15804:2012 outlining common Product Category Rules (PCRs) for EPD development in the construction sector. This standard is widely adopted in Australia in the broader infrastructure sector, including pavements, steel and concrete. The lifecycle stages (modules) of construction works as applied in EN 15804:2012 are similar to ISO 21930:2017.Figure 4.2.

Figure 4.2: ISO 21930:2017 lifecycle stages



Source: ISO 21930:2017.

EPDs have mandatory declarations against 'cradle-to-gate' lifecycle environmental impacts in the product stage (modules A1–A3). Modules A4–A5, B1–B7 and C1–C4 are optional for 'cradle-to-grave' LCAs. Module D – Potential net benefits from reuse, recycling and/or energy recovery from beyond the system boundary – is optional supplementary information.

SAT4P is a 'cradle-to-grave' LCA tool with its key phases being aligned with the EN 15804 lifecycle phases A – C as shown in Table 4.1.

Table 4.1: SAT4P and ISO 21930:2017 lifecycle stages

SAT4P lifecycle phase	ISO 21930:2017 lifecycle stages
Extraction and production	Product stage A1 – Extraction and upstream production (extraction of virgin materials and sourcing of recycled materials) A2 – Transport (to asphalt or manufacturing plant) A3 – Manufacturing (production processes)
Construction	Construction processes stage A5 – Construction-installation process (mixing and placement) C1 – De-construction demolition (optional removal of existing pavement in preconstruction)
Maintenance	Use stage B2 – Maintenance (routine) B3 – Repair (periodic) B4 – Replacement (rehabilitation) B5 – Refurbishment (resurfacing) C1 – De-construction demolition (optional layer removal)
EoL	EoL stage C1 – De-construction demolition (optional) C3 – Waste processing (applicable only for in situ reuse) C4 – Disposal
Transportation/materials haulage	Construction processes stage A4 – Transport (materials to site) EoL stage C2 – Transport to waste processing (including recycling facilities) or disposal
Use (traffic)	Use stage B1 – Use (traffic) B6 – Operational energy use (not applicable) B7 – Operational water use (not applicable)

SAT4P also generates material use outputs (see Sections 5.2 and 10.5), which contribute to the supplementary information beyond the system boundary captured in Module D of ISO 21930:2017.

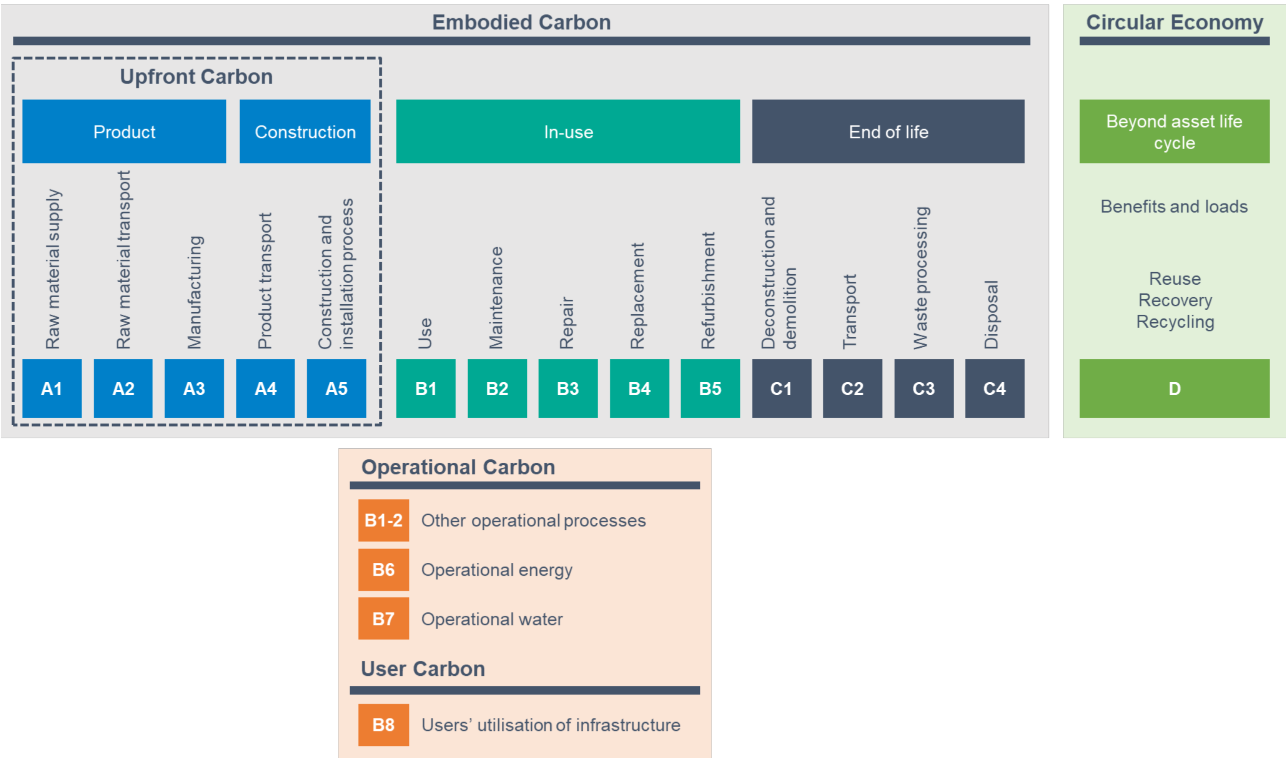
4.1.2 Alignment with Whole-of-life Carbon Measurement

On 7 June 2024, the Infrastructure and Transport Ministers' Meeting (ITMM) agreed to a nationally consistent approach for measuring and reporting embodied carbon in transport infrastructure projects through the 'Embodied Carbon Measurement for Infrastructure: Technical Guidance', known as the National Measurement Guide (Infrastructure and Transport Ministers 2024). The lifecycle modules are based on BS EN 17472:2022 and are slightly different to the module coverage in the previous section, particularly around the operational phase of the asset, with a clearer distinction between embodied, operational and user carbon. The lifecycle modules associated with the upfront, embodied and whole-of-life carbon are outlined in Figure 4.3. The following are not covered within the guide's definition of embodied carbon for transport infrastructure (but should be included in any whole-of-life carbon assessment):

- some operational processes (Modules B1 – B2)
- operational energy and water use (Modules B6 and B7, respectively)
- asset user carbon emissions (Module B8)
- benefits and loads beyond the asset lifecycle (Module D).

As noted in Table 4.2, while SAT4P generally has good coverage of these lifecycle modules, its reporting outputs are not aligned and require some additional work to cover the whole-of-life carbon assessments for pavements.

Figure 4.3: Whole-of-life carbon and associated lifecycle stages from the National Measurement Guide



Source: Reproduced from Infrastructure and Transport Ministers (2024) and BS EN 17472:2022.

Table 4.2: SAT4P and BS EN 17472:2022 lifecycle stages

SAT4P lifecycle phase	BS EN 17472:202 lifecycle stages
Extraction and production	Product stage A1 – Extraction and upstream production (extraction of virgin materials and sourcing of recycled materials) A2 – Transport (to asphalt or manufacturing plant) A3 – Manufacturing (production processes)
Construction	Construction processes stage A5 – Construction-installation process (mixing and placement) C1 – De-construction demolition (optional removal of existing pavement in preconstruction)
Maintenance	Use stage B1 – Use (not applicable/included) B2 – Maintenance (routine) B3 – Repair (periodic) B4 – Replacement (rehabilitation) B5 – Refurbishment (resurfacing) C1 – De-construction and demolition (optional layer removal)
EoL	EoL stage C1 – De-construction demolition (optional) C3 – Waste processing (applicable only for in situ reuse) C4 – Disposal
Transportation/materials haulage	Construction processes stage A4 – Transport (materials to site) EoL stage

SAT4P lifecycle phase	BS EN 17472:202 lifecycle stages
	C2 – Transport to waste processing (including recycling facilities) or disposal
Use (traffic)	Use stage B8 – User's utilisation of infrastructure (traffic) B6 – Operational energy use (not included) B7 – Operational water use (not included)

4.2 Assessment-specific Boundaries

SAT4P users are required to define project-specific assessment boundaries to establish the common ground for the comparative analyses. Assessment-specific boundaries include user-defined elements such as the assessment date, location, assessment period and the physical assessment boundaries of the pavement (user defined, but limited to the pavement length, width and depth). Details are described in Section 7.1.

Figure 4.4 to Figure 4.7 outline representative plans and cross-section profiles of the physical assessment boundaries for a typical urban and a typical rural road.

Figure 4.4: Plan view of a typical urban road

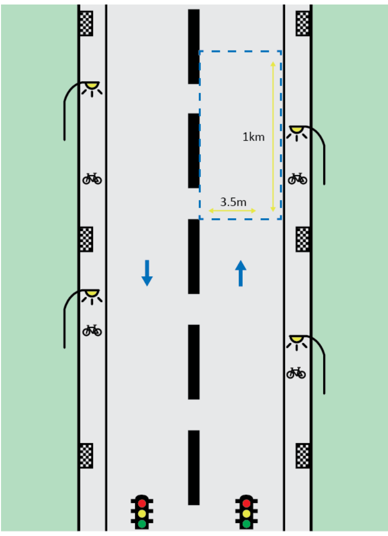


Figure 4.5: Pavement type cross-section of a typical urban road

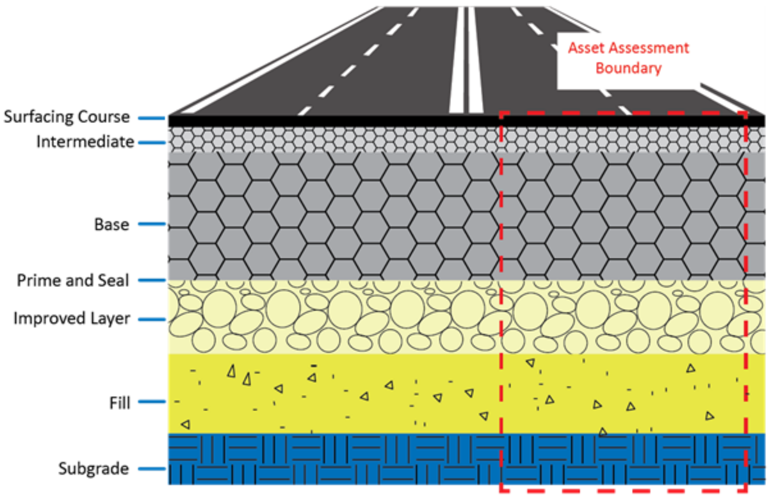
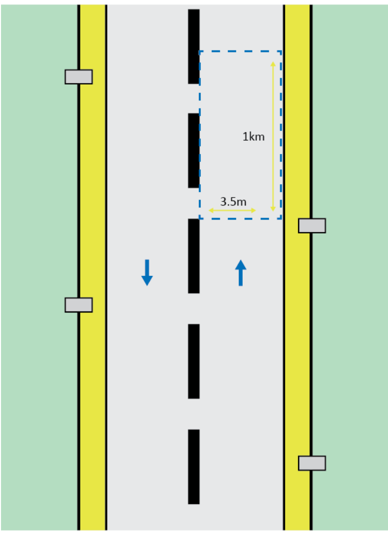
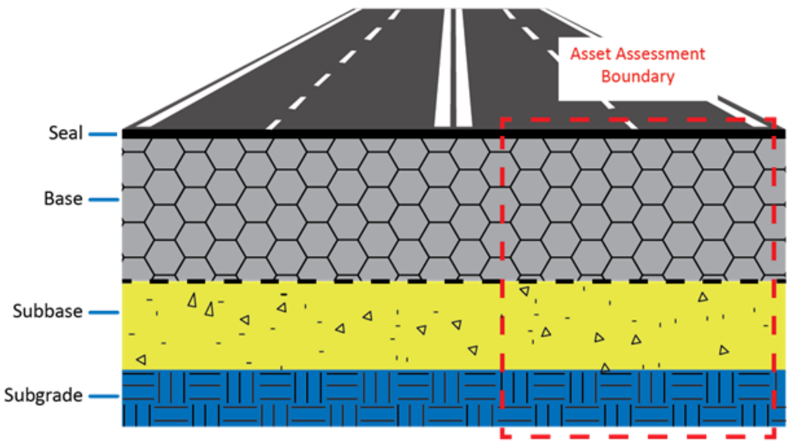


Figure 4.6: Plan view of a typical rural road



Source: NTRO (unpublished).

Figure 4.7: Pavement type cross-section of a typical rural road



4.3 Development Process

SAT4P was developed and has matured over a 5-year period (between 2019 and 2024). The staged pathway has included the following key phases:

1. user requirements and model scoping (2019–20)
2. an Excel-based 'proof-of-concept' or MVP tool that contains the core functions needed by Main Roads and TMR, but has not yet reached full development maturity in terms of extended capability, design and a user-friendly interface (2020–21)
3. an enhanced Excel-based SAT4P with additional sustainability outputs and economic indicators, developed from the MVP (2021)
4. finally, a web-based tool with an enhanced user interface, superior outputs visualisations and user authentication and access controls (2021 to 2024).
   Alpha and beta releases occurred in 2022, and a rigorous quality assurance program was completed in 2023. During 2023–24, a series of works packages were developed and implemented to deliver enhanced and improved user experience and calculation rigour.

4.4 Testing, Reviews and Refinements

The development of SAT4P also involved several phases of rigorous developer and user testing, an independent peer review and quality assurance processes to achieve a comprehensive, reliable and fit-for-purpose assessment package.

4.4.1 Developer and User Testing

Developer and user testing were carried out on the practical completion of the following key development stages:

- the Excel-based 'proof-of-concept' or MVP (developer and user testing)
- the enhanced Excel-based SAT4P with additional sustainability outputs and economic indicators and implementation of suggested peer review amendments (developer testing only)
- the initial web-based tool with an enhanced user interface, superior outputs visualisations and user authentication and access controls (2-stage user testing).

Testing proof-of-concept model

In May 2020, the project development team completed developer testing of the model, focussing on the capability of the model to generate consistent and reliable outputs. The results informed modifications and refinements to the tool, with an emphasis on improving the usability of the tool (i.e. clearer and more simple data entry and improved visualisation of model outputs) and verifying the accuracy of the reference data.

User testing by the intended end users of the tool provided feedback on how well it worked in terms of:

- ease of understanding, navigation and use
- time required to complete a comparative assessment
- delivery of expected outputs
- insights into modifications and further enhancements to the tool.

The user testing results were used to refine and finalise the proof-of-concept MVP tool, improve the reference databases and inform the scope of the web tool development, i.e. emphasising the need for a user-friendly interface.

Testing the enhanced model

Upon expanding the SAT4P's reference databases (see Section 8), building in a number of model enhancements and implementing the suggested peer review amendments (see Section 4.4.2), the project development team completed another round of developer testing. This testing focussed on the production of robust outputs and involved:

- checking and fixing formula, data or labelling gaps or errors
- undertaking 2 separate comparative assessments of a base case and alternative case pavement design and comparing results
- benchmarking EnviroPoints outputs against the IS Materials Calculator[2].

The testing identified some minor discrepancies that were corrected during the testing. It was concluded that the SAT4P produced repeatable, robust outputs for all sustainability and economic indicators.

Details of the testing methods and results were provided to Main Roads and TMR in a separate testing documentation.

Initial web-based tool testing

The web tool testing involved 2 stages of user testing. The alpha test was undertaken by end users from Main Roads and TMR who, over a 2-week period, tested the first release (alpha) web tool and recorded their observations. The testers were supported by a draft SAT4P user manual. However, user feedback suggested that the guidance needed to be embedded into the software. Feedback was also provided around the functionality and usability of cost estimates and around defining pavement layer target densities for compaction of materials.

The beta testing involved both internal Main Roads and TMR end-user testers from the pavement construction and infrastructure sustainability industries. User feedback was very positive overall, noting the comprehensiveness of the tool and its engaging user interface. Refinements were recommended around the visibility of background data and the assumptions used in the calculations, and further steps required to streamline the technical nature of the data requirements.

User acceptance testing

In February 2022, following significant software refinements, user acceptance testing (UAT) was conducted by selected industry participants, including experts in sustainability and pavement design disciplines. The UAT feedback covered several aspects, including functionality, database, user interface, inputs and outputs. These findings were documented in the SAT4P software improvement feedback spreadsheet. The UAT feedback prompted the need for further quality assurance (QA) to be undertaken by an experienced pavement engineer.

4.4.2 Peer Review

An independent peer review of the Excel-based SAT4P was conducted by consultants start2see ahead of its integration into the web-based tool. The aim of the independent third-party review was to validate the robustness of SAT4P to ensure that it achieved its primary objectives of being able to produce consistent and reliable lifecycle sustainability and economic assessment results for comparable pavement design options. The peer review covered the operation and structure of SAT4P and the data used to generate the various sustainability outputs.

Overall expert opinion from start2see

start2see was impressed by the quality and level of detail that went into the SAT4P MVP and provided the following strengths, challenges and recommendations.

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[2] While benchmarking SAT4P outputs against the EnviroPoints was possible, there were no comparable models available to benchmark water or air pollution outputs. The testing methodology investigated benchmarking other outputs aligned with the EN 15804 LCA reporting standard (as adopted by SAT4P) such as Australian EPDs. While EPDs present similar product-level environmental impact data, there was insufficient transparency of input data to replicate the products in SAT4P. The SAT4P peer reviewer noted that benchmarking air pollution, energy and water outputs ‘could be difficult due to the differences in approach and measurement’ (Rouwette, personal communications 22 April 2021).

The strengths included:

1. The tool is comprehensive (in terms of its lifecycle coverage) and transparent (i.e. formulae and data sources are clearly and consistently referenced).
2. The user input follows a step-by-step process, which is key to enabling users to work with a complex tool.
3. SAT4P shows a level of alignment with a number of industry initiatives (AusLCI data, IS Materials Calculator, TAGG Workbook, Carbon Gauge, etc.).

The challenges included:

1. The level of detail makes it difficult to thoroughly check all calculation steps.

The recommendations included:

1. Further alignment with key industry initiatives will be key to the tool's industry acceptance and useability beyond its core users.
2. Considering opportunities for further alignment would be beneficial; however, full alignment with the IS Materials Calculator would inhibit the SAT4P too much, so a balance between alignment and functionality needs to be maintained.

The peer review provided a number of suggestions to improve the robustness of SAT4P and its alignment with industry initiatives. Details of the peer review method and results are provided in a separate report (Rouwette 2021).

4.5 Revisions and QA Processes

In 2022–23, a comprehensive QA process was undertaken to provide confidence that the SAT4P was fit for purpose. The process sought to validate that the tool had:

- a clear and logical structure and approach
- functionality, i.e. the software worked as expected
- user-friendliness, i.e. user requirements and outputs were clear and easy to follow
- accuracy, i.e. calculations and outputs were reliable and repeatable.

A secondary objective was to understand the ISC verification processes and whether the SAT4P met those requirements.

The QA was undertaken by a team of experienced professionals, with the functionality testing being carried out by an experienced pavement engineer. The logic, structure and functionality testing focussed on:

- assessment logic, structure and functionality from a technical engineering accuracy perspective
- existing user/client feedback
- software functionality, including a review of the software's emissions and economic calculation functions
- assessment processes and outputs
- identifying issues that could be addressed in subsequent tasks.

Once the initial QA scope was completed, further work completed included:

- identifying themes and grouping issues to workshop potential areas of concern
- developing works packages to address the grouped issues
- system mapping and commentary of coding and logic flows
- cross checking the commentary coding with design calculations
- developing a calibration process
- prioritising works packages
- detailed scoping for the next stage of the project.

4.6 Works Package Development and Implementation

In 2023–24 the SAT4P development process moved from addressing individual issues to the developing themed works packages. Four major works packages were developed and implemented:

- cost architecture – reassigning how pavement costs are calculated based on common pavement products
- developer – addressing access issues and software bugs and enhancing user experience
- sustainability – automating several data selection options and calculations, including introducing national carbon values, to improve user experience and assessment reliability
- database – reviewing and updating all reference and default data.

A fifth major works package, implemented in 2024, focussed on developing and enhancing SAT4P output reports – i.e. to include transparent reporting on assessment inputs.

4.6.1 Cost Architecture Works Package

The cost architecture works package related to how the software architecture captures and calculates the costs of construction, removal, maintenance and the whole-of-life costs of the pavement. It covered the following key cost elements:

- product/material costs
- process costs
- manufacturing and construction costs
- maintenance costs
- material transport costs
- disposal costs
- whole-of-lifecycle costs, including a review of the salvage value methodology.

The works package included 10 broad tasks with a series of specific actions (i.e. subtasks) to form a comprehensive response to a suite of related issues. The 10 works package tasks were:

1. Simplify pavement design and costs based on pavement products rather than their constituent materials.
2. Consolidate the product library and associated cost databases.
3. Link the removal process with costs.
4. Hardwire the manufacturing/construction process with the products database.
5. Change the pavement design screen to allow viewing, inputting and adjusting costs of individual pavement layers.
6. Align the architecture of maintenance costs with the rest of the tool.
7. Include cost for rural waste disposal based on regions.
8. Update transport inputs.
9. Provide clarification for the EoL value.
10. Provide the same level of access provided to TMR staff to external users to enable them to see some sections of the tool (e.g. unit rates, maintenance schedules, etc.) that were previously hidden from external users (NACOE tool-specific task).

The cost architecture works package was fully delivered in 2024.

4.6.2 Developer Works Package

The developer works package included issues related to software functionality and/or calculations. The works package addressed issues such as bugs in copying project data into new project cases or copying entire projects. Additional issues were addressed to enhance the user interface and results processing time.

The developer works package was fully delivered in 2024.

4.6.3 Sustainability Works Package

The sustainability works package included issues and actions related to sustainability and LCA within SAT4P. It included 5 sub-works packages which focussed on:

- definitions, including issues related to terminology, guidance and training
- automation, including issues related to auto-calculating or auto-populating data to help reduce user error and improve accuracy, consistency and repeatability
- functionality, including issues related to the user interface, accessibility and calculations
- outputs, including issues on what and how results are presented
- miscellaneous issues not easily categorised in other works or sub-works packages.

Following the publication and national agreement on a set of national carbon values for transport and infrastructure project business cases, these values were implemented into SAT4P, replacing the existing user-defined value approach.

The sustainability works package was fully delivered in 2024.

4.6.4 Database Works Package

The database works package included issues related to pavement products (i.e. materials and mixes) and processes for construction, removal and maintenance in the software. This works package included:

- reviewing existing databases
- identifying gaps in materials, products and processes that were not currently covered in the SAT4P databases
- identifying changes that needed to be made due to updates to specifications that may have occurred during the development of SAT4P
- identifying changes and updates that needed to be made due to industry trends, i.e. may require new material blends due to new developments in the industry
- recommending future improvements.

The database works package was delivered in 2024.

4.6.5 Input–Output Works Package

The input–output works package delivered enhanced SAT4P reporting content, format and functionality. The key improvements included:

- developing an Excel report inclusive of assessment input data and assessment outputs (i.e. calculation results)
- adding assessment input data to the existing assessment outputs-focussed PDF report
- building a comparison of case-vs-case functionality into all reports
- generating additional data visualisations, e.g. annualised GHG emissions and pavement deterioration profile charts
- date and time stamping of all reports and other data security measures.

The input–output works package was delivered in 2024.

5 SAT4P Capabilities

The SAT4P's core capabilities were identified and categorised as operational and output capabilities.

5.1 Operational Capabilities

The operational capabilities include:

- **a user-friendly interface with user guidance material**
  SAT4P is a web-based tool with a logical, easy-to-follow user interface that guides the user through the assessment process (see Section 6). It is supported by a user manual that is embedded into the software, and in-model guidance, e.g. cursor hover-over explanatory text. The tool has been pre-filled with background default/reference data and products, materials, processes and costs, to enhance usability (detailed in Section 8). Additionally, SAT4P has also been configured to accommodate Main Roads' and TMR's data names and definitions to allow existing datasets to be used (e.g. pavement designs, project briefs, tender and procurement information).
- **flexible assessment parameters**
  SAT4P allows technology-based or project/route-specific assessment, variable assessment periods and sensitivity and scenario modelling to allow users to tailor assessments to meet a variety of specific needs. There are 2 options when undertaking pavement assessments:
  - when project-specific parameters are known, entering a kilometre value (lane-kilometres)
  - when project specific parameters are unknown, using a m^2-based assessment.

  With project specific parameters, results can be generated on a project-, or route-specific basis, based on user input of lane-width, number of lanes, road length, horizontal (curvature) alignment and vertical (rise and fall) grades. Sensitivity testing and scenario modelling can also be conducted by varying one or more of the input variables. SAT4P also includes built-in sensitivity analyses for carbon values and discount rates.
- **flexible input data fields**
  SAT4P allows users to set local or project-specific data values (e.g. pavement designs, products/materials, road alignments and dimensions, haulage distances) that are not constrained by predefined design standards (detailed in Section 7). This flexibility to changes to the pavement parameters provides the capability to compare innovative and new sustainable pavement designs with traditional road technologies. It also allows the user to add customised data or to modify existing reference data.
- **lifecycle analyses**
  SAT4P includes 6 lifecycle phases (as detailed in Section 4). The results can be generated for each lifecycle phase individually or for the entire lifecycle (including the ability to toggle on/off the use phase, which represents the vast majority of lifecycle environmental impacts).
- **comparative analyses**
  SAT4P compares pavement lifecycle environmental impacts, resource use, waste outputs and costs between a base pavement design and an alternative or multiple alternative pavement design(s) over a user-defined lifecycle period (as detailed in Section 5.2).
- **progressive development approach**
  The development of SAT4P was phased to include a rigorous quality assurance, testing regime and iterative refinements (as described in Section 1).
- **background reference (or default) data**
  SAT4P provides a tailored product; it includes Western Australian and Queensland state-specific databases that draw on state, national and international data sources. Full details of data inclusions are provided in Section 8.
- **alignment and compatibility with existing LCA tools.**
  Two examples of these existing tools include the IS Materials Calculator v2.0 Infrastructure Sustainability Council (2018) and the Carbon Gauge Tool (Transport Authorities Greenhouse Group 2013) (refer to peer review expert opinion in Section 4.3 and ISC-aligned outputs in Sections 5.2 and 10).

5.2 Output Capabilities

SAT4P generates a set of output metrics aligned with relevant government policy objectives, targets and measures (e.g. carbon and waste reduction targets, recycling targets and cost effectiveness). The key output lifecycle metrics include:

- GHG emissions (tCO2eq)
  - GHG emissions savings versus base case
  - total lifecycle GHG emissions
  - lifecycle GHG emissions for each lifecycle phase
  - lifecycle GHG emissions by emissions scope
- other air-borne emissions savings versus base case, including:
  - NO_x (kg)
  - SO_x (kg)
  - NMVOCs (kg)
  - PM2.5 and PM10 (kg)
  - PAHs (kg)
- energy and water consumption – savings versus base case
  - total energy use (GJ)
  - diesel use (L)
  - petrol use (L)
  - gas use (kg)
  - electricity use (kWh)
  - total freshwater use (m^3)
- EnviroPoints – an upstream environmental impact measure as used in the IS Materials Calculator (see Section 9.2.2 for an overview of EnviroPoints and alignment with IS ratings)
- material use and 'waste' quantities (resource efficiency) – tonnes savings versus base case
  - lifecycle virgin and recycled material use quantities
  - lifecycle 'waste' material quantities, includes quantities reused on site, recycled and disposed of in landfill
- economic – $net present value (NPV) savings versus base case
  - lifecycle $NPV savings, inclusive and exclusive of carbon costs
  - sensitivity analysis around the national carbon values and discount rates.

The SAT4P outputs also align with IS ratings including:

- CO_2eq emissions for scope 1 and 3 emissions – for each lifecycle phase
- quantities of materials used, recycled and disposed of as landfill (tonnes)
- EnviroPoints – as used in the IS Materials Calculator
- economic outputs – for options analyses.

SAT4P may be used to complement the ISC rating process; however, it is not intended to replace the IS Materials Calculator.

5.3 Exclusions

SAT4P is lifecycle sustainability assessment tool that calculates economic and environmental outputs based on pavement design and other pavement attributes. SAT4P outcomes can help inform pavement designs; however, **SAT4P is not a pavement design tool.** Users of SAT4P should always engage with a suitably qualified and experienced pavement engineer regarding pavement designs that are expected to be implemented.

Further exclusions of SAT4P include:

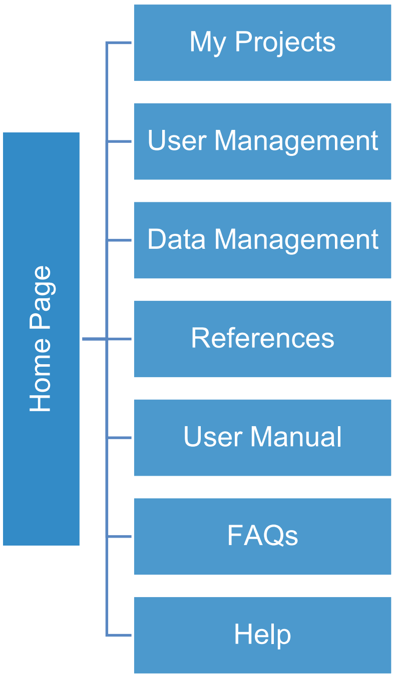
- the assessment of non-pavement infrastructure elements, such as bridges, culverts, drainage, earthworks, vegetation clearing, delineation, lighting, signals and signage (note: a proposed later stage of the project will conduct a feasibility assessment of the inclusion of these elements in possible future developments of the model)
- the quantification or economic evaluation of pavement sustainability co-benefits other than GHG emissions
- the identification and evaluation of safety impacts – these should be considered separately
- government 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
- additional requirements under ISC Design and As Built Ratings v2.0 (and subsequent releases), beyond those identified Section 10.

6 Structure and Operation

6.1 Structure

SAT4P's high-level structure is shown in Figure 6.1.

Figure 6.1: SAT4P web tool structure



The structure includes the following:

- Home page – launching page, providing an overview of the software and a starting point to navigate the software (accessible following sign-in and acceptance of product disclaimers)
- My Projects – the operational component of SAT4P and the main data entry workflow and results section
- Data Management – data administration/management
- User Management – user administration/management (visible only to registered administrators)
- References – data references
- User Manual –PDF user manual
- Frequently Asked Questions (FAQs)
- Help – a web-service helpdesk function.

Data management, user management and SAT4P references are detailed in the SAT4P User Manual (accessible from within the software and as a separate, stand-alone document).

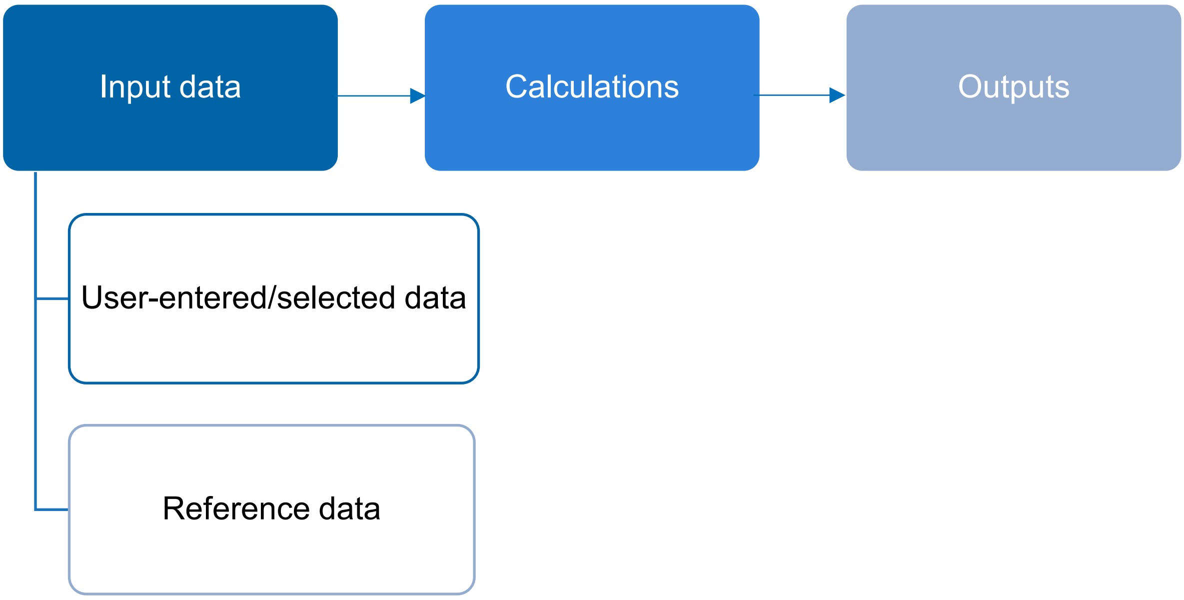
6.2 Operation

My Projects is the main operational component of SAT4P. The key elements of its operation are:

- user-entered project- and case-specific data (detailed in Section 7)
- reference (or default) data (detailed in Section 8)
- model calculations (detailed in Section 9)
- SAT4P outputs (detailed in Section 10).

An overview of the linkages between SAT4P's key operational elements is shown in Figure 6.2.

Figure 6.2: SAT4P operational elements



7 User-entered Data

SAT4P requires various inputs to calculate environmental and economic impact outputs.

With reference to in-software guidance and the SAT4P User Manual, users are guided through the data entry steps, from creating a new project and entering the pavement design details through to the generation of comparative lifecycle economic and sustainability results.

Throughout the assessment, users may:

- select input data from drop-down lists that are built into SAT4P
- enter assessment-specific data (e.g. pavement designs, project/site-specific parameters and expert judgements)
- add custom data, where applicable.

When setting up a new project, users need to establish the assessment basis (see Section 7.1), which includes assessment parameters that are common to both the base case and the alterative case(s).

Once the project is set up, users need to enter pavement option-specific input data for the base case and alternative case(s). This data entry is broken down into 7 steps (as shown in Figure 7.1):

1. pavement design
2. construction
3. maintenance
4. EoL
5. transport (of materials)
6. use phase
7. sensitivity (analysis).

Figure 7.1: Project data input sections – navigation tabs

7.1 Assessment Basis

The assessment basis, which defines the comparison parameters and assessment period, is presented in Table 7.1.

Table 7.1: Assessment basis input data

Input data	Explanation
Project name	An identifier of the project or assessment, Naming could include all or some of the following: • project information e.g. Test project 1 • location detail e.g. Regional highway NW region • design information e.g. Warm-mix asphalt in local government
Base/alternative case pavement name	An identifier of the base or alternative cases, e.g. standard hot mix asphalt pavement
Assessment date	An identifier of when the assessment was conducted, e.g. today's date
Assessment period – between 1 year and 100 years	Number of years to include in the 'lifecycle' assessment. This may be the same or longer than the pavements' design lives to include or exclude EoL processes and/or residual asset values.
Opening year	The opening year is defined as the year the asset is commissioned for operation, e.g. 2024. It establishes the basis to apply the national carbon values.

Input data	Explanation
	SAT4P assumes all construction activity occurs in year zero (even if construction was to take several years). The opening year is defined as Year 1 and is the first year of operation.
Pavement length (in kilometres)	Establishes an element of physical assessment boundary. For m^2-based assessments, users should enter a value of 0.001 (kilometres).
Pavement width (in metres)	Establishes an element of physical assessment boundary. For m^2-based assessments, users should enter a value of 1.0 (metres).
Number of lanes	Establishes an element of physical assessment boundary. Drop-down list containing a multiplier value – must be a whole number.
Discount rate (%)	Discount rates discount future costs. They are used to calculate the PVs of the lifecycle pavement costs. Discounting is an important part of a cost-benefit analysis (CBA). A discount rate considers both the time value of money and the alternative use to which the financial capital could have been applied. CBAs typically involve comparing benefits and cost streams that occur over long timeframes; 7.0% is a standard default discount rate for infrastructure projects in Australia (TMR 2011).

Note: The state where the assessment is undertaken is linked to the state of the user registration. For example, TMR-registered users (and their contractors) will draw upon Queensland-specific SAT4P data calculations. Similarly, Main Roads-registered users (and their contractors) will draw upon Western Australian-specific data.

7.2 Pavement Design

In SAT4P, pavement design refers to pavement layers, including select fill layers and the subgrade. The pavement design input data is shown in Table 7.2:

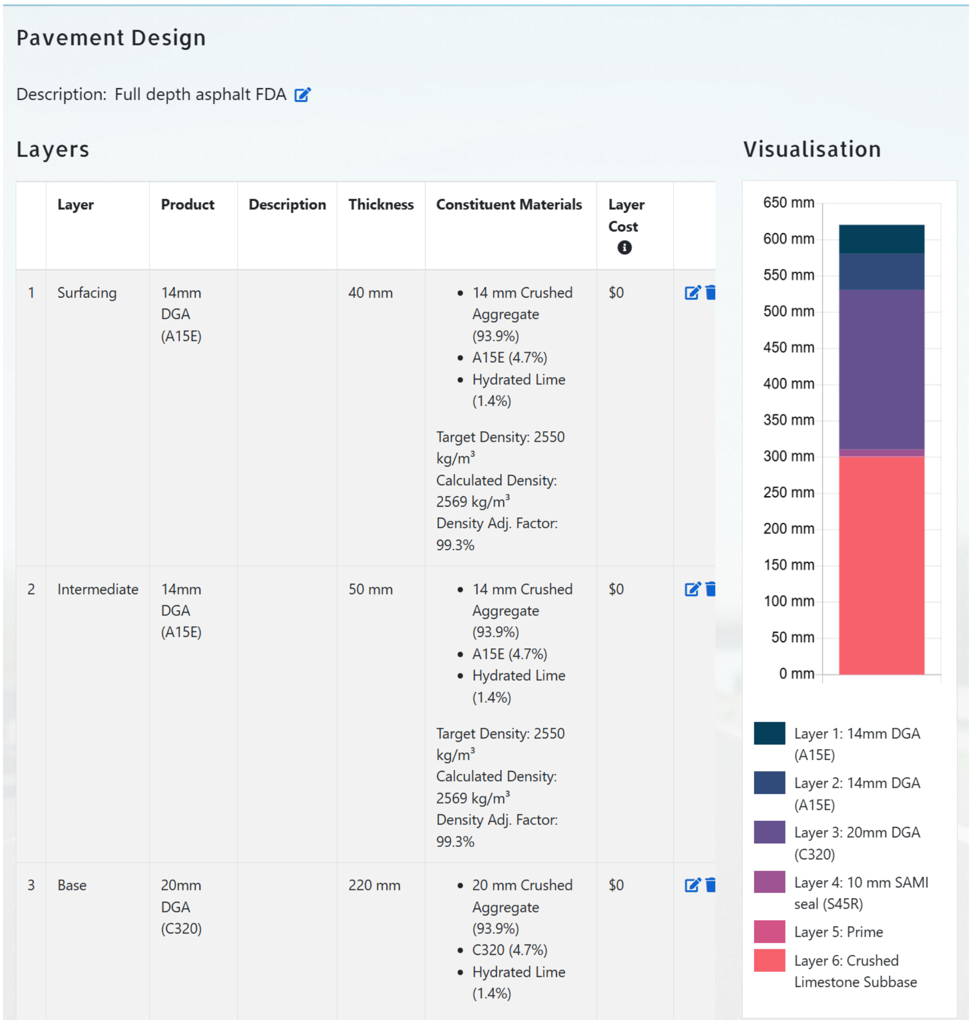
Table 7.2: Pavement design input data

Input data	Explanation
Pavement description	A short 'free-text' description (for user reference only), e.g. DGA with AC14. Descriptions help users differentiate between alternative designs within an assessment.
Layer	Identifies a unique layer name from a drop-down list (e.g. surface, base, subgrade). Several layers can be added to build the pavement design.
Select product (using either the 'Load from Product Library' or '+Add New Product' options)	Each layer is made up of pavement products (e.g. AC14) that are defined by one or more materials (e.g. aggregate, binder, additive). Pavement products are selected from the Product Library. Pavement products are verified combinations of constituent pavement materials referenced to specifications. New or alternative products can be created by clicking on the '+Add New Product' button (refer to the User Manual for guidance on selecting, amending and creating new pavement products).
Amount and unit (of measure)	SAT4P allows material amounts to be entered in different units of measure. Available units include: • mass % • L/m^2 • m^2/m^3 • kg/m^2 Amounts refer to the value of material within the layer in terms of the specified unit of measure. For mass percentage, the total material amounts must add up to 100% (a notification will appear if the total does not equal 100%). There are no such constraints when using L/m^2, m^2/m^3 or kg/m^2 units.
Layer thickness	Layer thickness (in millimetres). Note layer thicknesses are automatically calculated for sprayed sealing products, based on their spread and spray rates and induvial material densities.
Target density	SAT4P calculates the pavement layer density (kg/m^3) based on the compacted density values of each material (if the layer is a composite layer made up of a combination of materials) in the layer. Users can specify a target density (kg/m^3) for each layer when adjusting the calculated values. This adjustment applies a factor to modify the mass of material used as less compacted layers reduce the mass required.

Input data	Explanation
Layer description	A short 'free-text' description (for user reference only) for pavement layers, e.g. 50 mm asphalt surface. Layer descriptions help users differentiate between different layers within a pavement design.

The pavement design screen shot, including pavement design details and visualisation by layer thickness, are shown in Figure 7.2.

Figure 7.2: Pavement design screen shot



Note: Constituent materials and density values are populated from the Product Library. Layer costs are calculated based on pavement assessment parameters and pavement product unit rates (also from the Product Library).

7.3 Pavement Construction

The pavement construction inputs section is broken down into 2 tabs:

1. existing pavement removal (optional, if applicable)
2. new pavement construction (required).

The removal and construction processes contribute to the total emissions, depending on the amount of fuel required to complete the construction processes. Site works emissions are based on diesel consumption, whereas the emissions generated by the manufacture of off-site materials (e.g. hot mix asphalt) can originate from a mix of fuels and energy sources (e.g. diesel, natural gas and electricity). State-specific electricity emissions factors are used in the calculations.

The removal of the existing pavement is a preconstruction activity that can be used for road upgrade projects where an existing pavement is present. This step is optional and should not be used for new, greenfield road projects or when undertaking new pavement design assessments that are not linked to a specific project.

When undertaking a formal LCA, users should be conscious of the lifecycle boundaries of the assessment and careful not to double-count processes that may be considered in the EoL stage of the existing pavement's lifecycle. In formal LCAs, users will need to clarify which processes are included in the LCA.

The construction input data is shown in Table 7.3.

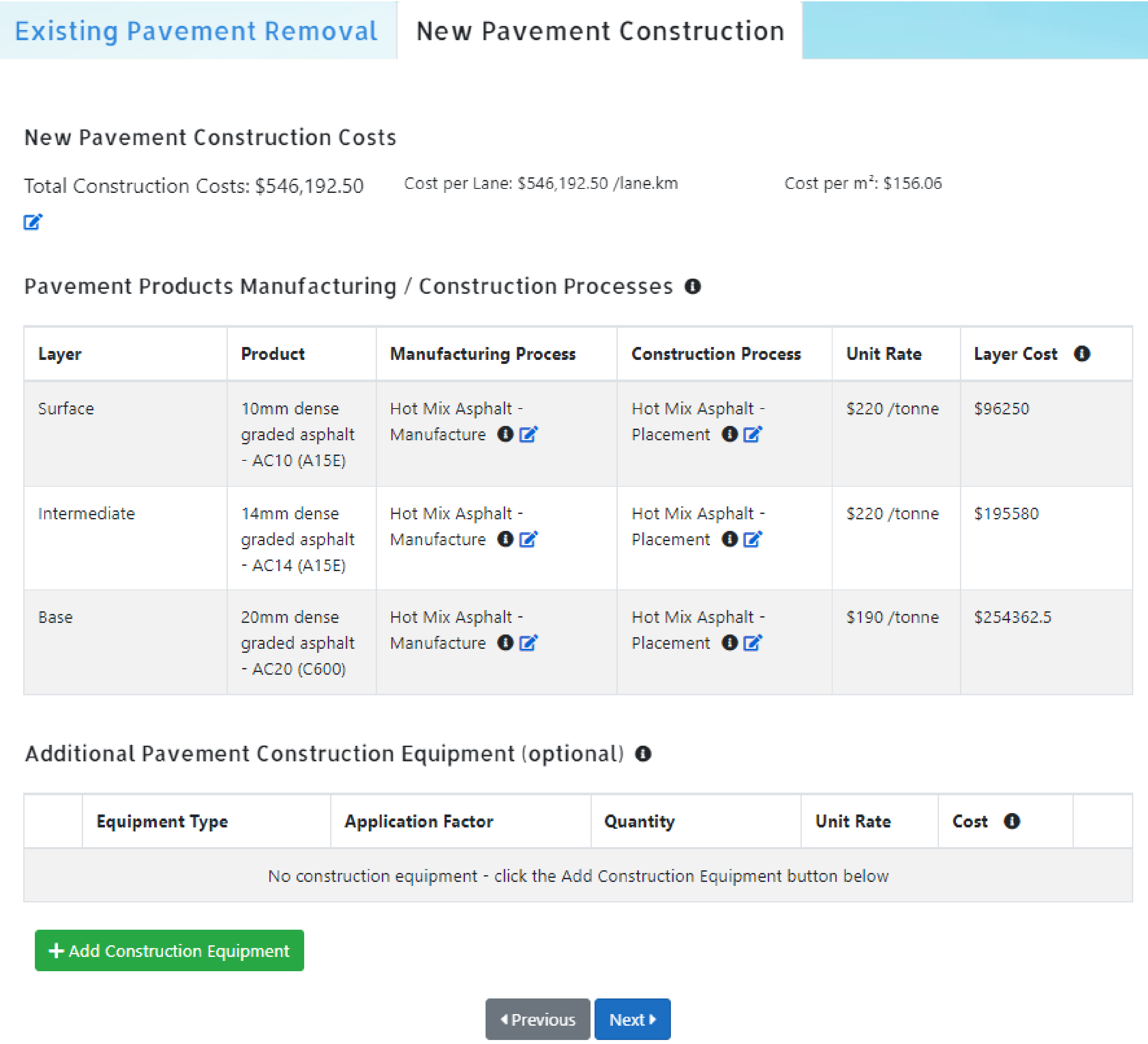
Table 7.3: Construction (including preconstruction removal) input data

Input data	Explanation
Existing pavement removal (optional, if applicable)	
Pavement removal processes: • Process type • Removal process description • Density (kg/m^3) • Removed area (m^2) • Thickness removed (mm) • Mass removed (tonnes, auto calculated) • Recycled (%) • Re-used on site (%)	Pavement removal process types include excavating, grading and profiling. 'Removal Process Description' allows free text to describe the removal process. Density – removed area and thickness of pavement removed are input values used to calculate the mass of material removed (tonnes). The area removed is the proportion of the total surface area; it is defined by the physical asset boundaries of width and length. The percentage of material that is reused on site, or recycled, splits the total mass of material removed into 3 different waste streams (with the percentage remaining assumed to be sent to landfill). The total of reused and recycled material percentages cannot exceed 100. If no values are entered, then SAT4P assumes all material removed is sent to landfill.
Additional pavement removal equipment (optional): • Equipment type • Application factor • Quantity (hours)	Additional pavement removal equipment is an optional entry to capture equipment and machinery use not captured in the removal processes. Equipment types include removal machinery and associated equipment options (e.g. truck haulage, mobilisation, lighting towers, etc.). Application factor options include 3 options (low, medium or high) where: • Low = light road maintenance, machine movement, idling, etc. • Medium = average earthmoving, scraper hauling, road mix work, etc. • High = ripping, heavy pushing, operations under full load, etc. (Transport Authorities Greenhouse Group 2013). Quantity is the number of hours the equipment is operating.
Total removal costs	Pavement removal process and additional pavement removal equipment costs are auto calculated using cost data. Users can edit the total removal cost by adjusting the regional cost index factor or specifying an alternative total removal cost value.
New pavement construction (required)	
Pavement products manufacturing/ Construction processes • Manufacturing process	Material manufacturing processes refers to the heating and mixing of materials to produce a product. Manufacturing process types include: • hot mix asphalt • warm mix asphalt • concrete.
Pavement products manufacturing/ Construction processes • Construction processes	Pavement construction processes refers to the placement of the pavement products. Pavement construction processes include: • hot mix asphalt (placement) • warm mix asphalt (placement) • concrete (placement) • stabilised material (placement) • unbound granular material (placement) • in situ stabilisation (bitumen, cement or lime) • microsurfacing/slurry sealing • seal single coat • two coat seal • prime (bituminous) • crack sealing • sweeping preparation. Note: placement and stabilisation processes are expressed in units of m^3. Surface layer-only applications are expressed in units of tonnes.

Input data	Explanation
Additional pavement construction equipment (optional): • Equipment type • Application factor • Quantity (hours)	Additional construction equipment is an optional entry to capture equipment and machinery use not captured in the pavement construction processes. Equipment types include removal of machinery and associated equipment options (e.g. truck haulage, mobilisation, lighting towers, etc.). Application factor options include low, medium or high, where: • Low = light road maintenance, machine movement, idling, etc. • Medium = average earth moving, scraper hauling, road mix work, etc. • High = ripping, heavy pushing, operations under full load etc. (Transport Authorities Greenhouse Group 2013). Quantity is the number of hours of operations of the equipment.
Total construction costs	Pavement construction process and additional pavement construction equipment costs are auto calculated using cost data. Users can edit the total construction cost by adjusting the regional cost index factor or specifying an alternative total construction cost value.
Custom processes and equipment (optional, if applicable)	
Custom processes: • Scope 1 and 3 emissions • Reference • Comments and assumptions.	For custom processes, users/administrators will need to provide additional technical information, including: • specifying the process type (free text) • specifying the diesel usage of the process (L/m^3) • specifying the Scope 1 and 3 emissions (tCO_2eq/m^3) • specifying the cost of the process as a unit cost (users can choose units per L, m^2 or m^3) • providing a data reference • adding comments and/or assumptions.
Custom equipment: • Scope 1 and 3 emissions • Reference • Comments and assumptions.	For custom processes, users/administrators will need to provide additional technical information, including: • specifying the equipment type (free text) • specifying the diesel usage of the equipment (L/m^3) • specifying the Scope 1 and 3 emissions (tCO_2eq/m^3) • specifying the cost of the process as a unit cost (users can choose units per L, m^2 or m^3) • providing a data reference • adding comments and/or assumptions.

Figure 7.3 illustrates a screen shot of the pavement construction screen, including sample inputs for overall construction costs, asphalt manufacturing and the placement for each applicable pavement layer. The existing pavement removal tab is visible to the left of the construction tab.

Figure 7.3: Pavement construction screen shot



7.4 Maintenance

SAT4P allows users to select a predefined maintenance schedule or create a custom maintenance schedule based on the project requirements.

Maintenance activities occur and accrue costs over the pavement's lifecycle, and the maintenance schedules accordingly allocate maintenance activities to years within the assessment period. Maintenance schedules include:

- periodic maintenance (e.g. pot-hole repair, heavy patching, resurfacing and resealing)
- rehabilitation or reconstruction (e.g. major layer replacement).

Note: resurfacing, rehabilitation and reconstruction activities trigger a reset of the pavement surface roughness (IRI values), which has a positive impact on the reduction of use phase emissions.

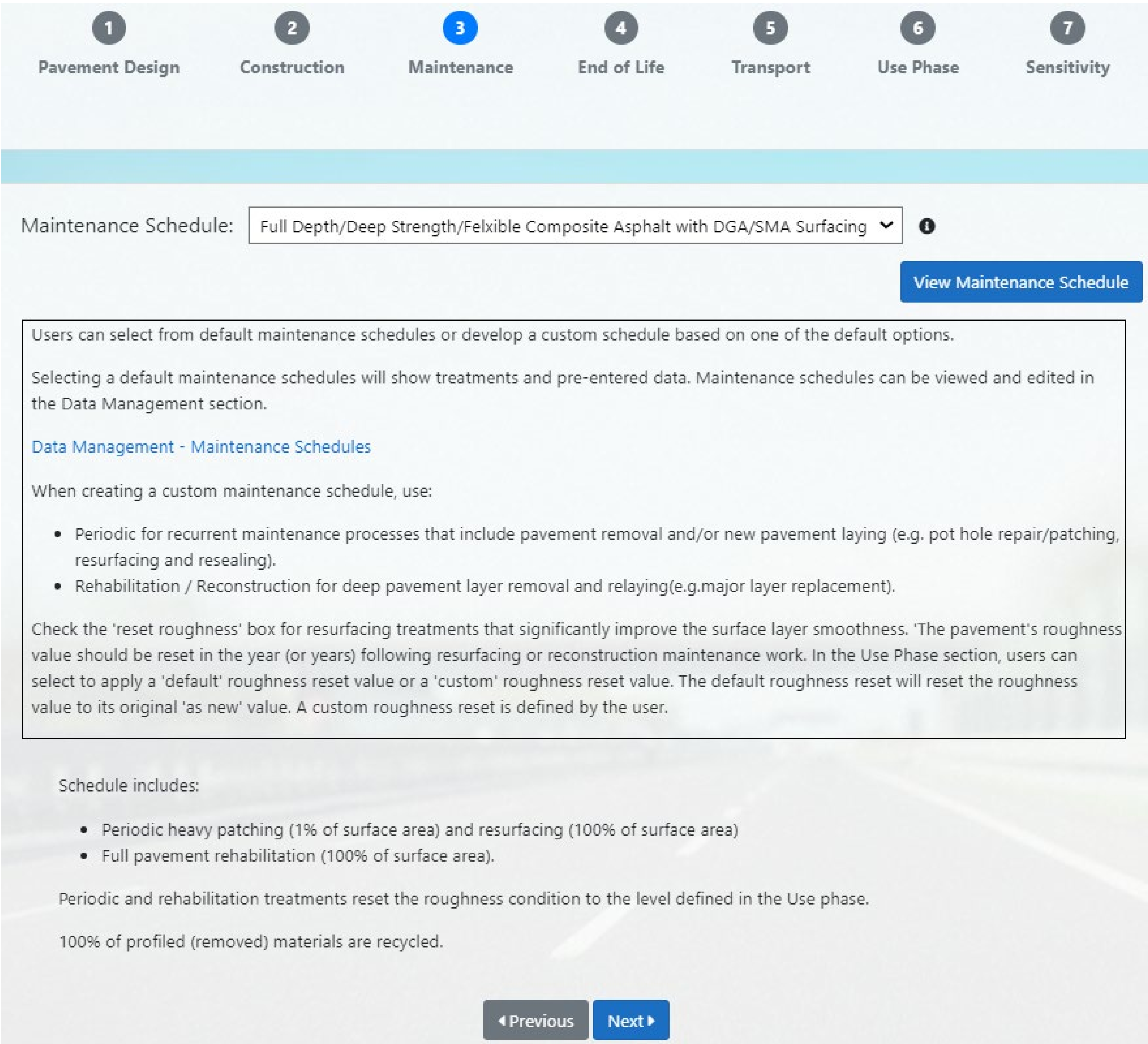
The maintenance input data is shown in Table 7.4.

Table 7.4: Maintenance input data

Input data	Explanation
Maintenance schedule (required)	
Maintenance schedule	Maintenance schedules allocate maintenance activities to years in the pavement's lifecycle (e.g. every 5 years within the assessment period). Maintenance schedules include the following maintenance activities: • periodic maintenance (e.g. resurfacing and resealing) • rehabilitation or reconstruction (e.g. major layer replacement). SAT4P allows users to select a predefined maintenance schedule or to create a custom maintenance schedule (refer to the User Manual for guidance on creating a new, or editing an existing, maintenance schedule). No further information is required for predefined maintenance schedules. A predefined maintenance schedule, however, can be edited and tailored to specific pavement or project needs.
Maintenance costs	Maintenance costs are auto calculated using unit rate cost data for defined removal processes, pavement products and processes according to the maintenance schedule.

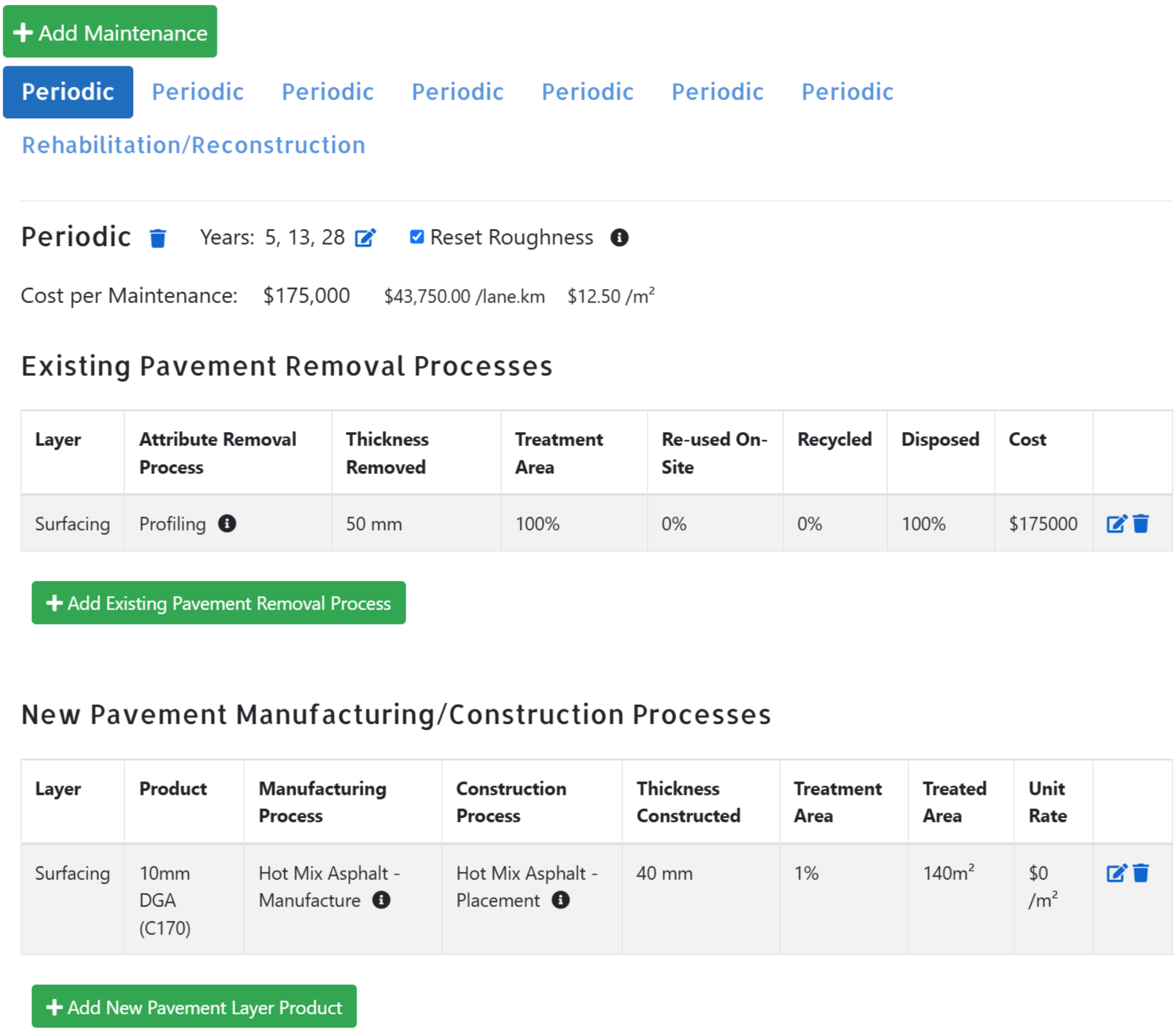
The pavement maintenance screen shot is shown in Figure 7.4, where a default maintenance schedule has been selected.

Figure 7.4: Pavement maintenance screen shot (selecting a predefined maintenance schedule)



The pavement maintenance screen shot, where a custom maintenance schedule is being prepared, is shown in Figure 7.5. In this case, it is a copy of one of the predefined schedules, allowing the user to modify the default options. A period maintenance activity that removes and replaces 1% of the surface area (signifying a patching activity) in years 5, 13 and 28 is also shown in Figure 7.5. Additional periodic and rehabilitation/reconstruction activities in the schedule are shown as tabs visible to the right of the current periodic tab.

Figure 7.5: Pavement maintenance screen shot (modifying a pre-defined maintenance schedule)


+ Add Maintenance

Periodic Periodic Periodic Periodic Periodic Periodic Periodic

Rehabilitation/Reconstruction

Periodic Years: 5, 13, 28 Reset Roughness

Cost per Maintenance: $175,000 $43,750.00 /lane.km $12.50 /m²

Existing Pavement Removal Processes

Layer	Attribute Removal Process	Thickness Removed	Treatment Area	Re-used On-Site	Recycled	Disposed	Cost	
Surfacing	Profiling	50 mm	100%	0%	0%	100%	$175000	

+ Add Existing Pavement Removal Process

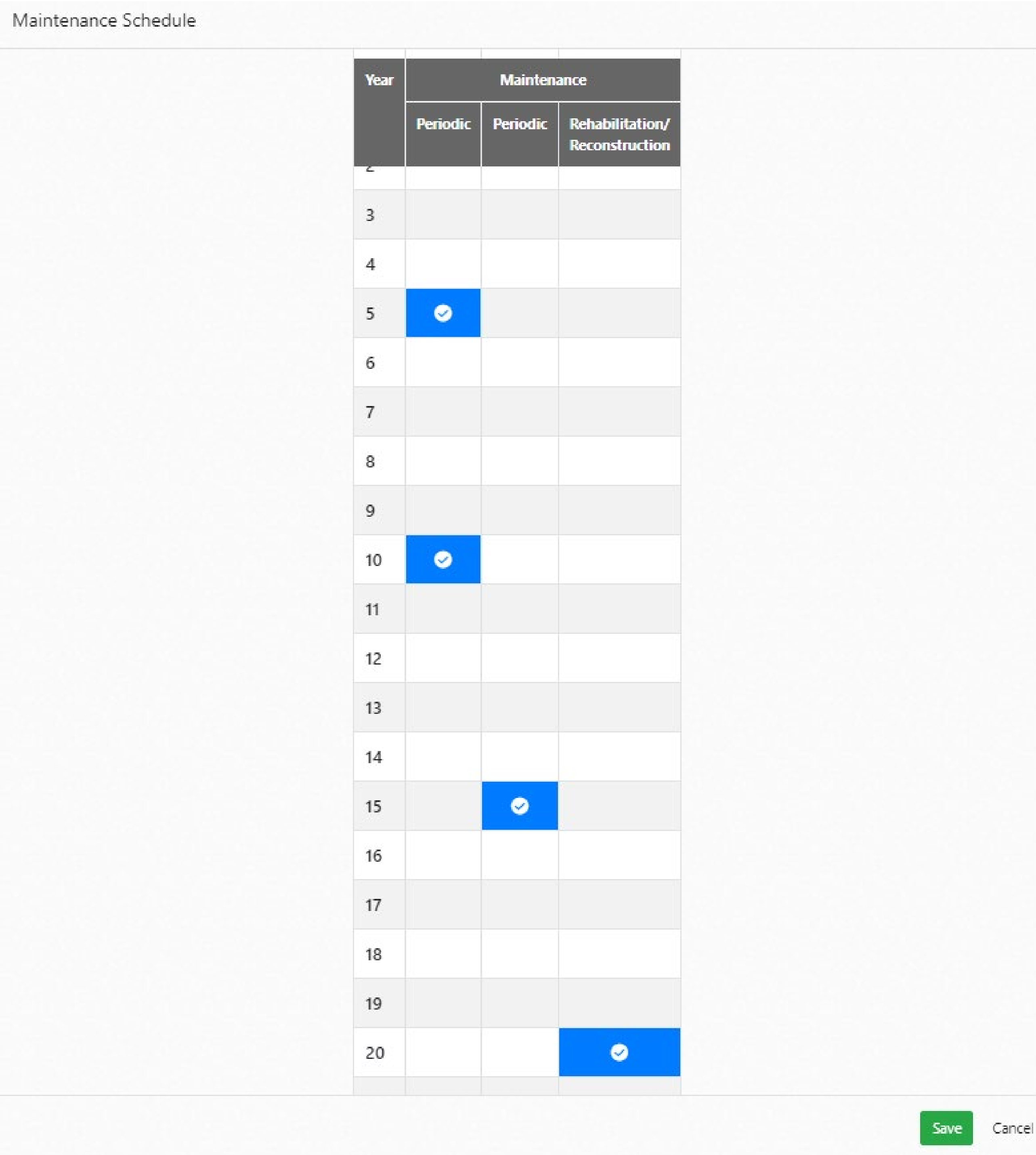
New Pavement Manufacturing/Construction Processes

Layer	Product	Manufacturing Process	Construction Process	Thickness Constructed	Treatment Area	Treated Area	Unit Rate	
Surfacing	10mm DGA (C170)	Hot Mix Asphalt - Manufacture	Hot Mix Asphalt - Placement	40 mm	1%	140m²	$0 /m²	

+ Add New Pavement Layer Product

Maintenance interval frequencies can be viewed and amended by clicking on the 'View Maintenance Schedule' button. Figure 7.6 shows the editable maintenance schedule view.

Figure 7.6: Pavement maintenance schedule view



7.5 End of life

SAT4P calculates an EoL asset value. It comprises a residual asset value and an optional salvage value. The EoL value calculated at the end of the assessment period is presented in PV terms, with future values discounted by the central discount rate. Both the assessment period and the central discount rate are both defined in the New Project assessment setup.

The EoL input data, along with the initial construction cost data, is used to determine the economic value of the pavement asset at the end of the assessment period.

7.5.1 Economic Value of the Pavement Asset at the End of the Assessment Period

The economic value of the pavement asset at the end of the assessment period is made up of 2 components:

1. residual asset value
2. salvage value.

Both are single values that are attributed to the final year and incorporated in the lifecycle PV for the entire assessment period. These value concepts are related but independent of each other. While existing guidance on residual value (e.g. TMR's guide to whole-of-life costing of heavy-duty pavements) and many practitioners use these terms interchangeably, the following text describes the differences in how the concepts are applied in SAT4P.

Residual value

The residual asset value of a pavement is the value at the end of the assessment period as defined by the user (e.g. 40 years). The value is determined by SAT4P based on a set of inputs that are provided by the user. These inputs are:

- initial construction costs (including material and transport costs)
- the design life of the pavement surface (which needs to be reflected in the maintenance schedule and which has an impact on the deterioration profile of the pavement over time), e.g. 10 years
- the design life of the remainder of the pavement (i.e. layers below the surface layers), e.g. 40 years
- the value of the pavement surface as a percentage of the total pavement value (i.e. construction costs), e.g. 10%
- the assessment period, e.g. 40 years.

The residual asset value of the pavement at the end of the assessment period is calculated by depreciating the initial pavement asset value (construction costs). Depreciation for the pavement base (layers below the surface) follows a linear curve based on its design life. Depreciation for the pavement surface uses a separate linear curve based on the overall pavement design life. The depreciation curves will be reset through pavement maintenance activities, such as resurfacing or reconstruction, which increase the values of the pavement surface and/or base and other layers.

Salvage value

Salvage value is an optional adjustment to the EoL value. The salvage value recognises the ongoing value of the materials in the pavement that could be reused, or 'salvaged', in another pavement – either in the same alignment or as a new pavement in a different alignment/location. An example is asphalt that has a potential second life as reclaimed asphalt pavement (RAP). In such cases, even if the pavement reaches the end of its operational life, there is a clear value of the material left in the pavement.

Salvage value is an estimate of the economic value of the in situ materials at the end of the assessment period. The salvage value is determined by estimating the savings associated with new materials; they should be inclusive of all reusable materials. There are several ways to estimate the salvage value, including:

- as a proportion of the replacement costs
- as the difference between the initial construction cost and the expected full rehabilitation costs
- as the value of the raw materials at the end of the assessment period, minus any removal and processing costs.
  If the quality of the materials has been compromised through their use in previous treatments (e.g. cement stabilisation) or if they are non-standard materials (e.g. crushed concrete, or crumb rubber or plastic), then this may detrimentally affect the future value of the materials. Expert judgement is needed.

Each of these estimation approaches require consideration of the future use of the road alignment, the feasibility of treatment options to upgrade or strengthen the existing pavement and whether the pavement would need to be removed before any reconstruction activity. These considerations could increase or decrease the estimated salvage value of the materials in the pavement. For example, if the pavement is at the end of its useful life and has no potential to be upgraded (e.g. the road has been replaced by a new bypass), there could be a different salvage value as compared to if there were genuine opportunities to treat or upgrade the existing pavement. The extent and direction of the difference depends on the respective economic value of the options considered.

The salvage value option should be used when there is a real expectation that the pavement materials will be sold or reused in a future pavement and there is a reasonable expectation of a positive outcome. In all other cases, the salvage value should be set to zero.

All data needed to calculate the environmental impacts of the disposal of waste pavement materials (i.e. quantity of material removed and proportion sent to landfill) is provided in the construction and maintenance data entry screens (where applicable). SAT4P assumes that all landfilled pavement materials are inert construction and demolition waste, and emissions are not generated during its decomposition.

Additional EoL environmental impacts associated with material disposal arise from the transportation of the materials away from the site (either to a recycling facility or landfill). These emissions are captured in the materials transport phase (see Section 0).

The EoL input data is shown in Table 7.5.

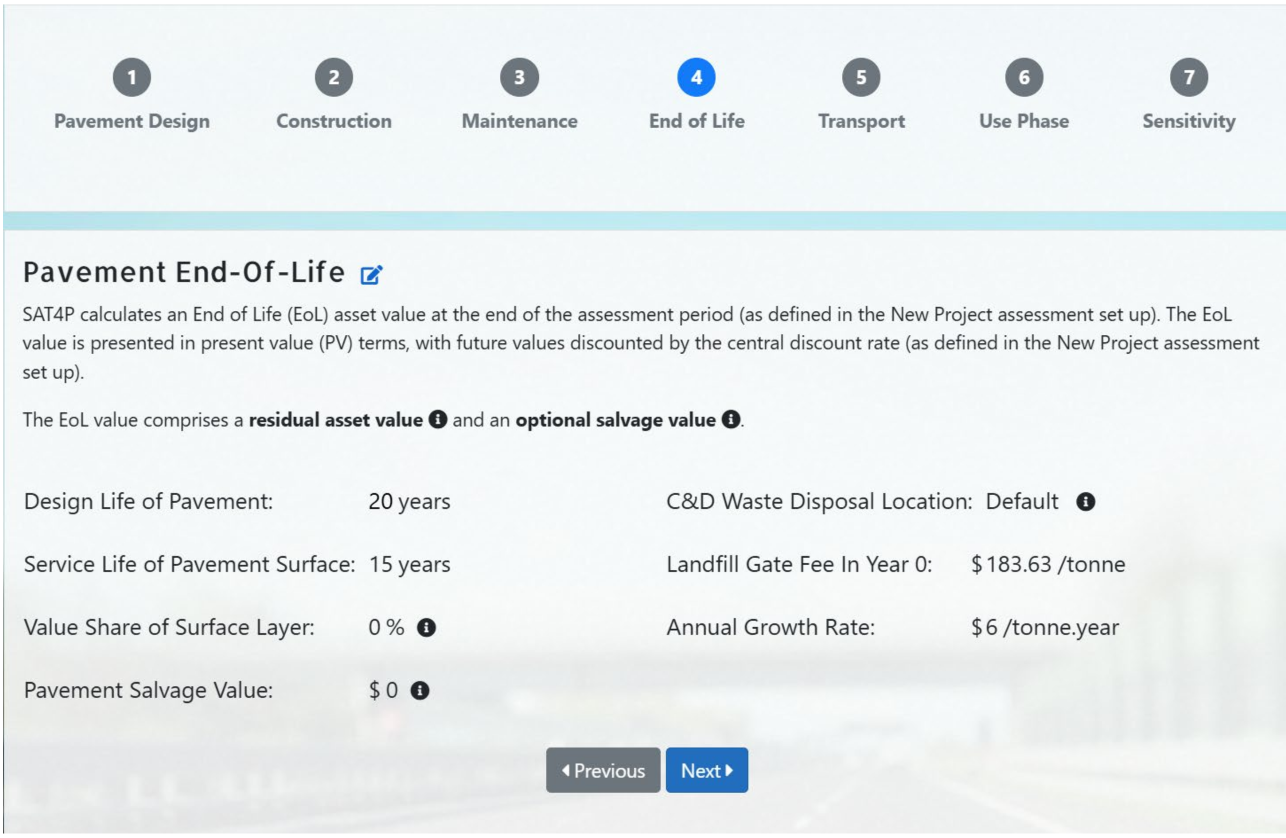
Table 7.5: End of life input data

Input data	Explanation
Design life of the pavement	The design life (in years) of the pavement layers below the surface layer (or wearing course). This may be the same as, or greater than, the design life of the surface layer.
Service life of pavement surface	The design life (in years) of the surface layer (or wearing course). This should be equal to, or less than, the design life of the entire pavement
Value share of pavement surface	The percentage of total construction costs attributable to the surface pavement construction costs. The value share of the surface is an estimate of the construction cost of the surface layer as a percentage of the total construction cost. This percentage value is used to calculate the EoL residual asset value – one of the EoL cost elements. The value share of the surface layer is auto calculated.
Pavement salvage value (optional)	The salvage value recognises the ongoing value of the materials in the pavement that could be reused, or 'salvaged', in another pavement. Salvage value is an optional input that adjusts the economic value of the pavement at the end of the assessment period.
C&D[1] waste disposal location	Location of project according to region. The selection of the region activates the calculation of predefined waste disposal fees and levies, and growth rates. The user can also enter custom waste disposal values. See User Manual for details.
For custom C&D waste disposal locations: • Landfill gate fee in year 0 • Landfill gate fee annual growth rate • Additional disposal costs	Gate fee in year 0 and additional disposal costs are entered in units of $/tonne. Landfill gate fee annual growth rate costs are entered in units of $/tonne.year.

1. Construction and demolition

The EoL screen shot, including sample inputs, is shown in Figure 7.7.

Figure 7.7: End-of-life screen shot



7.6 Transportation/Materials Haulage

The transport or haulage inputs for pavement materials is specified as:

- materials transported to site
- materials transported from site.

This breakdown allows details of the transport (vehicle types, transportation distances, etc.) to be specified for individual pavement products, noting that different products can be sourced from different locations and transported using different vehicle types. Materials transported away from a site (either to a recycling facility or landfill site) are considered homogeneous, thus not requiring more detailed specifications.

Transport costs are embedded in the product and removal costs data. There is no user requirement to enter transport cost data unless adding custom products or processes (see User Manual for guidance).

Transport input data is shown in Table 7.6.

Table 7.6: Materials transport/haulage input data

Input data	Explanation
Materials transported to site	
Haulage details are defined for each pavement product selected, including: • single or return trip • vehicle type • haulage distance • custom vehicles (optional).	A single trip includes the loaded leg of the materials transported. A return trip assumes an unladen (empty) return trip. Vehicle type options are: • 2-axle truck (rigid) • 3-axle truck (rigid) • 4-axle truck (rigid) • 3-axle articulated truck • 4-axle articulated truck • 5-axle articulated truck • 6-axle articulated truck • B-double/Rigid truck & 5-axle trailer (truck & dog) • double road train • triple road train. Haulage distance (km) refers to the travelling distance between the product source (i.e. quarry or plant) and the pavement site. Note: return trips will double the haulage distance (i.e. one laden leg, one unladen leg).
Materials transported from site	
Haulage details are assumed equivalent for all material removed, including: • single or return trip • vehicle type • haulage distance • custom vehicles (optional).	A single trip includes the loaded leg of the 'waste' materials transported from the site to either a recycling facility and/or a landfill site. A return trip assumes an unladen (empty) trip to the site for picking up waste materials. Vehicle type options are as specified above. Haulage distance (km) refers to the distance between the pavement site and the recycling facility (i.e. RAP plant) or landfill site. Note: return trips will double the haulage distance (i.e. one laden leg, one unladen leg).

The transport screen shot, including product details, vehicle types and haulage distances, and auto-calculated removal quantities for alternative EoL destinations, is shown in Figure 7.8.

Figure 7.8: Transport screen shot

Materials Transport To Site

One-way or return trip? Return Trip

Product	Material	Vehicle Type	Haulage Distance	
10mm dense graded asphalt - AC10 (A15E)	A15E	B-Double/Rigid Truck & 5-axle Trailer (Truck & dog)	20 km	
	Crushed Rock			
	Hydrated Lime			
	Recycled Asphalt Pavement (RAP)			
14mm dense graded asphalt - AC14 (A15E)	A15E	B-Double/Rigid Truck & 5-axle Trailer (Truck & dog)	20 km	
	Crushed Rock			
	Hydrated Lime			
	Recycled Asphalt Pavement (RAP)			
20mm dense graded asphalt - AC20 (C600)	C600	B-Double/Rigid Truck & 5-axle Trailer (Truck & dog)	20 km	
	Crushed Rock			
	Hydrated Lime			
	Recycled Asphalt Pavement (RAP)			

Materials Transport From Site

One-way or return trip? Return Trip

Step	Mass Removed	Facility Type (recycling/disposal)	Vehicle Type	Haulage Distance
Pre-Construction Removal	0.15 tonnes	Recycling	B-Double/Rigid Truck & 5-axle Trailer (Truck & dog)	20 km
Pre-Construction Removal	2.08 tonnes	Disposal	B-Double/Rigid Truck & 5-axle Trailer (Truck & dog)	20 km

7.7 Use Phase

The environmental impacts (i.e. GHG and other air-borne emissions) from the pavement's use phase originate from the vehicles that drive over it during the specified assessment period. SAT4P calculates vehicle fuel use, which is then converted into environmental impacts. See Section 8.5 for details on fuel use calculations.

The use phase input data is shown in Table 7.7.

Table 7.7: Use phase input data

Input data	Explanation
Road traffic parameters, including: • average annual daily traffic (AADT) • fleet composition (from drop-down list, e.g. urban, rural or custom) • AADT growth rate (%/year) • average traffic speed (km/h) • average heavy vehicle payload • traffic flow type (uninterrupted or interrupted)	AADT is an estimate of the traffic level for year 1 of the assessment period. Selecting predefined urban or rural fleet compositions links to reference traffic data with predefined heavy vehicle traffic percentages. If the 'custom' road category is selected, the user will be able to specify detailed light and heavy fleet mixes. AADT growth rate is the expected annual growth in traffic levels (%/year). Average heavy vehicle payload (%) is an estimated average mass loading as a percentage of the allowable carrying mass of heavy vehicle traffic. If uninterrupted traffic flow is selected, then users must also select horizontal alignment (degrees/km curvature) and longitudinal grades (m/km rise and fall). If interrupted traffic flow is selected, there is no requirement for horizontal alignment and longitudinal grade selections.
Road alignment parameters, including: • horizontal road alignment • longitudinal grades.	Horizontal road alignment refers to the road's curvature (in degrees per kilometre). Longitudinal grade refers to the road's rise and fall (in metres per kilometre). Road alignment input data is only required if uninterrupted traffic flow is selected (see Section 7.7.3 on the selection of horizontal road alignment and longitudinal grade options).
Road roughness and deterioration parameters, including: • roughness value (IRI) in opening year • pavement deterioration rate • roughness reset type.	Road surface roughness value, or International Roughness Index (IRI), is specified for the opening year (i.e. year 1). It sets the starting roughness value for the newly constructed pavement and the default roughness reset value. In-software hover-tips provide guidance on converting NASRAA roughness values to IRI values. Pavement deterioration rate options include fixed value or percentage value. Deterioration rate is the value/year that the pavement deteriorates. Rates need to be defined for gradual and rapid deterioration. Roughness reset type values represent the roughness value (IRI) that the pavement returns to following resurfacing, rehabilitation or reconstruction treatments. Roughness reset type value options are default or custom. Default values equal the opening year roughness value. Custom values are defined by the user.

7.7.1 Fuel Use Models

SAT4P calculates vehicle fuel use using formulae and look-up data provided in the *Australian Transport Assessment and Planning Guidelines: PV2 Road Parameter Values* (ATAP 2016)[3]. For interrupted traffic experienced on urban and suburban arterials and freeways, SAT4P uses 2 ATAP functions: the stop–start model and the free-flow model. Both models require users to identify an average traffic speed, while the remaining model coefficients (inputs) are built into the model using data provided in the ATAP publication. The stop–start model is best used when the user has selected an average traffic speed of 60 km/h or less, whereas the free-flow model is best used when average traffic speeds are greater than 60 km/h.

For roads characterised as having uninterrupted traffic flows (typically rural roads and freeways), SAT4P allows users to select horizontal alignment (curvature) and longitudinal grades (vertical rise and fall) options that impact vehicle fuel consumption in the use phase.

7.7.2 Horizontal Road Alignment and Longitudinal Grades

The horizontal road alignment options in SAT4P are:

- 20°/km (straight)
- 120°/km (curvy)
- 300°/km (very curvy).

The vertical road alignment options are:

- 0 m/km (flat)

3 The ATAP PV2 Road Transport Parameter Values are currently being updated by the NTRO. It recommends revisiting the application of the ATAP values after the new parameter values are published.

- 40 m/km or 4% grade change over 1 km (gentle rise and fall)
- 60 m/km or 6% grade change over 1 km (moderate rise and fall)
- 80 m/km or 8% grade change over 1 km (steep rise and fall)
- 100 m/km or 10% grade change over 1 km (very steep rise and fall).

SAT4P requires users to select a combination of one horizontal and one longitudinal grade option. Section 7.7.3 provides some guidance on selecting the appropriate horizontal alignment and longitudinal grade options.

7.7.3 Guidance on Selecting Appropriate Horizontal Alignment and Longitudinal Grade Options

Users will need to apply a degree of judgement when selecting the appropriate horizontal alignment and longitudinal grade option for each road segment. The horizontal alignment and longitudinal grade options reflect the cumulative changes in the road alignment over 1 km.

Horizontal alignment

For example, for a 1 km road section that had 2 curves, each with a curvature of 10°, the 20° curvature would be the most appropriate for a relatively straight road section. Likewise, another 1 km section may have 6 curves, each with a curvature of 20°, in which case the 120° (curvy) option would be the most appropriate selection.

For each road section, determine the average cumulative horizontal alignment change per kilometre. This is calculated by dividing the total change over the section by the section's length. For instance, if a 6.5 km section has a cumulative horizontal alignment change of 150°, the average change per kilometre is 23° (150° / 6.5 km).

When selecting the most suitable horizontal alignment change option, choose the closest available option. For example, if the calculated average is 23°/km and the available options are in increments of 5°/km, select 20°/km as the closest option.

Longitudinal grades

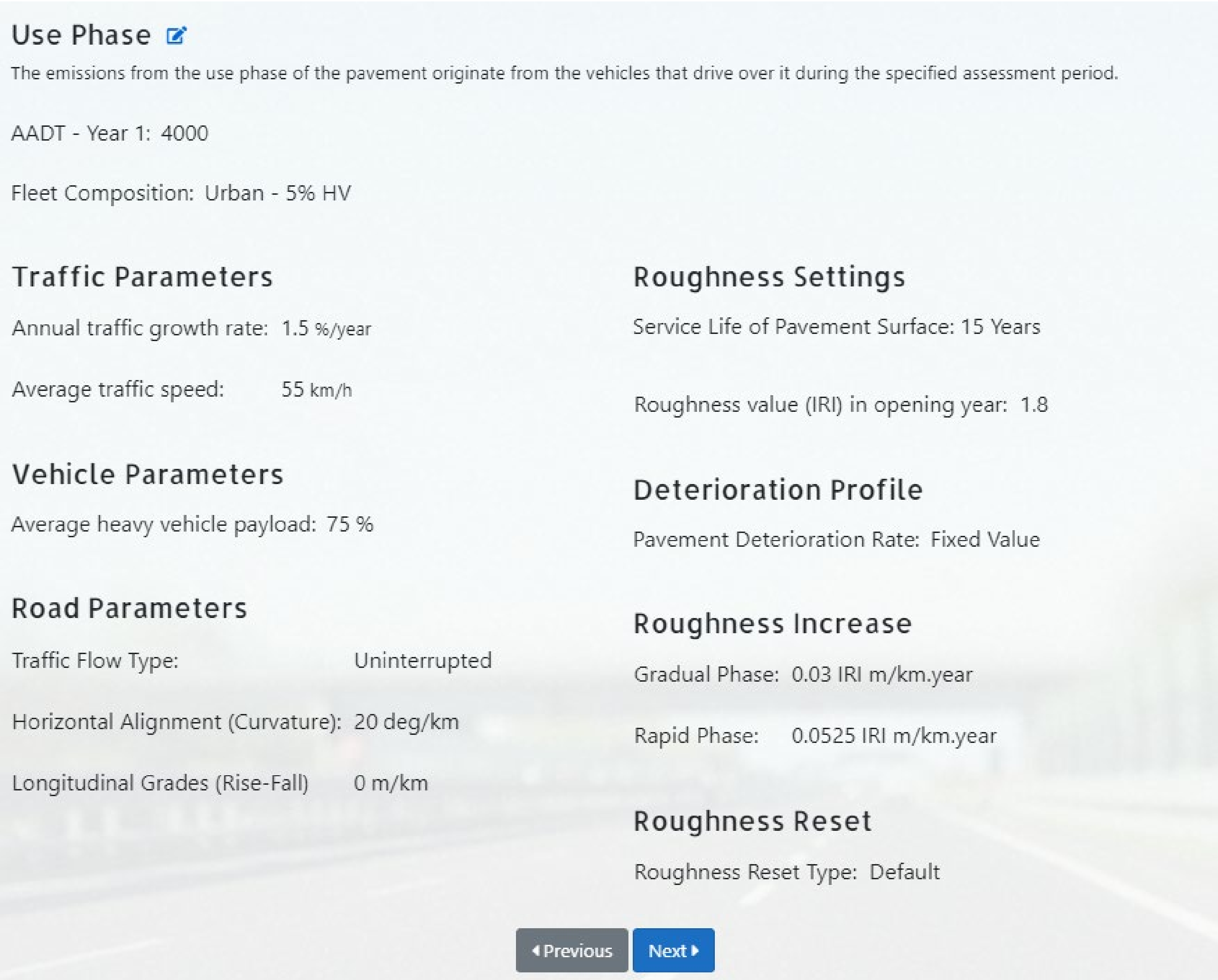
Similarly, for the longitudinal grades, the m/km is an aggregate of cumulative rises and falls over a 1 km road segment. For example, a road that has 3 rises of 10 m each and one fall of 10 m would suggest that the 40 m/km (4%) grade change option be used.

If there is uncertainty in selecting the most appropriate horizontal alignment or longitudinal grade option, consider comparing the results using both a higher and lower option as if they were different pavement design options.

For road projects where there are significant changes in the rise and fall and/or curvature – for example, there may be several kilometres of straight, flat road and then, due to geographic changes, the road may have a more curvy or hilly alignment – SAT4P users should create duplicate project assessments and define the road geometry parameter for each distinct segment. Users can aggregate multiple project segment results using the Excel outputs report function.

The phase screen shot, including sample input data, is shown in Figure 7.9.

Figure 7.9: Use phase screen shot



7.8 Sensitivity Analysis

The sensitivity analysis in SAT4P helps users understand how model outputs are affected by changes in the input variables. This is particularly useful when there is a degree of uncertainty in the value or influence of certain parameters. SAT4P automates common sensitivity analysis parameters that are the traditional sources of uncertainty by providing default 'low' and 'high' values, where the 'medium' value is the central assumption used for the key results. SAT4P applies a sensitivity analysis for the following parameters:

- discount rate (%)
- high, medium and low carbon values (A$/t$CO_2$eq) for every year until 2050, as per the national carbon values published by Infrastructure Australia (IA) and applied in accordance with IA's guidance (IA 2024).

In addition, parameters describing a potential future electric vehicle (EV) adoption rate allow users to assess the impact of lower-emissions vehicles on the use phase emissions. Default, editable values are specified for:

- EV percentage in year 1 of the assessment period
- percentage of emissions savings by replacing a conventional vehicle with an EV by considering emissions from electricity generation
- a year in which market saturation (assumed 90% EV penetration) is achieved, which may occur after the end of the assessment period.

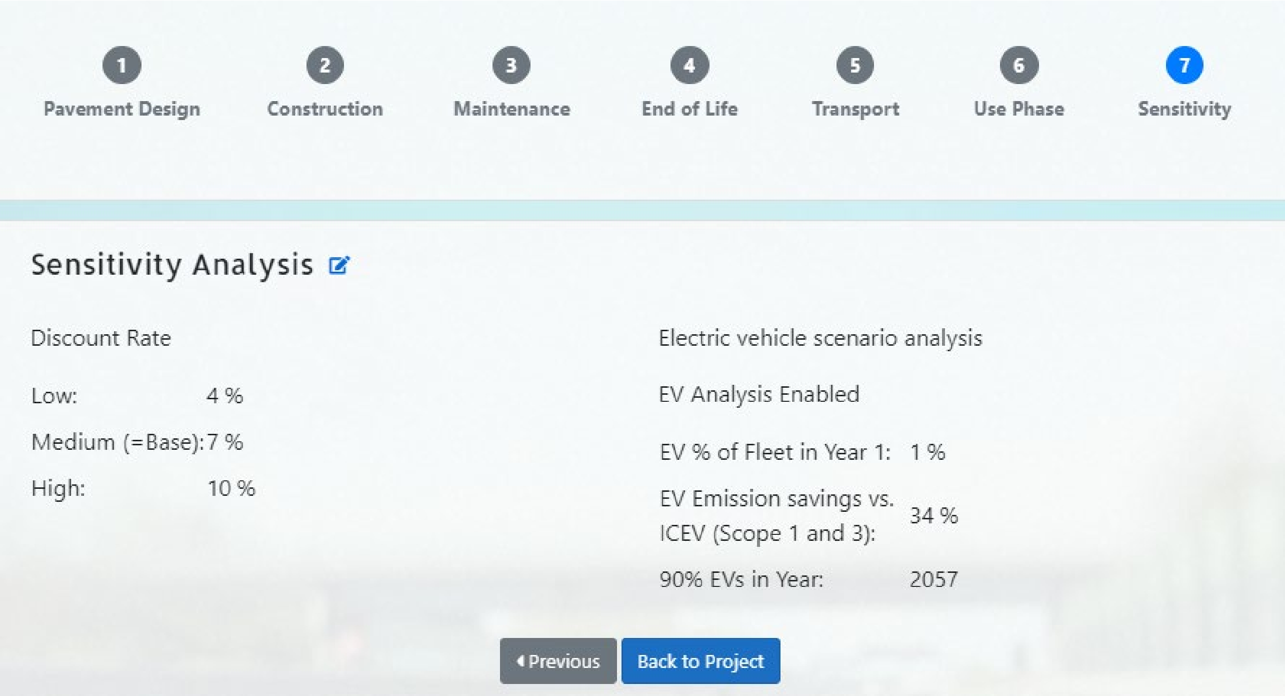
The sensitivity input data is shown in Table 7.8.

Table 7.8: **Sensitivity analysis input data**

Input data	Explanation
Discount rates	Low and high discount rates (% per year). Note central estimates are defined in the assessment basis step (see Section 7.1).
Carbon values	Low and high carbon values (A$/t$CO_2$eq). Note the national carbon values are pre-entered and viewable in the Data Management Section.
EV scenario • EV analysis enabled/disabled • EV % in fleet in year 1 • EV emissions savings vs internal combustion engine vehicle (ICEV) • 90% EV penetration in year	Turn on or off the EV scenario analysis. If EV scenario is disabled, no further input data is required. If EV scenario is turned on: • EV % in fleet in year 1 allows users to nominate the percentage of EVs present in the vehicle fleet in year 1. • EV emissions savings vs ICEVs allows users to define the relative GHG emissions benefit of EVs over ICEVs. This percentage could be up to 100% if the EV fleet is powered by clean, renewable energy sources, but it would be lower if the fleet relies on grid power. • 90% EV penetration in year refers to the year (YYYY) that EV penetration is expected to reach 90% of the total vehicle fleet. A high adoption rate will lead to an earlier 90% EV fleet penetration year.

The sensitivity screen shot, including sample input data, is shown in Figure 7.10.

Figure 7.10: **Sensitivity screen shot**



8 Reference Data

SAT4P contains reference databases for the following:

- **pavement materials**, including emissions, consumption and environmental impact factors, and material densities
- **pavement products,** including defined mixes of constituent materials sourced from TMR and Main Roads specifications along with product categories, densities and unit costs
- **construction and removal processes**, including emissions and consumption factors and unit costs
- **maintenance processes**, including predefined maintenance schedules
- **various data to calculate use phase emissions**, including vehicle classifications, fuel consumption and emissions data
- **cost data,** incorporated across various databases
- **national carbon values**, used for determining the GHG values and in sensitivity analyses.

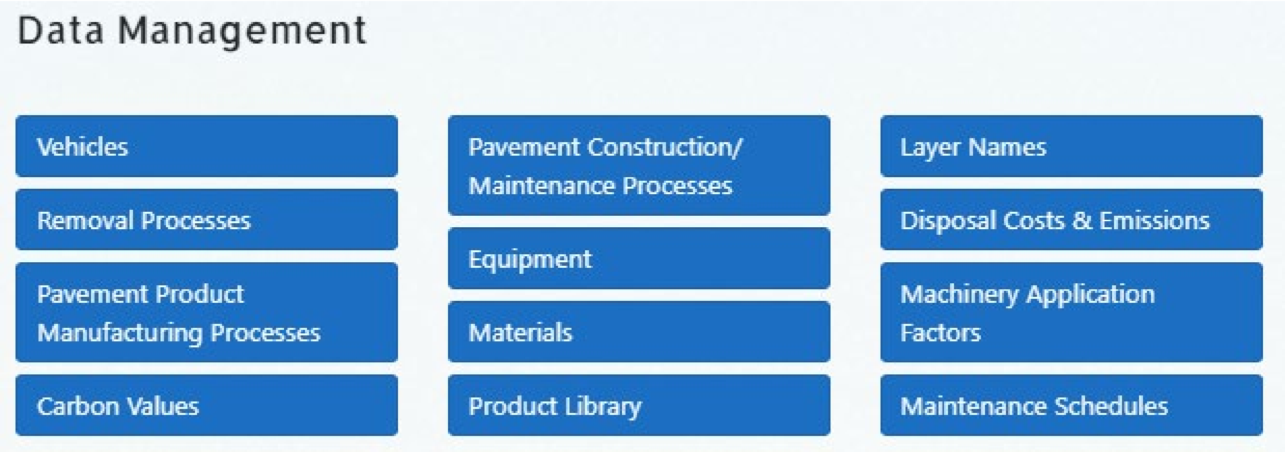
As outlined in the user requirements and model scoping study, the aim of the project was to obtain and build reference databases that, in the first instance, were specific to Western Australia and Queensland. Where the state-based information was not available, relevant data was sourced from national data sources and, if national information was not available, from international sources.

State-specific data was available, or could be inferred, for construction and maintenance processes and costs. Section 8.1.2 outlines the approach taken for developing state-specific materials data.

Australian data was used for the calculation of transportation and use phase outputs, as there were no discernible differences between states for this type of data. A combination of state-specific and Australian data was used for EoL outputs.

Users can access the reference data to review or edit it in the Data Management section (see Figure 8.1). Users have access to the relevant state-specific data linked to their registration account.

Figure 8.1: Data Management screen shot



The energy use and environmental impacts data for the materials and construction and maintenance processes were initially produced in 2021. A comprehensive review of this data was undertaken in June 2024, and the outputs were re-processed to produce updated values[4].

[4] Materials’ energy consumption (natural gas, diesel and electricity) could not be updated. The original data generated in 2021 has been retained.

8.1 Materials Data

The materials database is tailored for Western Australian and Queensland. It consists of state-specific 'constituent' pavement materials, including material densities, GHG emissions factors, emissions factors for other air-borne pollutants, energy and water consumption factors, and EnviroPoints values.

8.1.1 Materials

The NTRO, TMR and Main Roads identified an extensive list of pavement materials used by the jurisdictions. The available pavement materials are categorised by material types as unbound materials, aggregates, asphalt and sealing materials, binders, concrete, and supplementary materials. The list of materials included for each category is presented in Table 8.1.

Table 8.1: Materials included under each category

Unbound materials	Aggregates	Asphalt and sealing materials	Binders	Supplementary materials	Concrete
In situ material General/imported fill Metal dust/quarry fines Crushed limestone Natural gravel Crushed gravel Crushed rock Recycled crushed glass Recycled crushed concrete Recycled sand Rock fill Recycled crushed brick Select fill	20 mm crushed aggregate 16 mm crushed aggregate 14 mm crushed aggregate 10 mm crushed aggregate 7 mm crushed aggregate 5 mm crushed aggregate 3 mm crushed aggregate Natural sand Crusher dust Fine aggregate Surface grit	RAP Lime kiln dust Hydrated lime Ground limestone EvoTherm Sasobit Cutting oil Flux oil Adhesion agent Fibres (cellulose) Crumb rubber Plastics (styrene-butadiene-styrene copolymer, ethylene vinyl acetate, low density polyethylene, high density polyethylene, polyethylene terephthalate) Crack sealant	C170, C320, C450, C600 EME2 binder A10E, A15E, A20E, A25E, A35P S45R, S10E, S20E, S15E, S25E, S35E, S9R/S9RF, S15R/S15RF/S45R C170 5% rubber S18RF/C170 18% rubber CRS 170-30, CRS 170-48, CRS 170-60, CRS 170-70, ASS 170-60 Polymer modified bitumen (PMB) emulsion Type GP Cement[1], Type GB Cement[2], Type LH Cement[3]	Slag (ground granulated blast furnace slag) Fly ash Quicklime Air-entraining admixture Water-reducing admixture Set-retarding admixture Set-accelerating admixture Wetting agents Concrete curing compound Foaming agent Geotextile fabric	Steel reinforcement Steel fibre

1. General purpose cement
2. General blend cement
3. General low heat cement

Material densities were sourced from Infrastructure Sustainability Council of Australia (2018), EPDs and general research. Materials data can be accessed, viewed and edited by clicking on the 'Materials' button in the Data Management screen.

8.1.2 State-specific Emissions and Consumption Factors

SAT4P calculates the overall GHG emissions using the calculated material masses and emissions factors associated with each material (see calculation formula in Section 9). GHG emissions factors for each material are expressed as tonne of CO_2eq per tonne of material (tCO_2eq/tonne) based on the lifecycle inventory (LCI) processes.

Material emissions factors were sourced from LCI databases (AusLCI Database v3.6[5], AusLCI shadow database and ecoinvent) and adjusted to reflect state-based emissions intensities in electricity generation and transportation distances.

Pre-existing LCI data and emissions factors were only available for a limited number of pavement materials and asphalt products. In some instances, where a sourced material was a near-equivalent to the constituent material, the inventory data for the similar material was used. For example, AusLCI had inventory data for bitumen, which was applied consistently across C170 to C600 bitumen grades. For materials where there was no equivalent data, SimaPro[6] was used to disaggregate and interrogate the AusLCI data and then re-model them using additional data from ecoinvent and information sourced directly from suppliers. Once the comprehensive materials database was established, the background inventory data was adjusted to specify them for Queensland and Western Australia – in effect, creating 2 parallel datasets. Adjustments were also made to Queensland and Western Australian emissions from electricity generation and transportation distances. These state-specified emissions fed into all the embodied processes that consume electricity. No adjustments were made for the use or consumption of petrol or diesel as the CO_2eq intensities of these fuels are equivalent across jurisdictions.

For imported materials, the transportation distances were adjusted to reflect the freight distances from a major export port to either Perth or Brisbane. This adjustment had only a very minor impact on the emissions factors generated.

SimaPro and the EN 15804:2012 + A2:2019impact assessment method (aligned with the latest ISC Materials LCA guideline) was then used to generate state-specific emission factors. The state-specific emissions factors and key modelling assumptions are presented in Table A.1 in Appendix A.

Once the material GHG emissions factors were generated, various air pollutant impact, and energy and water consumption assessment processes were applied to generate additional tables for these factors for each material. The reproduced data tables are shown in Appendix A, while Appendix B details how the data was generated.

8.1.3 Data Caveats

Prior to generating the updated dataset in 2024, a thorough review of the LCI materials data was conducted to assess the quality of its technological, geographical and time-related coverage. The outcomes from this assessment are outlined in this section. Caveats for using the data were identified, and future avenues for improvement were noted. The issues identified are applicable to all LCA data used in Australia and are not unique to SAT4P.

Data quality issues and recommendations for future updates

The data quality assessment revealed several insights into the materials data and the underlying databases:

- While the data provides robust coverage of materials, much of the data is based on outdated international databases (ecoinvent or the AusLCI shadow database). Beyond undertaking individual assessments, the underlying AusLCI database needs support to be regularly maintained and updated.
- Recycled/waste materials currently have no emissions impact (only due to processing the material). The LCA community is actively developing new approaches to better consider the embodied GHG emissions associated with recycled materials, especially in cases where the recycled material has a clear and mature value stream.

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5 The Australian National Life Cycle Inventory Database (AusLCI) is a national, publicly accessible database with authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services over their entire lifecycle. The database brings together stakeholders from industry, government and academia to develop a methodology to standardise the interpretation of ISO 14040:2006 in Australia and is an important resource for those involved in environmental assessment and, particularly, LCA. The inventory data is estimated by assuming Australian average processes and input parameters. This assumption may lead to either under or over estimating state-specific lifecycle emissions.

6 SimaPro (https://simapro.com/) is the professional tool to collect, analyse and monitor the sustainability performance data of products and services.

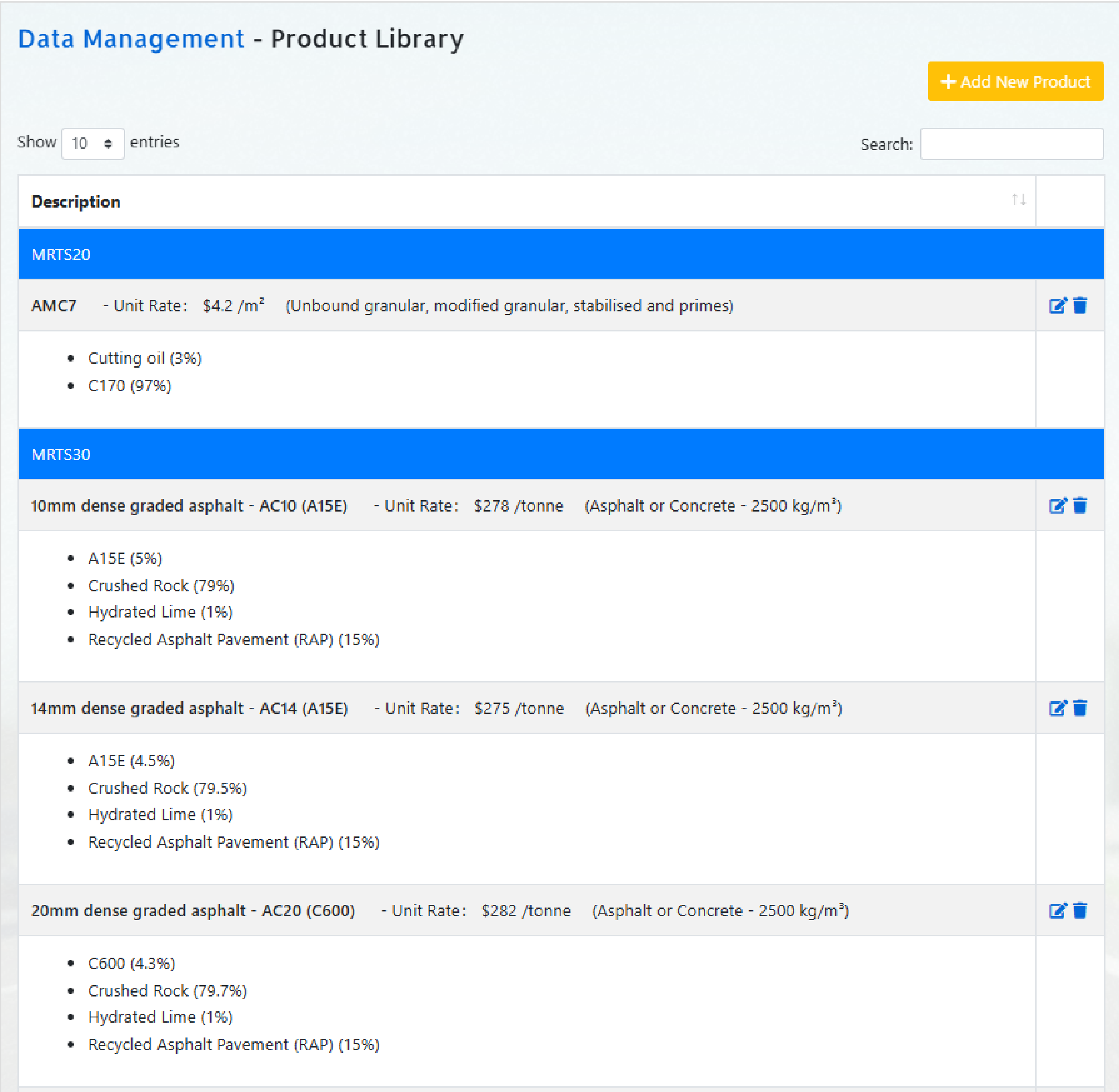
- The regeneration of the GHG emissions factors showed, in general, that the values reduced by around 5–10% compared to the previous values from 3 years ago. This is likely due to changes in the carbon intensity of the electricity grid. It is recommended that the data is updated every 1 to 3 years to account for these (and other) changes.

8.2 Pavement Product Library

SAT4P includes a product library of verified pavement products (i.e. combinations of constituent materials) linked to TMR's and Main Roads' specifications. The pavement products are displayed with descriptions that include references to relevant state specifications (e.g. MRTS30 (TMR 2024) or Specification 501 (Main Roads 2023)); a short product description; a product categorisation; the constituent materials and their quantities; product densities (for asphalt and concrete pavement products); and unit costs for the supply, transport and placement of the product on site.

A sample section of the pavement material product library with references to the relevant TMR specifications is shown in Figure 8.2.

Figure 8.2: Pavement product library



Each product has also been linked to display appropriate options within manufacturing and construction (placement) processes.

The User Manual explains the process for pavement product selection. The product library can be accessed, viewed and edited in the Data Management section of the tool. Custom products can also be developed in the Data Management section.

8.3 Manufacturing and Construction Process Data

8.3.1 Manufacturing Process Emissions

The AusLCI database was used to determine the emissions associated with the manufacture of asphalt and concrete. The database processes provide the quantities of natural gas, diesel and electricity used to manufacture the products. These values were then multiplied by the state-specific energy factors detailed in the Department of Climate Change, Energy, the Environment and Water (2023) to determine the tCO2eq/tonne of the manufactured product.

Emissions were calculated for the manufacture of hot mix and warm mix asphalt in a typical batch plant, as well as for concrete. No emissions are associated with the manufacture of stabilised materials as no primary manufacturing is required; the emissions for these materials are only produced during pavement construction and maintenance.

8.3.2 Construction Process Emissions

A first principles approach was used to determine the emissions related to the construction processes. This approach involved estimating the amount of work that can be completed in a single shift, identifying the relevant construction plant used to complete the work during the shift, and using the fuel consumption rates to calculate the diesel usage (detailed in Appendix A). The fuel usage per cubic metre of work was then calculated by dividing the total fuel usage by the assumed cubic metres of work that can be completed in a shift. Emissions per cubic metre (tCO_2eq/m^3) were then calculated by multiplying the fuel use (L/m^3) by the emissions factor (in tCO_2eq/kL of diesel) outlined in Transport Authorities Greenhouse Group (2013). These values were then compared to the values detailed in Transport Authorities Greenhouse Group (2013), and back-calculated values were obtained from the outputs of the Carbon Gauge Tool.

The results obtained using this approach were within approximately 10% of the results from Transport Authorities Greenhouse Group (2013) and the Carbon Gauge Tool, and this demonstrates its validity. While either the first principles approach data or the TAGG data could have been used, SAT4P adopted the data generated by the first principles approach as this enabled a consistent way of estimating emissions for processes not in the Carbon Gauge Tool or Transport Authorities Greenhouse Group (2013), e.g. road profiling. All processes were reviewed and updated in 2023–24 to align with the relevant jurisdictional specifications and industry practice.

8.3.3 Equipment Emissions

Emissions factors per unit of measurement (tCO_2eq/hours) for each piece of equipment were calculated using the diesel usage estimates (L/hr), mainly those provided by Transport Authorities Greenhouse Group (2013), and the diesel emissions factors (tCO_2eq/kL) from the Department of Climate Change, Energy, the Environment and Water (2023). See Appendix A for further details.

8.4 Maintenance Schedules

SAT4P includes default state-specific maintenance schedules for periodic maintenance (e.g. pothole repair, heavy patching, resurfacing and resealing) and rehabilitation or reconstruction (e.g. major layer replacement). Each schedule outlines treatment types applied at intervals over the assessment period. These treatment types can include removal and construction activities, which are linked to products and their unit costs, and replicate the data options and approaches used in the pavement design and construction sections.

Main Roads and TMR will regularly review and amend maintenance schedules included in SAT4P.

8.5 Use Phase Databases

The emissions generated during the pavement's service life primarily originate from the vehicles travelling over it within the specified assessment period. The emissions estimate is based on a set of parameters that influence the vehicles' fuel consumption and, thus, their emissions. SAT4P uses fuel consumption data and formulae from the ATAP *Guidelines: PV2 Road Parameter Values* (ATAP 2016). The fuel use emissions factors were based on values provided by the Department of Climate Change, Energy, the Environment and Water (2023). Additional data sources were also used to estimate fuel consumption and emissions; however, formats were not consistent across the data sources, i.e. different data sources used different vehicle classifications.

The ATAP guidelines provide fuel consumption data for 20 vehicle classes. Additional data from the Australian Bureau of Statistics (ABS) was used to develop fuel distribution data according to fuel type (petrol, diesel, other) (ABS 2019), vehicle fleet distribution and annual average daily traffic (AADT) data (ABS 2018). Austroads vehicle classification data was used for definitions of haulage vehicles (Austroads 2019).

This section describes the vehicle classes used in SAT4P and how the different vehicle classes were matched by combining the data from the different sources to estimate use phase fuel usage and emissions.

8.5.1 Vehicle Classes

Matching ATAP's 20 vehicle classes to those used by other sources (ABS and Austroads) is shown in Table 8.2 and Table 8.3.

Table 8.2: Matching vehicle classes from different sources

	ATAP 2016	ABS 2019	ABS 2018	Austroads 2019
01	Small car	Passenger vehicles	Passenger vehicles	1 – Short: car, ute, light van, motorcycle, bicycle
02	Medium car	Passenger vehicles	Passenger vehicles	1 – Short: car, ute, light van, motorcycle, bicycle
03	Large car	Passenger vehicles	Passenger vehicles	1 – Short: car, ute, light van, motorcycle, bicycle
04	Courier van-utility	Light commercial vehicles	Light commercial vehicles	1 – Short: car, ute, light van, motorcycle, bicycle
05	4WD mid-size, petrol	Passenger vehicles	Passenger vehicles	1 – Short: car, ute, light van, motorcycle, bicycle
06	Light rigid	Light rigid trucks	Light commercial vehicles	3 – Two-axle truck/bus
07	Medium rigid	Avg. light rigid/heavy rigid	Rigid trucks	3 – Two-axle truck/bus
08	Heavy rigid	Heavy rigid trucks	Rigid trucks	4, 5 – Avg. three-axle truck/bus, four-axle truck
09	Heavy bus	Buses	Buses	4, 5, 6 – Avg. three-axle truck/bus, four-axle truck, three-axle articulated
10	Articulated 4 axle	Articulated trucks	Articulated trucks	7 – Four-axle articulated
11	Articulated 5 axle	Articulated trucks	Articulated trucks	8 – Five-axle articulated
12	Artic 6 axle	Articulated trucks	Articulated trucks	9 – Six-axle articulated
13	Rigid + 5 axle dog	Articulated trucks	Articulated trucks	10 – B-Double
14	B-Double	Articulated trucks	Articulated trucks	10 – B-Double
15	Twin steer + 5 axle dog	Articulated trucks	Articulated trucks	10 – B-Double
16	A-Double	Articulated trucks	Articulated trucks	11 – Double road train
17	B-Triple	Articulated trucks	Articulated trucks	11 – Double road train
18	A B combination	Articulated trucks	Articulated trucks	11 – Double road train
19	A-Triple	Articulated trucks	Articulated trucks	12 – Triple road train
20	Double B-Double	Articulated trucks	Articulated trucks	12 – Triple road train

Sources: ABS (2018); ABS (2019); ATAP (2016); Austroads (2019).

Table 8.3: Matching Austroads' haulage vehicle classes with ATAP vehicle classes

Class	Austroads 2019 (12 vehicle classes)	ATAP 2016 (20 classes)	Emissions factors in A$/vehicle-km (1)	Emissions factors in A$/tonne-km (1)
3	Two-axle truck	Avg. light rigid/medium rigid	482.1	98.1
4	Three-axle truck	Heavy rigid	756.8	69.2
5	Four-axle truck	Heavy rigid	756.8	69.2
6	Three-axle articulated	Avg. heavy rigid/artic 4 axle	841.6	65.7
7	Four-axle articulated	Artic 4 axle	926.4	62.3
8	Five-axle articulated	Artic 5 axle	1,013.3	51.9
9	Six-axle articulated	Artic 6 axle	1,107.8	53.2
10	B-Double	Avg. rigid + 5 axle dog/B-Double/twin steer + 5 axle dog	1,284.6	44.2
11	Double road train	Avg. A-Double/B Triple/A B combination	1,592.0	43.8
12	Triple road train	Avg. A-Triple/Double B-Double	1,850.0	39.1

4. Emissions factors combine scope 1 and scope 3 (full cycle emissions). Calculations based on matching Austroads vehicle classes (12 classes) to ATAP vehicle classes (20 classes) as presented in this table.

Sources: ATAP (2016) and Austroads (2019).

8.5.2 Fuel Consumption and Associated Parameters

ATAP (2016) provides the fuel consumption data which is the basis for the use phase emissions estimation. Fuel consumption varies depending on vehicle type and road alignment (i.e. the horizontal (curvature) alignment and longitudinal grade (rise and fall) of the road) and other user-defined parameters (e.g. average speed, road surface roughness, vehicle payload). The fuel consumption method is provided by ATAP (2016) and explained in Section 9.

A fuel consumption example is provided in Table 8.4 and is based on an average of the fuel types used by the vehicles (i.e. petrol, diesel, other fuels such as liquid petroleum gas (LPG), compressed natural gas (CNG) or electricity).

Table 8.4: Example data used to determine total fuel consumption

	Vehicle classes ATAP (2016)	GCM[1] (tonnes) ATAP (2016)	Max. payload (tonnes) ATAP (2016)	Base fuel consumption (L/100 km) ATAP (2016)	Total fuel consumption (L/100 km)
01	Small car	1.2	0.4	6.4	8.3
02	Medium car	1.4	0.4	7.8	9.5
03	Large car	1.6	0.4	9.8	11.4
04	Courier van-utility	2.2	0.9	7.6	9.8
05	4WD mid-size, petrol	2.7	0.9	10.2	12.3
06	Light rigid	3.8	2.2	8.1	13.6
07	Medium rigid	10.4	7.2	12.5	21.5
08	Heavy rigid	22.5	13.5	23.2	37.6
09	Heavy bus	19.0	7.0	23.3	31.5
10	Artic 4 axle	31.5	20.5	27.2	50.6
11	Artic 5 axle	39.0	26.0	30.4	53.2
12	Artic 6 axle	42.5	27.5	33.8	57.0
13	Rigid + 5 axle dog	59.0	40.0	38.1	65.9
14	B-Double	62.5	40.5	41.5	69.5
15	Twin steer + 5 axle dog	64.0	43.0	41.0	69.6
16	A-Double	79.0	48.0	47.8	78.9
17	B-Triple	82.5	48.5	50.3	81.9

	Vehicle classes ATAP (2016)	GCM[1] (tonnes) ATAP (2016)	Max. payload (tonnes) ATAP (2016)	Base fuel consumption (L/100 km) ATAP (2016)	Total fuel consumption (L/100 km)
18	A B combination	99.0	60.0	54.3	90.3
19	A-Triple	115.5	71.5	58.7	99.1
20	Double B-Double	1.2	0.4	61.2	102.1

Note: The fuel consumption values are for a single (example) set of parameters: 20°/km curvature, flat road (0% rise/fall), 90 km/h average speed, IRI of 2.13 and 75% payload.

Source: ATAP (2016)

1. Gross combined mass.

8.5.3 Calculation of Emissions

Converting fuel consumption values into annual emissions requires the information presented in Table 8.5 to Table 8.7, including the fleet composition (number of light and heavy vehicles), the distribution of those vehicles by fuel type and the emissions created by those fuels when combusted. Specifically:

- Fleet composition by road category (Table 8.5) shows the percentage of total kilometres trafficking the pavement by cars, trucks or buses on different road types. Data from the ABS (2018) regarding the total kilometres travelled according to state/territory was used to create pre-set fleet compositions. Custom data can be entered by the user (see User Manual).
- Vehicle distribution by fuel type (Table 8.6) indicates the percentages of vehicles using petrol, diesel or other fuels based on motor vehicle census data (ABS 2019).
- Fuel type emissions factors (Table 8.7) shows how emissions vary by fuel type when combusted by the vehicles (scope 1 emissions) and when produced and distributed to petrol stations (scope 3 emissions). Data from the Department of Climate Change, Energy, the Environment and Water (2023) was used to generate fuel GHG emissions factors.

Table 8.5: Pre-set kilometre-based vehicle fleet compositions for different road categories

	Vehicle type	Capital city	Other urban areas	Other areas	Urban – 5% HV	Rural – 12.5% HV	Remote rural – 20% HV
Qld	Passenger vehicles	74.39%	67.23%	53.94%	70.78%	47.60%	40.10%
	Light commercial vehicles	18.51%	24.48%	34.28%	18.51%	34.28%	34.28%
	Rigid trucks *	4.65%	5.46%	4.90%	4.65%	4.90%	4.90%
	Articulated trucks	1.39%	1.66%	6.15%	5.00%	12.50%	20.00%
	Buses	1.06%	1.17%	0.73%	1.06%	0.73%	0.73%
WA	Passenger vehicles	74.70%	65.46%	50.23%	70.83%	48.88%	41.38%
	Light commercial vehicles	19.76%	28.00%	30.76%	19.76%	30.76%	30.76%
	Rigid trucks *	3.59%	3.80%	6.18%	3.59%	6.18%	6.18%
	Articulated trucks	1.12%	2.04%	11.16%	5.00%	12.50%	20.00%
	Buses	0.82%	0.70%	1.68%	0.82%	1.68%	1.68%

* Includes non-freight carrying trucks.

Note: Attribution of vehicle types has been made according to the 20 vehicle categories in Table 8.2.

Source: ABS (2018), Table 7.

Table 8.6: Estimated vehicle distribution according to fuel type

	Vehicle type	Petrol	Diesel	Other *
Qld	Passenger vehicles	83.45%	15.32%	1.23%
	Light commercial vehicles	27.08%	71.18%	1.74%
	Light rigid trucks	3.34%	96.06%	0.60%
	Heavy rigid trucks	2.44%	97.34%	0.22%
	Articulated trucks	0.73%	99.16%	0.11%
	Buses	14.51%	83.18%	2.31%
WA	Passenger vehicles	83.91%	14.65%	1.44%
	Light commercial vehicles	27.98%	69.92%	2.10%
	Light rigid trucks	3.50%	95.77%	0.73%
	Heavy rigid trucks	2.56%	97.17%	0.27%
	Articulated trucks	0.77%	99.09%	0.14%
	Buses	15.07%	82.13%	2.80%

* LPG, CNG and electricity fall into the category 'other'.

Source: Estimations based on ABS (2019), Tables 4 and 5.

Table 8.7: Fuel GHG emissions factors

Fuel type	Unit	Scope 1 emissions	Scope 3 emissions
Petrol (post-2004 vehicles)	$kgCO_2eq/L$	2.3126	0.5882
Diesel (post-2004 vehicles)	$kgCO_2eq/L$	2.7178	0.6678
Diesel (heavy vehicles, Euro VI or higher)	$kgCO_2eq/L$	2.7163	0.6678
LPG (post-2004 vehicles)	$kgCO_2eq/L$	1.5982	0.5292
CNG (heavy vehicles) (Qld) *	$kgCO_2eq/L$	2.1301	0.3282
CNG (heavy vehicles) (WA) *	$kgCO_2eq/L$	2.1301	0.1592
Electricity (Qld) *	$kgCO_2eq/L$	–	1.76 **
Electricity (WA) *	$kgCO_2eq/L$	–	1.14 **
Natural gas (Qld) – metro	$kgCO_2eq/GJ$	51.4	8.8
Natural gas (WA) – metro	$kgCO_2eq/GJ$	51.4	4.1

* For CNG and electricity, emissions factors are reported in $kgCO_2eq/m^3$ and $kgCO_2eq/kWh$, respectively. These factors were converted to $kgCO_2eq$ per litre of fuel (energy equivalent) to create a comparable basis for calculations in the tool.

** Scope 2 and 3 emissions for electricity generation and distribution were combined under scope 3 emissions.

Source: Factors based on Department of Climate Change, Energy, the Environment and Water (2023).

The fuel energy content conversion factors used in SAT4P to harmonise the energy content of different fuel sources are provided in Table 8.8.

Table 8.8: Fuel energy conversion factors used in SATP4

Fuel source	Unit	Energy factor
Petrol	MJ/L	34.2
Diesel	MJ/L	38.6
LPG	MJ/L	26.2
Natural gas (heating value)	MJ/kg	52.5
Electricity	MJ/kWh	3.6

Sources: Factors based on Department of Climate Change, Energy, the Environment and Water (2023), Hahn (2019).

Air pollutant emissions factors classified by vehicle type, machinery type and fuel type are provided in Table 8.9.

Table 8.9: Fuel air pollutant emissions factors

Fuel use (by vehicle or machinery type)	Unit	NO_x	SO_x	NMVOC	$PM_{2.5}$	PM_{10}	PAH
Car (petrol)	g/L	5.51	4.589	5.21	0.206	0.089	0.00003
Car (LPG)	g/L	4.28	4.589	4.15	0.144	0.040	0.00003
Car (diesel)	g/L	11.07	3.922	1.65	2.130	0.351	0.00035
LGV (petrol)	g/L	7.40	4.651	7.82	0.211	0.093	0.00004
LGV (LPG)	g/L	4.19	4.589	5.87	0.144	0.037	0.00003
LGV (diesel)	g/L	12.41	3.922	1.87	2.430	0.348	0.00019
Medium trucks (diesel)	g/L	17.39	3.922	2.41	2.330	0.499	0.00087
Heavy trucks (diesel)	g/L	14.38	3.922	1.73	1.830	0.219	0.00074
Buses (petrol)	g/L	10.67	4.651	11.57	2.344	0.111	0.00087
Buses (natural gas)	g/L fuel-e	6.55	0.033	0.23	2.203	0.050	0.00084
Buses (diesel)	g/L	17.56	3.922	1.60	2.330	0.154	0.00087
Electricity (Qld)	g/L fuel-e	7.90	6.119	0.12	0.087	0.148	0.00002
Electricity (WA)	g/L fuel-e	4.61	4.280	0.11	0.277	0.543	0.00003
Stationary machinery ≤ 450 kW (diesel)	g/L	73.6	3.9	6.6	5.1	5.1	0.00000
Stationary machinery > 450 kW (diesel)	g/L	32.6	3.9	2.6	1.7	1.6	0.00000
All processes (natural gas)	g/MJ	0.1491	0.0017	0.0112	0.0039	0.0001	0.00000
Electricity (Qld)	g/kWh	3.95	3.060	0.06	0.043	0.074	0.00001
Electricity (WA)	g/kWh	2.30	2.140	0.05	0.138	0.271	0.00002

Sources: Factors based on NTRO analysis using data from Department of Agriculture, Water and the Environment (2021) and Cosgrove, D, 15 October 2020, data spreadsheet, personal communications).

8.6 Other Emissions, Consumption and Impact Factors

In addition to GHG emissions factors, SAT4P generates other air-borne emissions, energy and water consumption, and IS EnviroPoints outputs.

The reference data needed to calculate these outputs was generated in SimaPro based on state-specific LCI data for:

- materials (i.e. materials data referred to in Section 8.1)
- lifecycle processes (referred to in Section 8.3 and 8.4)
- use phase (referred to Section 8.5).

For every material in the materials database, lifecycle process and in the use phase, the following reference data for emissions, consumption and environmental impact factors was created:

- other air-borne pollutants, in kilograms, of emissions per kilogram of material (kg/kg of material):
  - NO_X
  - SO_X
  - NMVOC[7]
  - particulate matter PM2.5 and PM10[8]
  - PAH

7 Methane is both a greenhouse gas (GHG) and a volatile organic compound (VOC). As a GHG, methane is a component of the CO_2eq estimates already reported in the SAT. To avoid double-counting, methane is sometimes excluded from other VOC emissions and a non-methane volatile organic components (NMVOC) measure is used.

8 PM2.5 = Particulate matter less than 2.5 µm and PM10 = Particulate matter less than 10 µm.

- energy and water consumption outputs
- total energy use (GJ per kg of material):
  - diesel (L per kg of material)
  - petrol (L per kg of material)
  - natural gas (kg per kg of material)
  - electricity (kWh per kg of material)
  - water (m^3 per kg of material)
- EnviroPoints (points per kg of material, as normalised and weighted values).

The EnviroPoints are based on environmental impact characterisation factors aligned with EN 15804 standard for EPDs. These factors describe the different impacts of materials on global warming, ozone depletion, acidification, eutrophication, photochemical smog and abiotic depletion of elements and fossil fuels. The characterisation factors are specific to every material.

In addition to the embodied emissions, total energy and water use factors are calculated. For unbound materials, additional water use factors were applied to capture the water use during compaction and dust suppression. The additional water factors for unbound materials (m^3 per kg of compacted material) were calculated based on the typical optimum moisture content (OMC) of the granular material and adjusted for climatic conditions, i.e. evaporation rates for Perth and Brisbane. Dust suppression was assumed to use an average of 2 water carts per day across the year, with the understanding that actual water use may vary seasonally and by site. Detailed descriptions of the methods used are provided in Appendix B.

8.7 Cost Data

Main Roads– and TMR-provided product and process cost data have been integrated into SAT4P. Product cost unit rates include the production, supply, transport and placement of pavement products. Additional costs are defined for removal processes, including those for transport from the site and for additional equipment used. These unit costs can be applied to both initial construction and individual maintenance processes or whole schedules.

When material is removed from the pavement site and sent to an EoL landfill destination, landfill gate fees are applied, including relevant state- or regionally based waste levies and annual disposal cost growth rates.

8.8 National Carbon Values

SAT4P adopts the national carbon values published by IA in its *Valuing Emissions for Economic Analysis* guidance document (IA 2024).

9 Model Calculations

9.1 Lifecycle Greenhouse Gas Emissions

The total lifecycle emissions E of a pavement expressed in tCO_2eq over an assessment period of n years is calculated as the sum of all annual emissions E_y in every year y of the assessment period (Equation 1).

$$E = \sum_{y=0}^{n} E_y \tag{1}$$

E_y is the sum of the emissions in a given year. It includes the embodied emissions from material production or disposal E_m (for materials used during pavement construction and maintenance and from non-inert pavement materials after their disposal); the emissions from pavement product/material manufacturing, construction and maintenance processes E_p; the emissions associated with the transport of materials to or from site E_t; and the emissions created during the use phase by the vehicles trafficking the pavement E_u (Equation 2).

$$E_y = E_m + E_p + E_t + E_u \tag{2}$$

The individual components of E_y are further split up as follows (Equation 3):

- E_m is the sum of the emissions from the materials used during construction $E_{m,c}$, materials used during all maintenance activities during the assessment period $E_{m,m}$, and emissions released in non-inert pavement materials after disposal $E_{m,d}$ ($E_{m,d}$ is considered as an option and its value is zero by default). $E_{m,c}$ will only accrue in year 0 of the assessment period when the pavement is constructed.
- E_p is the sum of the emissions generated by the construction processes and machinery applied during construction $E_{p,c}$ and the emissions generated during maintenance processes $E_{p,m}$. $E_{p,c}$ and $E_{p,m}$ include emissions that are generated during pavement product/material manufacturing (e.g. asphalt).
- E_t is the sum of the emissions associated with the transport of the materials to the site during construction ($E_{t,c}$) and maintenance activities ($E_{t,m}$), plus the sum of the emissions associated with the transport of materials off site for recycling ($E_{t,r}$) or disposal ($E_{t,d}$).
- E_u is the sum of the emissions generated by all the vehicles trafficking the pavement during a year. Twenty different vehicles classes v are specified (see Equation 3), with E_u being the sum of the emissions generated by the vehicles in the individual classes $E_{u,v}$.

For year y:

$$\begin{aligned} E_m &= E_{m,c} + E_{m,m} + E_{m,d} \\ E_p &= E_{p,c} + E_{p,m} \\ E_t &= E_{t,c} + E_{t,m} + E_{t,r} + E_{t,d} \\ E_u &= \sum_{v=1}^{20} E_{u,v} \end{aligned} \tag{3}$$

It is important to note that a proportion of each of these emissions is classified as scope 1 emissions and the remainder as scope 3 emissions. An overview is provided in Table 9.1.

Table 9.1: Emissions overview

Emissions	Variable	Scope 1	Scope 3
Construction materials (embodied emissions)	$E_{m,c}$	–	Yes
Construction materials/products manufacturing	$E_{p,c}$	Yes	Yes
Construction processes/equipment		Yes	Yes
Maintenance materials (embodied emissions)	$E_{m,m}$	–	Yes
Maintenance materials/products manufacturing	$E_{p,m}$	Yes	Yes
Maintenance processes/equipment		Yes	Yes
Disposal (non-inert material emissions)	$E_{m,d}$	–	Yes
Transport to site: construction materials	$E_{t,c}$	Yes	Yes
Transport to site: maintenance materials	$E_{t,m}$	Yes	Yes
Transport off site: recycling	$E_{t,r}$	Yes	Yes
Transport off site: disposal	$E_{t,d}$	Yes	Yes
Use phase	E_u	Yes	Yes

9.1.1 Material Emissions

The same formula is used for the calculation of both $E_{m,c}$ and $E_{m,m}$; the difference is in the input values. $E_{m,c}$ accrue in the construction year (year 0), whereas $E_{m,m}$ accrue in every maintenance year.

For each pavement layer, the user specifies either the layer thickness plus all materials in that layer and their mass% (totalling 100%) or the materials in that layer and their quantities in L/m^2 or kg/m^2 (the material quantities are then converted into a layer thickness in the tool, and the mass% is calculated).

If thickness is entered, $E_{m,c}$ is calculated as the sum of the emissions for all layers l and all materials m in each layer (Equation 4). The emissions generated by the production or extraction of an individual material is the emissions factor for that material e_m. It is measured in tonnes tCO2eq per tonne of material, and the material's mass m_m.

$$E_{m,c} = \sum_l \left(\sum_m (e_m \cdot m_m) \right) \quad 4$$

The material mass m_m depends on other variables as described in Equations 5 to 7.

$$m_m = m\%_m \cdot m_l \quad 5$$

$$m_l = \delta_l \cdot h_l \cdot a \quad 6$$

$$\delta_l = \sum_m (m\%_m \cdot \delta_m) \quad 7$$

where

$m\%_m$	=	the mass% of a material in a layer
m_l	=	the layer mass
δ_l	=	the (average) layer density
h_l	=	the user-entered layer thickness
a	=	the area of the pavement, defined by the user-entered length, lane width and number of lanes
δ_m	=	the compacted density of the material in a layer

If the material quantity is entered in L/m², this value contributes to the layer thickness h_l in millimetres. If the material quantity is entered in kg/m², the quantity is converted into a thickness using the material density δ_m, which contributes to the layer thickness h_l (Equation 8). In these cases, the material's mass% does not need to be entered by the user.

$$h_l = \sum_m \frac{q_m}{\delta_m} \quad (8)$$

The resulting emissions are approximations based on the calculated average layer density, which is calculated from the individual layer material quantities, in mass%, and their respective densities. If material quantities are entered by the user in L/m² or kg/m², mass% and layer thicknesses are calculated automatically (no thickness or mass% needs to be entered in addition to the quantities). In cases where materials amalgamate into a single layer (e.g. bitumen fills voids in aggregate material), the actual mass or thickness may be slightly different, as well as the associated material emissions.

Emissions factors e_m are specific for each material; they reflect the amount of energy required, or the emission-intensity, during material production. The tool differentiates between virgin and recycled materials, which have different emissions factors. For every material, the emissions factors e_m and material densities d_m are provided in the materials database (see Section 8.1).

$E_{m,d}$ are emissions that may occur after a material is disposed of (e.g. after a maintenance process). Generally, $E_{m,d}$ is zero, but the user can specify an average emissions factor e_d in tCO2eq per tonne of material for all disposed materials. $E_{m,d}$ is calculated using Equation 9, where m_d is the total mass of all disposed materials.

$$E_{m,d} = e_d \cdot m_d \quad (9)$$

9.1.2 Process and Machinery Emissions

$E_{p,c}$ accrue in the construction year 0, and $E_{p,m}$ accrue in every year of the assessment period for which the user has specified a maintenance activity to take place. If applicable, $E_{p,c}$ may include emissions associated with the removal of an existing pavement prior to the construction of a new pavement. Both $E_{p,c}$ and $E_{p,m}$ usually also include emissions associated with the manufacture of pavement products (e.g. asphalt).

The calculation methods of $E_{p,c}$ and $E_{p,m}$ are equivalent; the explanation below focusses on $E_{p,c}$.

The tool differentiates between the emissions generated during the manufacture of material/pavement products, process emissions, and machinery (equipment) emissions. Manufacturing emissions include emissions associated with the manufacturing of the pavement products from individual constituents, e.g. the manufacture of asphalt from aggregates and binders. Process emissions include emissions associated with the complete construction or maintenance processes; these emissions depend on the pavement layer thicknesses and the area to be paved (i.e. lane length, lane width and the number of lanes). Machinery (mobile plant) emissions include direct emissions generated using machinery on site. The extent of the machinery emissions depends on the operating hours or lane-kilometres and the usage amount of an individual piece of machinery, which is specified by the user. Specifying machinery emissions is optional as they may already be included in the emissions associated with the construction/maintenance process. Check the construction and maintenance process details to review the included vehicles/machinery.

Material manufacturing emissions are calculated using Equation 10. They depend on the energy consumption (usually diesel, electricity and/or natural gas), per tonne, associated with the manufacturing of the material. Using the material density, a volume-specific emissions factor e_{manu,m^3} is calculated. The factor is multiplied by the layer thickness h_l and the area of the pavement a. $(h_l \cdot a)$. $E_{p,c,1}$ can be considered as the volume of the material that is manufactured.

$$E_{p,c,1} = e_{manu,m^3} \cdot (h_l \cdot a) \quad (10)$$

Construction process emissions are calculated using Equation 11. For processes that strongly depend on the layer thickness, part (1) of the equation applies, where $E_{p,c,2}$ is the product of the volume-specific emissions factor for the process e_{pro,m^3}, the layer thickness h_l and the area of the pavement a. For processes where the layer thickness is not applicable or only has a minor effect on the emissions, part (2) of the equation applies, where $E_{p,c,2}$ is the product of the area-specific emissions factor for the process e_{pro,m^2} and the area of the pavement a. The emissions factors e_{pro,m^3} and e_{pro,m^2} were estimated as outlined in Section 8.3. These (construction) processes can also include removal of existing pavement material.

$$(1)\ E_{p,c,2} = e_{pro,m^3} \cdot (h_l \cdot a)$$

or 11

$$(2)\ E_{p,c,2} = e_{pro,m^2} \cdot a$$

Construction machinery emissions $E_{p,c,3}$ are calculated as the product of an emissions factor specific to a piece of machinery e_{mac}, the operating time that piece of machinery requires to complete the construction step t_{mac} and an application factor app_{mac} that represents the intensity of operating the item of equipment (low, medium or high) (Equation 12).

$$E_{p,c,3} = e_{mac} \cdot t_{mac} \cdot app_{mac} \qquad 12$$

The total construction process and machinery emissions $E_{p,c}$ are the sum of the manufacturing, construction process and machinery emissions (Equation 13):

$$E_{p,c} = E_{p,c,1} + E_{p,c,2} + E_{p,c,3} \qquad 13$$

Although the calculation of the construction and maintenance processes and machinery emissions are equivalent, it is worth noting that different layer thicknesses may apply. For example, maintenance may involve a pavement layer to be removed by a process (e.g. profiling) or added (e.g. laying asphalt). The new layer may have a different thickness than the removed layer, and SAT4P will automatically adjust the layer thicknesses accordingly.

All the emissions factors e_{manu,m^3}, e_{pro,m^3}, e_{pro,m^2} and e_{mac} include both emissions under scope 1 (direct fuel usage in processes) and scope 3 (fuel production and distribution). SAT4P outputs both individual scope emissions and total emissions.

9.1.3 Transport Emissions

Transport emissions depend on the weight of the material (material mass) and the haul distance that the materials need to be transported to or from the site. The calculations for all emissions for transport of materials to site ($E_{t,c}$ or $E_{t,m}$) or from site ($E_{t,r}$ *or* $E_{t,d}$) are equivalent. The following explanations focus on $E_{t,c}$.

For each material m, the emissions for the transport of construction materials E_{t,c_m} are the product of the emissions factor $e_{tonne.km}$ for the haulage vehicle used (in tonnes of CO_2eq per tonne-kilometre of materials transported, tCO_2eq/tonne·km), the material mass m_m and the transport distance d_m (Equation 14).

$$\text{For each material } m\text{: } E_{t,c_m} = e_{tonne.km} \cdot m_m \cdot d_m \qquad 14$$

The emissions factor $e_{tonne.km}$ itself depends on the per-kilometre emissions factor of haulage vehicle $e_{km,l}$ (in tonnes of CO_2eq per kilometre, tCO_2eq/km) and considering the actual payload l of the vehicle in tonnes (Equation 15). l is specified by the user, who enters a loaded% value (usually 100%), which is applied to the maximum allowable payload of the vehicle l_{max}.

$$e_{tonne.km} = \frac{e_{km,l}}{l} = \frac{e_{km,l}}{loaded\% \cdot l_{max}} \qquad 15$$

If empty return trips are considered in the transport emissions, $E_{t,c_{m,empty}}$ is added. This is calculated as the product of the emissions factor for an empty vehicle with 0% payload $e_{km,0}$, the material-specific transport distance d_m and the number of trucks n_{trucks} that were required to transport all the materials to site (Equation 16). n_{trucks} depends on the vehicles' payload l.

$$\text{If empty return trips apply, add: } E_{t,c_{m,empty}} = e_{km,0} \cdot d_m \cdot n_{trucks} \quad (16)$$

The total emissions for transport of construction materials $E_{t,c}$ is the sum of the emissions created by transporting all materials m to site (Equation 17).

$$E_{t,c} = \sum_m \left(E_{t,c_m} + E_{t,c_{m,empty}} \right) \quad (17)$$

It is important to note that the emissions factors $e_{km,p}$ (and, as a result, $e_{tonne.km}$) are specific to each vehicle type, as every vehicle type has its own fuel consumption, which is affected by the payload. Emissions factors for all haulage vehicles, assuming a 100% payload (i.e. fully loaded), are provided in Table 8.3.

A detailed description of how emissions factors are calculated for different vehicle types, based on various parameters including the payload, is provided in the following section.

9.1.4 Use-phase Emissions

The calculation of the emissions from vehicles in an individual vehicle class $E_{u,v}$ depends on the AADT for the road segment in any year within the assessment period. The AADT can change throughout the year based on a user-entered annual growth percentage, e.g. to reflect increased traffic over time in line with population increase or seasonal demands. The AADT in any given year y is based on the user-entered AADT in year 1 (Equation 18):

$$AADT_y = AADT_1 \cdot (1 + growth\%)^{y-1} \quad (18)$$

$AADT_y$ is then multiplied by the percentages of the AADT that correspond to the different vehicle classes v in the fleet, expressed by a weighting factor w_v and an emissions factor e_v that depends on the vehicles' fuel consumptions (Equation 19). The weighting and emissions factors are specific for every one of the 20 vehicle classes v that are listed in Table 8.2.

$$E_{u,v} = AADT_y \cdot w_v \cdot e_v \quad (19)$$

The weighting factors w_v are calculated in the tool based on the traffic load distribution (TLD) of the different road types, i.e. what percentage of the fleet trafficking the new pavement falls into which vehicle class. SAT4P offers some predefined road categories (see Table 8.5), e.g. rural with a heavy vehicle percentage of 15%, or the user can specify the vehicle distributions or heavy vehicle percentages. The user's selection or data entry is then attributed to the 20 vehicle classes (refer to Section 8.4 and Table 8.2) in order to define all 20 w_v values. The sum of all w_v values equals 100%.

The emissions factors e_v are measured in gCO_2eq/km. They depend on a range of parameters that ultimately determine the fuel usage of the vehicles in the fleet.

In the first step for determining the emissions factors, the fuel consumption $cons_v$ for vehicles in all 20 vehicle classes is calculated based on ATAP (2016). The following parameters are relevant:

- vehicle parameters: base fuel consumption $cons_{v,base}$, gross vehicle mass GVM (see examples of fuel consumption and mass subject to vehicle payload in Table 8.4)
- traffic parameters: average actual speed V (not the posted speed limit), traffic flow type (uninterrupted vs interrupted, e.g. by traffic lights)
- road parameters: horizontal alignment (degree per kilometre) and longitudinal grades (metres rise/fall per kilometre), road surface roughness (IRI).

For an uninterrupted traffic flow, the fuel consumption is (Equation 20):

$$cons_v = cons_{v,base} \cdot \left(k_1 + \frac{k_2}{V} + k_3 \cdot V^2 + k_4 \cdot IRI + k_5 \cdot GVM\right) \qquad 20$$

For an interrupted traffic flow, the fuel consumption is (Equation 21):

$$cons_v = A + \frac{B}{V} \; (V \leq 60\text{km/h})$$

$$cons_v = C_0 + C_1 \cdot V + C_2 \cdot V^2 \; (V \geq 60 \text{ km/h}) \qquad 21$$

k_1 to k_5, A, B and C_0 to C_2 are model parameters according to ATAP (2016). They reflect the traffic flow type, horizontal alignment and longitudinal grades of the road.

In the second step, the fuel consumption $cons_v$ are converted into emissions factors e_v based on the following parameters:

- fuel parameters: emissions from fuel combustion (scope 1) and from fuel production and distribution (scope 3) for every fuel type, represented by emissions factors e_{fuel} in gCO_2eq/L (see Table 8.5)
- fleet parameters: %distribution by fuel type for every vehicle class (e.g. petrol, diesel, see Table 8.6).

For every vehicle class v, scope 1 and scope 3 emissions factors are calculated based on the average fuel consumption of vehicles in that vehicle class $cons_v$, and the weighted average of the emissions factors e_{fuel}, using the %distribution by fuel type in that vehicle class $fueldist\%_v$ as a weighting factor (Equation 22).

$$e_v = cons_v \cdot \sum_{fuels} fueldist\%_v \cdot e_{fuel} \qquad 22$$

Note: It is assumed that $cons_v$ is an average fuel consumption for a vehicle class, which reflects the differences between fuel consumptions of vehicles using different types of fuels (e.g. petrol, diesel).

9.2 Additional Lifecycle Values

The calculations of lifecycle outputs including total energy use, fuel use (petrol, diesel, natural gas and electricity), water use and emissions of 6 air pollutants largely follow the same principles as those used for GHG emissions (see Section 9.1). Therefore, the detailed calculations are not explained again. However, some differences exist and are explained in Section 9.2.1 . No distinction is made between scope 1 and scope 3 (emissions). EnviroPoints are calculated by applying normalisation and weighting factors to environmental impact characterisations for each material used (Section 9.2.2).

9.2.1 Energy and Fuel Use, Water Use and Air Pollutant Emissions

The energy and fuel use, water use and air pollutant emissions calculations are based on the same relationships as presented in the formulae in Section 9.1.

Material production

For material production, energy and fuel use, water use and air pollution factors for each material were generated using SimaPro. These factors are used in the same way as the materials emissions factors e_m and e_d (see Equation 4 and Equation 9) to calculate the materials production energy use (in GJ), the petrol, diesel, natural gas and electricity use (in L for petrol and diesel, kg for gas and kWh for electricity), the water use (in m^3) and the amount of air pollutants (in kg).

Processes and machinery

For energy use, the fuel use for processes and machinery (described in Section 8.3) are first converted into energy values (in GJ per m^3 or m^2 of pavement) using the conversion factors in Table 8.8. The energy and fuel use are then calculated as explained in Equation 10 to Equation 12, whereby the emissions factors

e_{manu}, e_{pro,m^3}, e_{pro,m^2} and e_{mac} are replaced by energy or fuel use values (in GJ per m^3 or m^2 for energy and L, kg and kWh per m^3 or m^2 for petrol/diesel, natural gas and electricity use, respectively).

The same principle is followed for water use, applying values in m^3 of water per m^3 or m^2 of pavement. However, no water use was assumed for the machinery types and for some processes.

For the air pollution, the emissions factors were estimated by converting the fuel use for various processes into pollution factors in kg per kg or m^3 or m^2 (depending on the process), using some of the fuel-based factors in Table 8.9. The pollution factors can replace the emissions factors in Equation 10 to Equation 12 to calculate the air pollution impact in kg for each of the 6 air-pollutants.

Material transport and use phase

To calculate the respective energy use, fuel use and air pollutant emissions, GHG emissions factors used in Equation 14 to Equation 16 and Equation 19 are replaced by energy consumption, fuel consumption or air pollution factors for the different vehicle classes (per km or per tonne-km). The fuel consumption factors in Table 8.4, energy conversion factors in Table 8.8 and pollutant factors in Table 8.9 are used instead of GHG emissions factors as explained throughout this section.

9.2.2 EnviroPoints

To calculate the EnviroPoint value EP_m for each material m, the characterisation factors for every material and impact type $f_{char,m}$ are normalised and weighted using ISC-defined normalisation factors f_{norm} and weighting factors f_{weigh}. These adjusted values are then added up across all impact types imp (see Equation 23).

$$EP_m = \sum_{imp} f_{char,m} \cdot f_{norm} \cdot f_{weigh} \qquad 23$$

EnviroPoints EP_m are expressed in points per kg of material. In order to evaluate a pavement base case or alternative case using the EnviroPoints, the material-specific factors EP_m are multiplied by the total mass m_m of each material used during construction and maintenance activities during the assessment period (Equation 24). This results in the total EnviroPoints EP for a case, representing its overall environmental impact as defined by ISC.

$$EP = \sum_{m} EP_m \cdot m_m \qquad 24$$

9.3 Lifecycle Costs

The total lifecycle costs C of a pavement for the assessment period of n years are the sum of all annual costs C_y in every year y of the assessment period (Equation 25). The total lifecycle costs can be offset partially by the residual asset (or EoL) value of the pavement at the end of the assessment period, C_{EoL}.

$$C = \sum_{y=0}^{n} C_y \qquad 25$$

C_y itself is the sum of all costs in a given year y. Those costs include carbon emissions costs C_e, which depend on the total emissions in a year E_y, the costs for construction and maintenance processes for the pavement C_p and the costs for material disposal C_d (e.g. as a result of maintenance activities) (Equation 26).

$$C_y = C_e + C_p + C_d + C_{EoL} \qquad 26$$

The individual components of C_y are further split up as follows (Equation 27):

- C_e does not have subcomponents but depends on the user-entered carbon price.

- C_p is the sum of the costs for the pavement construction $C_{p,c}$ and for every pavement maintenance activity $C_{p,m}$ plus old pavement removal costs $C_{p,r}$ if removal prior to construction is required. $C_{p,m}$ may also have a removal component if pavement layers are removed as a part of a maintenance activity.
- C_d does not have subcomponents but depends on the applicability of waste levies and additional user-entered disposal costs.
- The costs in year n (i.e. at the end) of the assessment period also include the residual asset value C_{EoL}, which is typically a negative cost, indicating a positive residual asset value.

For every year y:

C_e (see details in Section 9.3.1)

$$C_p = C_{p,c} + C_{p,m} \quad (27)$$

C_d (see details in Section 9.3.3)

The following subsections explain each of the costs in greater detail.

9.3.1 Carbon Emissions Values

The carbon emissions values reflect nationally agreed values for carbon emissions. The carbon emissions values C_e in any given year y are calculated as the product of the total emissions E_y and the carbon value price for that year p_e in A$/t$CO_2$eq (Equation 28):

$$C_e = E_y \cdot p_e \quad (28)$$

9.3.2 Process Costs

The costs for removal, construction and maintenance activities $C_{p,r}$, $C_{p,c}$ and $C_{p,m}$ are user-entered lump sum values. These cost values can be sourced externally. Alternatively, SAT4P offers a simple cost estimator which uses material volumes, masses or the pavement area as a basis to estimate the costs. $C_{p,r}$, $C_{p,c}$ and $C_{p,m}$ are calculated the same way. Equation 29 shows the estimation for $C_{p,c}$ as an example.

$$C_{p,c} = \sum_{r\ or\ m\&p} (c_{r\ or\ m\&p} \cdot q)$$

or (29)

$$C_{p,c} = \sum_{r\ or\ m\&p} (c_{r\ or\ m\&p} \cdot a)$$

$r\ or\ m\&p$ refer to removal or material manufacturing and placement activities that may apply for pavement construction. $c_{r\ or\ m\&p}$ is the cost per unit, q is the material quantity in tonnes, m^3 or the pavement area a in m^2.

9.3.3 Disposal Costs

Disposal costs C_d occur in maintenance years when materials from maintenance activities may need to be disposed. The disposed material mass is the remainder of all the material that is removed from a pavement during a maintenance activity but not sent to a recycling facility or reused on site (the fractions that are recycled or reused on site are specified by the user). To obtain C_d, the disposed material mass m_d is multiplied by the disposal costs factor c_d (Equation 30):

$$C_d = m_d \cdot c_d \quad (30)$$

Note: the material mass that is disposed (m_d), recycled or reused on site depends on the total pavement mass, which is the sum of the individual layer masses m_l. The layer masses depend on the materials used in each layer, their densities, the layer thicknesses and the total pavement area.

The disposed material mass m_d is calculated as the product of the disposed material fraction $disposed\%$ and the total material mass that is removed $m_{removed}$

$$m_d = disposed\% \cdot m_{removed} \quad (31)$$

The disposal cost factors c_d are state and regionally specific and provided in Appendix A.5.4. The disposal cost rates are based on an average gate fee for disposal of inert construction and demolition waste and include state government waste levies in some regions. Each region has a landfill gate fee and an annual growth rate ($c_{d,growth}$) to account for escalating levies and inflation. These variables and growth rates are summarised in Table 9.2. In addition, the user can enter additional disposal costs $c_{d,add}$, for example to account for surcharges by the disposal facility that go beyond the state-regulated levies.

Table 9.2: State-specific disposal costs – variables and growth rates

State	Variable	Unit
Construction and demolition waste levy in year 0 (prior to pavement operation)	$c_{d,base}$	A$ per tonne
Construction and demolition waste levy annual growth rate	$c_{d,growth}$	A$ per tonne and year

Consequently, the disposal cost factors c_d in any year n of the assessment period in which material from maintenance activities needs to be disposed is calculated as described in (Equation 32):

$$c_d = c_{d,base} + n \cdot c_{d,growth} + c_{d,add} \quad (32)$$

9.3.4 End-of-life Value

The EoL value represents the remaining economic value of a pavement asset at the end of an assessment period (e.g. 40 years). The value can be zero or negative (representing a positive EoL value). It is made up to 2 components:

1. residual asset value
2. salvage value.

The residual asset value of a pavement C_{EoL}, is determined based on a user-defined set of specifications. These specifications are:

- initial construction costs C_e (including material and transport costs)
- the design life of the pavement surface (which needs to be reflected in the maintenance schedule and has an impact on the deterioration profile of the pavement over time), e.g. 10 years
- the design life of the pavement, e.g. 40 years
- the value of the pavement surface $v_{\%}$ as a percentage of the total pavement value (i.e. construction costs), e.g. 10%
- the assessment period of n years, e.g. 40 years.

The residual asset value of the pavement at the end of the assessment period is determined through depreciation of the initial pavement asset value (construction costs) over time, using a linear depreciation curve for the pavement based on the design life of the entire pavement, and a second linear curve for the pavement surface based on the design life of the pavement surface. The depreciation curves will be reset through pavement maintenance activities such as resurfacing or reconstruction, which increase the values of the pavement surface and/or pavement (Equation 33). n_s is the remaining pavement surface life at the end of the assessment period, and n_b is the remaining pavement design life at the end of the assessment period. n_s and n_b are determined by the maintenance schedule and represent a fraction of the design lives of the surfacing and overall pavement, respectively.

The pavement salvage value V_{sal} is a user-entered (adjustment) value that is added to the residual pavement value to complete the EoL value.

$$C_{EoL} = -(C_c \cdot v_{\%} \cdot n_s + C_c \cdot (1 - v_{\%}) \cdot n_b + V_{sal}) \quad 33$$

C_{EoL} is zero or negative. A negative EoL value, i.e. a positive cost value C_{EoL}, is not considered.

9.3.5 Cost Summary

SAT4P calculates the total lifecycle cost C by lifecycle phase for each base case and alternative case, expressed in PV terms.

The PV of C, denoted PV_C, is calculated using Equation 34 where C includes the carbon emissions costs C_e, the process costs (manufacturing and construction) C_p, the transport costs C_t, the disposal costs C_d and the pavement EoL costs C_{EoL}.

$$PV_C = \sum_{y=o}^{n} \frac{C_y}{(1+i)^y} \quad 34$$

n is the number of years in the assessment period, y refers to an individual year within the assessment period, C_y denotes the total costs in year y, and i is discount rate specified by the user. To calculate the PV of the components of C (i.e. emissions costs C_e, process costs C_p, transport costs C_t, disposal costs C_d and the pavement EoL costs C_{EoL}), C_y needs to be replaced by the respective costs for emissions, processes, transport or disposal in each year y (i.e. C_{e_y}, C_{p_y}, C_{t_y}, C_{d_y} and C_{EoL_y}). C_{EoL_y} only accrues in the last year n of the assessment period.

The PV of GHG emissions costs C_e is expressed in Equation 35.

$$NPV_{C_e} = \sum_{y=o}^{n} \frac{C_{e_y}}{(1+i)^y} \quad 35$$

10 Outputs

The key outputs of SAT4P as outlined in Section 5.2, include:

- GHG emissions
- other air-borne pollutants
- energy and water consumption
- EnviroPoints
- material use and 'waste' quantities
- economic factors, i.e. lifecycle costs and cost sensitivity analyses.

This section provides additional details and clarification on the data outputs including:

- output definitions – units of measure and breakdowns
- interpretation and qualifications about the data – where needed
- alignments with ISC's IS rating credits.

SAT4P enables users to rank the pavement design options by any of the key outputs. Options are ranked based on whole-of-life sustainability and economic outputs. This capability allows users to rank assessed pavement design options based on selected sustainability and economic performance metrics. SAT4P users can select whether the outputs and associated rankings are inclusive or exclusive of the use phase.

10.1 GHG Emissions

GHG emissions outputs are expressed in terms of tonnes of carbon dioxide equivalent units (tCO_2eq) for each pavement assessment case and as a comparison 'savings' of the alternative case vs the base case. GHG emissions outputs are reported as:

- total lifecycle GHG emissions
- lifecycle GHG emissions for each lifecycle phase
- lifecycle GHG emissions by emissions scope (scopes 1, 3 and full cycle emissions).

Emissions scopes

- Scope 1 (or direct) emissions are a direct result of an activity, or series of activities. Examples include emissions produced from the manufacturing processes, such as from the manufacture of cement, or emissions from the burning of diesel fuel in trucks.
- Scope 2 (or indirect) emissions are from the indirect consumption of an energy commodity. For example, 'indirect emissions' come from the use of electricity produced by the burning of coal in another facility.
- Scope 3 (or upstream and downstream) emissions are generated in the wider economy. They occur as a consequence of the activities but from sources not owned or controlled by the project owner. Examples include the extraction and production of materials, transportation of fuels and materials and disposal of landfilled materials.
- Full cycle emissions are the sum of applicable scope 1, 2 and 3 emissions.

Pavements do not directly consume energy, meaning they would generate scope 2 emissions. However, energy is consumed by third-party contractors during construction and maintenance activities, generating scope 3 emissions. As such, SAT4P reports emissions in terms of scope 1 (direct) and 3 (upstream and downstream) emissions only.

Future developments that incorporate direct energy consumption, such as electricity used to power streetlights, would need to include reporting of scope 2 emissions.

Model testing showed that the vast majority of GHG emissions (e.g. between 97 and 99% over a 40-year assessment period) were attributed to the use phase of the pavement. GHG outputs are, therefore, provided as either inclusive or exclusive of the use phase. Excluding the use phase helps highlight the relative GHG emissions contributions of other lifecycle phases (i.e. the construction, maintenance and EoL phases, which might otherwise be obscured). This function is particularly important in the graphical representation of outputs in the charts.

10.2 Other Air-borne Pollutants

Other air-borne emissions include substances that are particularly harmful to human health when inhaled or ingested. SAT4P reports these emissions in terms of kg units for each pavement assessment case and as a comparative 'savings' of the alternative case vs the base case. Other air-borne emissions generated across the pavement lifecycle include the following:

- NO_X (kg) – including nitrogen monoxide (also known as nitric oxide) and nitrogen dioxide. After GHG emissions, NO_X are the most prominent air-borne pollutants. NO_X are critical components of photochemical smog.
- SO_X (kg) – includes sulfur monoxide, sulfur dioxide and sulfur trioxide. SO_X are critical components of acidification.
- NMVOC (kg) – NMVOC outputs include dangerous and non-toxic substances excluding methane (which is largely harmless to human health). Methane is both a GHG and a volatile organic compound (VOC). As a GHG, methane is a component of the CO_2eq estimates already reported in SAT4P. To avoid double-counting, methane is sometimes excluded from other VOC emissions by using a NMVOC measure. NMVOCs are critical components of photochemical smog.
- Particulate matter (kg PM2.5 and kg PM10) – a component of photochemical smog.
- PAH (kg) – hydrocarbon chemical compounds that contain only carbon and hydrogen. PAHs are found in coal and in oil deposits and occur in minuscule quantities over the pavement's lifecycle.[9]

Australia has set national benchmarks for 5 priority air toxics in ambient air under the National Environment Protection Measure for Air Toxics (Department of Agriculture, Water and the Environment 2020). These include benzene, toluene, xylenes, formaldehyde (also a VOC) and PAHs.

SAT4P reports other air-borne pollutants in kg units rather than tonnes, reflecting their relatively low mass compared to GHG emissions.

Although the different air-borne pollutant outputs are somewhat discrete from one another, there is some overlap. As such, air-borne pollutants cannot be aggregated into a single air pollution figure.

Air pollution estimates are used in IS ratings to support the environmental impacts credit (Env-4 Air Quality) (Infrastructure Sustainability Council of Australia 2018).

10.3 Energy and Water Use

Energy and water outputs capture the consumption of resource inputs across the pavement lifecycle. These outputs are expressed in various units for each pavement assessment case and are also used to compare 'savings' of an alternative case compared to the base case. The reported energy and water outputs include:

- total energy use (GJ) – captures all energy inputs throughout the lifecycle
- diesel use (L) – captures diesel usage in all lifecycle stages, including the use phase
- petrol use (L) – captures petrol usage, only in the use phase
- gas (CNG) use (kg) – captures gas usage in all lifecycle stages, including the use phase

[9] PAH emissions factors for diesel fuel combustion is not well researched or understood (de Souza & Corrêa 2016).

- electricity use (kWh) – captures electricity usage in all lifecycle stages, including the use phase (e.g. electric vehicles)
  Electricity outputs include a range of upstream energy sources used in the production of electricity (i.e. coal, renewables and nuclear)[10]
- total freshwater use (m^3) – captures water usage in the extraction and production of raw materials, construction, maintenance and disposal phases.
  Water outputs include the wetting of unbound materials to achieve an average OMC.

The energy outputs represent the most common fuel sources within the pavement lifecycle. However, the aggregated energy content of the reportable energy (fuel-based) outputs may differ slightly from the total energy use, due to the inclusion of 'other energy sources', e.g. LPG or fuel oil.

Although there is a strong correlation between energy use and GHG emissions, users should apply caution in using energy parameters for decision-making. As noted in the peer review of SAT4P (see Section 4.4.2), 'the carbon footprint is much better suited for decision making than the individual energy values.'

The water use outputs of SAT4P use the first principles approach (which is similar to the generation of the manufacturing, construction and maintenance emissions), estimating water usage for each process on a unit basis. This involved developing a water use worksheet for each process, sourcing available and suitable water usage estimates developed by Main Roads and tested by TMR. Where no suitable water usages were available, water usage was estimated using the following assumptions:

1. water use in the manufacture of concrete and stabilised materials was sourced from industry for available products
2. water use in the manufacture of asphalt is excluded as volumes are assumed to be insignificant
3. water factors for unbound materials (m^3 per kg of compacted materials) were calculated based on the typical OMC of granular material
4. adjustment factors were applied based on the climatic conditions (evaporation rates for Perth and Brisbane)
5. dust suppression was assumed to use 2 water carts per day
6. water usage for activities such as profiling, stabilisation etc. were sourced from industry.

Energy use estimates are used in IS ratings as evidence to support the Energy and Carbon credit (Ene-1 Energy Efficiency). Water use estimates are used to support the water impacts credit (Wat-1 Avoiding unnecessary water use) (Infrastructure Sustainability Council of Australia 2018).

10.4 EnviroPoints

EnviroPoints are an indexed measure of the environmental impact of infrastructure materials developed by the ISC. EnviroPoints are a requirement for IS assessments under the ISC v.2.1 rating scheme, which has been adopted by Main Roads and TMR. The EnviroPoints index comprises normalised[11] and weighted environmental impacts as summarised in Table 10.1.

Table 10.1: EnviroPoints normalisation and weighting factors by environmental category

Category	Normalisation factor [-/kg of material]	Weighting factor [%]
Global warming	0.01442	47.5%
Ozone depletion	2,683.35441	10.0%

[10] Note: Users should apply caution with energy outputs as there is an unquantifiable risk of double counting. When natural gas is used to generate electricity, the energy is counted as natural gas (kg) and electricity (kWh).

[11] Normalisation factors for each EnviroPoint category are available as fixed values in the IS Materials Calculator. The application of normalisation factors converts the mid-point values into a percentage of the annual average global per capita impact (for that category). For example, if a product takes 3 kg of resources to produce and the average annual consumption of a global resident is 300 kg, then the normalised impact is 3/300 = 1%.

Category	Normalisation factor [-/kg of material]	Weighting factor [%]
Acidification	2.54949	7.5%
Eutrophication	3.84553	7.5%
Photochemical smog	16.55039	7.5%
Abiotic depletion (elements)	2908.48845	10.0%
Abiotic depletion (fossil fuels)	0.00160	10.0%

Source: Infrastructure Sustainability Council of Australia (2018).

EnviroPoints are presented as both a total points value for all materials used in the pavement lifecycle and on a per material basis. They serve as evidence in ISv 2.0 ratings to support the resource efficiency credit (Rso-6 Material Lifecycle Impact Measure and Management) (Infrastructure Sustainability Council of Australia 2018).

10.5 Material Use and 'Waste' Quantities

Material use and 'waste' outputs are presented in units of mass (tonnes). Material use refers to the quantity of virgin or recycled material placed into the pavement across its lifecycle (i.e. during construction and maintenance). 'Waste' outputs capture the different pathways of materials removed and reused on the pavement site or materials leaving the site to be recycled or disposed of in landfill (i.e. removed in preconstruction or in resurfacing/rehabilitation maintenance treatments). 'Wasted' materials are considered as a homogenised C&D waste.

Material outputs are expressed for each pavement assessment case and used to compare 'savings' of the alternative case vs the base case. Material use and 'waste' outputs include:

- lifecycle material input quantities (tonnes) – total mass of virgin or recycled materials used, including quantities of all the materials used in the pavement lifecycle – on a 'per material' basis
- lifecycle 'waste' (tonnes) – total mass of material reused on site, recycled or disposed of in landfill.

Estimates of material use and 'waste' quantities are used in IS ratings as evidence to support the Resource Efficient credit (Rso-4 Resource Recovery) (Infrastructure Sustainability Council of Australia 2018).

10.6 Economic Outputs

Economic outputs include the lifecycle cost of each pavement assessment case as well as the comparison of savings between the alternative case and the base case. Economic outputs include:

- lifecycle $PV, inclusive and exclusive of carbon values
- sensitivity analyses of carbon values and discount rates.

The PV measures the lifecycle costs expressed in today's values (where future costs are discounted by a discount rate). The PV formula is provided in Equation 34 in Section 9.3.5. SAT4P reports $PV lifecycle costs inclusive and exclusive of carbon values.

Sensitivity analyses are used to account for uncertainties related to national carbon values and discount rates. SAT4P presents the results of the sensitivity analyses in a data matrix, with $PVs based on high, medium and low carbon values and discount rates.

Economic outputs are used in IS ratings as evidence to support the Options Assessment & Business Case and Benefits credits (Ecn-1 Options Assessment, Ecn-2 Valuing and Considering Externalities, Ecn-4 Economic and Financial and Ecn-5 Benefits Mapping) (Infrastructure Sustainability Council of Australia 2018).

10.7 Presentation of Results

SAT4P presents results in both tabular and graphical format. Examples are shown in Figure 10.1 to Figure 10.3. Further results details are described in the User Manual.

Figure 10.1: Sample results: Pavement designs – side-by-side comparisons

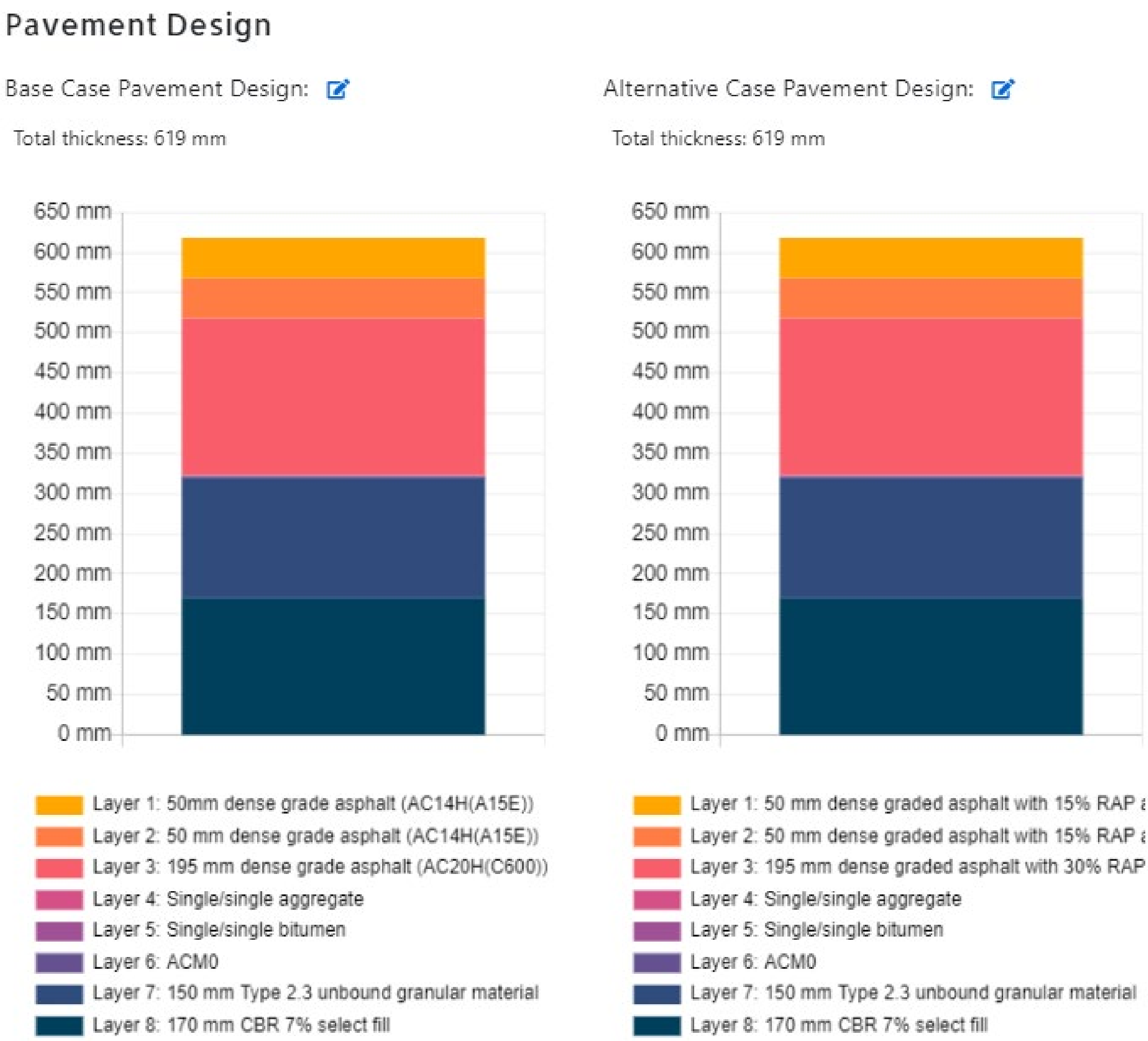


Figure 10.2: Sample results: Lifecycle cost and GHG emissions – side-by-side comparisons

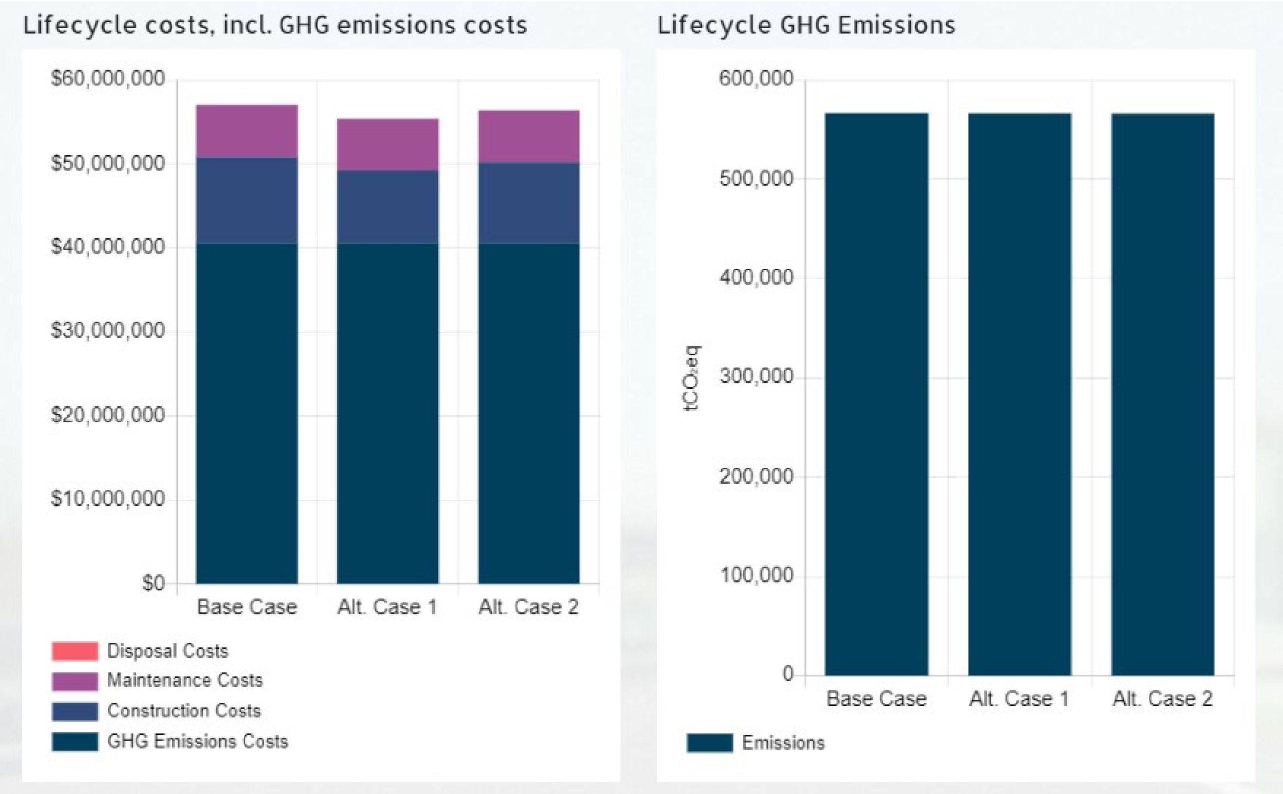


Figure 10.3: Sample results: GHG emissions – by emissions scope

Alternative Case 1 to Base Case Comparison

Overview | **GHG Emissions** | Materials Overview | Economic Outputs | Pavement Design

Emissions	Scope 1 (tCO_2eq)	Scope 3 (tCO_2eq)	Full Cycle (tCO_2eq)
Lifecycle Emissions (excluding use phase)	93.48 - 9.38	177.38 - 24.20	270.86 - 33.57
Use Phase	89,748.01 same	4,692.61 same	94,440.62 same
Lifecycle Emissions (including use phase)	89,841.49 - 9.38	4,869.99 - 24.20	94,711.48 - 33.57

11 User Support

SAT4P is a complex assessment tool designed with detailed functionality and user requirements. Every effort has been made to ensure the process is as user-friendly and straightforward as possible. These efforts include an intuitive user interface, in-software guidance tips, comprehensive databases, predefined default input data and auto-calculated values, where applicable.

In addition, SAT4P has a User Manual and a Helpdesk service to support users to operate the software and to provide feedback to the developers.

11.1 User Manual

The User Manual is accessible within the software by clicking on the ‘User Manual’ button. The User Manual provides step-by-step instructions on how to operate the software and generate comparative assessment results.

11.2 Helpdesk

The Helpdesk is accessible within the software by clicking on the ‘Help’ button. The Helpdesk operates as a web service that collects and tracks help support requests from SAT4P users.

The Helpdesk service has been tested and is available to all users.

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Appendix A Reference Data

A.1 GHG Emission Factors for Pavement Materials

Table A.1: Materials data – density and emission factors

Material	Maximum density (kg/m^3)	Emission factors (tCO_2eq/tonne)		Process Names	Assumptions
		Qld	WA		
Unbound materials					
In situ material	2,000	0.00E+00	0.00E+00	#N/A	Assumed nil impact
General/imported fill	2,000	3.942E-03	3.354E-03	Sand, at mine/[State]/AU U	
Metal dust/quarry fines	2,250	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed material
Crushed limestone	1,900	2.528E-03	2.371E-03	Limestone, crushed, washed/[State]/AU U	Assumed emissions associated with washing negligible
Natural gravel	2,300	3.942E-03	3.354E-03	Gravel, round, at mine, [State]/AU U	
Crushed gravel	2,300	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	
Crushed rock	2,300	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	
Recycled crushed glass (RCG)	2,600	1.511E-02	1.429E-02	Glass cullet, sorted [State], AU | treatment of waste glass from unsorted public collection, sorting | Cut-off, U	
Recycled crushed concrete (RCC)	2,000	3.727E-03	3.518E-03	Recycled aggregate, at plant, [State]/AU U	Assumed aggregate appropriate for pavements
Recycled sand	1,750	3.727E-03	3.518E-03	Recycled aggregate, at plant, [State]/AU U	Assumed aggregate appropriate for pavements
Rock fill	1,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	
Recycled crushed brick (RCB)	1,900	3.727E-03	3.518E-03	Recycled aggregate, at plant, [State]/AU U	Assumed aggregate appropriate for pavements
Select fill	1,750	3.942E-03	3.354E-03	Sand, at mine/[State]/AU U	Assumed nil impact
Aggregates					
20 mm crushed aggregate	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel
16 mm crushed aggregate	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel
14 mm crushed aggregate	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel
10 mm crushed aggregate	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel
7 mm crushed aggregate	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel
5 mm crushed aggregate	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel

Material	Maximum density (kg/m³)	Emission factors (tCO_2eq/tonne)		Process Names	Assumptions
		Qld	WA		
3 mm crushed aggregate	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel
Crusher dust	2,650	9.867E-03	7.899E-03	Gravel, crushed, at mine/[State]/AU U	Assumed similar emissions to crushed gravel
Fine aggregate	2,000	3.942E-03	3.354E-03	Sand, at mine/[State]/AU U	
Natural sand	1,750	3.942E-03	3.354E-03	Sand, at mine/[State]/AU U	
Surface grit	1,900	3.942E-03	3.354E-03	Sand, at mine/[State]/AU U	
Asphalt and sealing materials (excluding binders)					
Recycled asphalt pavement (RAP)	2,500	7.865E-04	7.865E-04	RAP, at processing plant/AU U	
Lime kiln dust	3,200	1.370E-02	1.370E-02	Fly ash, delivered to plant/SAT/AU U	Assumed to be same as fly ash
Hydrated lime	2,300	8.457E-01	8.331E-01	Lime, hydraulic, at plant/[State]/AU U	Replaced hydrated with hydraulic
Ground limestone	3,200	3.903E-02	3.200E-02	Limestone, milled, loose, at plant/[State]/AU U	Assumed emissions associated with washing negligible
EvoTherm	1,000	4.081E+00	4.081E+00	Diethanolamine, at plant/RER U/SAT/AusSD U	Assumed proxy diethanolamine, assumed emissions associated with washing negligible
Sasobit	900	7.601E-01	7.601E-01	Paraffin, at plant/RER U/SAT/AusSD U	Assumed proxy paraffin
Cutting oil	810	4.479E-01	4.473E-01	Kerosene, at regional storage, [State], AU U	
Flux oil	850	4.535E-01	4.520E-01	Diesel, at regional storage/[State]/AU U	
Adhesion agent	950	1.713E+00	1.713E+00	Non-ionic surfactant {GLO} | non-ionic surfactant production, fatty acid derivate | Cut-off, U/SAT	
Fibres (cellulose)	1,500	2.645E-01	2.423E-01	Cellulose fibre, inclusive blowing in, at plant/[State]/AU U	
Styrene-butadiene-styrene copolymer (SBS)	960	5.349E+00	5.349E+00	SBS copolymer, at plant/SAT/AU U	
Ethylene vinyl acetate (EVA)	940	2.727E+00	2.727E+00	EVA copolymer, at plant/RER U/SAT/AusSD U	
Low-density polyethylene (LDPE)	920	3.720E+00	3.496E+00	LDPE, at plant, [State]/AU U	
High-density polyethylene (HDPE)	950	2.364E+00	2.341E+00	HDPE, average, at plant, [State]/AU U	
Polyethylene terephthalate (PET)	1,380	2.921E+00	2.879E+00	PET, granulate, amorphous, at plant/[State]/AU U	
Crumb rubber	1,150	3.003E-01	2.272E-01	Rubber from waste tyres, [State], fine pulverised, crumb rubber (< 0.7 mm)/SAT/AU U	Only considered transformation emissions
Crack sealant	1,040	4.107E-01	3.860E-01	C170_5% CR, PMB, [State]/SAT/AU U	Rubberised bitumen

Material	Maximum density (kg/m³)	Emission factors (tCO_2eq/tonne)		Process Names	Assumptions
		Qld	WA		
Binders					
C170	1,030	3.932E-01	3.756E-01	Bitumen, at port, [State]/AU U	Assumed similar emissions for all bitumen
C320	1,030	3.932E-01	3.756E-01	Bitumen, at port, [State]/AU U	Assumed similar emissions for all bitumen
C450	1,030	3.932E-01	3.756E-01	Bitumen, at port, [State]/AU U	Assumed similar emissions for all bitumen
C600	1,030	3.932E-01	3.756E-01	Bitumen, at port, [State]/AU U	Assumed similar emissions for all bitumen
EME2 binder	1,030	4.013E-01	3.817E-01	EME bitumen, at port, [State]/AU U	
A10E	1,030	7.276E-01	7.076E-01	A10E, PMB, [State]/AU U	Assumed 5.5% SBS content
A15E	1,030	6.993E-01	6.791E-01	A15E, PMB, [State]/AU U	Assumed 5.0% SBS content
A20E	1,030	6.709E-01	6.505E-01	A20E, PMB, [State]/AU U	Assumed 4.5% SBS content
A25E	1,030	6.441E-01	6.714E-01	A25E, PMB, [State]/AU U	Assumed 6.5% polybutadiene content
A35P	1,030	5.357E-01	5.516E-01	A35P, PMB, [State]/AU U	Assumed 5.0% EVA
S10E	1,030	5.857E-01	5.648E-01	S10E, PMB, [State]/AU U	Assumed 3.0% SBS content
S15E	1,030	6.425E-01	6.219E-01	S15E, PMB, [State]/AU U	Assumed 4.0% SBS content
S20E	1,030	6.993E-01	6.791E-01	S20E, PMB, [State]/AU U	Assumed 5.0% SBS content
S25E	1,030	7.560E-01	7.362E-01	S25E, PMB, [State]/AU U	Assumed 6.0% SBS content
S35E	1,030	5.209E-01	5.217E-01	S35E, PMB, [State]/AU U	Assumed 3.0% polybutadiene content
S9R/S9RF	1,030	4.070E-01	3.801E-01	S9R (S9RF), PMB, [State]/AU U	Assumed 9% crumb rubber
S15R/S15RF/S45R	1,030	4.014E-01	3.712E-01	S45R, PMB, [State]/AU U	Assumed 15.0% crumb rubber
C170 5% rubber	1,030	4.107E-01	3.860E-01	C170_5% CR, PMB, [State]/AU U	Assumed 5.0% crumb rubber
S18RF/C170 18% rubber	1,030	3.987E-01	3.667E-01	C170_18% CR, PMB, [State]/AU U	Assumed 18.0% crumb rubber
CRS 170-30	1,030	1.766E-01	1.669E-01	CRS 170-30, bitumen emulsion, [State]/AU U	Emissions in terms of residual bitumen independent of the binder content of the emulsion
CRS 170-48	1,030	2.473E-01	2.344E-01	CRS 170-48, bitumen emulsion, [State]/AU U	Emissions in terms of residual bitumen independent of the binder content of the emulsion
CRS 170-60	1,030	2.945E-01	2.793E-01	CRS 170-60, bitumen emulsion, [State]/AU U	Emissions in terms of residual bitumen independent of the binder content of the emulsion

Material	Maximum density (kg/m^3)	Emission factors (tCO_2eq/tonne)		Process Names	Assumptions
		Qld	WA		
CRS 170-70	1,030	3.337E-01	3.168E-01	CRS 170-70, bitumen emulsion, [State]/AU U	Emissions in terms of residual bitumen independent of the binder content of the emulsion
ASS 170-60	1,030	2.945E-01	2.793E-01	CRS 170-60, bitumen emulsion, [State]/AU U	Assumed to be same as CRS 170-60
Polymer modified bitumen emulsion	1,030	9.771E-01	9.727E-01	Polymer modified bitumen emulsion/[State]/AU U	
Type GP cement	3,200	9.554E-01	9.481E-01	Ordinary Portland cement, [State]/AU U	
Type GB cement	3,200	9.554E-01	9.481E-01	Ordinary Portland cement, [State]/AU U	Assumed emissions to be same as Type GP cement
Type LH cement	3,200	9.554E-01	9.481E-01	Ordinary Portland cement, [State]/AU U	Assumed emissions to be same as Type GP cement
Supplementary materials					
Slag (ground granulated blast furnace slag)	3,200	1.722E-01	1.669E-01	Ground granulated blast furnace slag, at cement plant, [State]/AU U	Assume transport is to storage depot
Fly ash	2,500	1.370E-02	1.370E-02	Fly ash, delivered to plant/SAT/AU U	
Quicklime	3,200	1.011E+00	1.001E+00	Quicklime, in pieces, loose, at plant/[State]/AU U	
Air-entraining admixture	700	4.144E+00	4.144E+00	Melamine formaldehyde resin, at plant/RER U/SAT/AusSD U	Assume transport is to storage depot
Water-reducing admixture	700	4.144E+00	4.144E+00	Melamine formaldehyde resin, at plant/RER U/SAT/AusSD U	Assume transport is to storage depot
Set-retarding admixture	700	4.144E+00	4.144E+00	Melamine formaldehyde resin, at plant/RER U/SAT/AusSD U	Assume transport is to storage depot
Set-accelerating admixture	700	4.144E+00	4.144E+00	Melamine formaldehyde resin, at plant/RER U/SAT/AusSD U	Assume transport is to storage depot
Wetting agents	670	2.291E+00	2.291E+00	Trimethylamine, at plant/RER U/AusSD U	
Concrete curing compound	1,051	2.218E+00	2.218E+00	Acrylic dispersion, 65% in H2O, at plant/RER U/AusSD U	
Foaming agent	670	−1.204E+00	−1.204E+00	Foaming agent {GLO} | production | Cut-off, U/SAT	
Geotextile fabric	678	2.474E+00	2.474E+00	#N/A	Secutex® Environmental Product Declaration EPD-NAUE-STX-001-ref2 2017, includes modules A1 – A3
Concrete					
Steel reinforcement	7,580	1.909E+00	1.909E+00	Reinforcing steel {GLO} | market for | Cut-off, U/SAT	
Steel fibre	7,580	1.909E+00	1.909E+00	Reinforcing steel {GLO} | market for | Cut-off, U/SAT	Assumed same as steel reinforcement

Note: Processes with '[State]' have been developed for Queensland and Western Australia.

State-specific GHG emission factors (tCO_2eq/tonne) for pavement materials provided in Table A.1 were calculated using SimaPro software and the EN 15804:2012 + A1:2013 impact assessment method. AusLCI and ecoinvent references have been provided, along with any comparable materials and assumptions, for reference.

The main modelling assumptions were:

- Low-voltage electricity is assumed for both states. The following AusLCI processes are employed:
  - electricity, low voltage, Queensland/AU U
  - electricity, low voltage, Western Australia/AU U.
- The electricity requirement for the mixing process of bitumen and polymer or rubber is assumed to be 0.072 MJ (Eurobitume 2012).
- A 28-tonne fleet average truck is assumed for transport, using the following AusLCI process:
  - transport, truck, 28 tonne, SAT, fleet average/AU U.
- Water usage is state-specific using relevant processes.
- For commercial materials, such as Sasobit, Evotherm, admixtures, etc., a proxy chemical is assumed as a base material.

Individualised assumptions and process descriptions are listed in the SAT4P materials database.

A.2 Other Air-borne Emission Factors for Pavement Materials

Table A.2: Materials data – other air-borne emission factors

Material	NOx (kg/kg of mat.)		SOx (kg/kg of mat.)		NMVOC (kg/kg of mat.)		PM2.5 (kg/kg of mat.)		PM10 (kg/kg of mat.)		Poly aromatic hydrocarbons (PAH) (kg/kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
Unbound materials												
In situ material	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
General/imported fill	1.20E-05	4.16E-06	1.01E-05	3.97E-06	9.95E-07	1.03E-06	1.98E-07	2.21E-07	1.93E-07	2.34E-07	1.02E-10	1.00E-10
Metal dust/quarry fines	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
Crushed limestone	3.06E-05	2.85E-05	4.58E-06	2.95E-06	5.55E-06	5.55E-06	9.42E-06	9.43E-06	5.92E-08	6.99E-08	4.76E-10	4.76E-10
Natural gravel	1.20E-05	4.16E-06	1.01E-05	3.97E-06	9.95E-07	1.03E-06	1.98E-07	2.21E-07	1.93E-07	2.34E-07	1.02E-10	1.00E-10
Crushed gravel	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
Crushed rock	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
RCG	4.40E-05	3.33E-05	1.58E-05	7.36E-06	1.76E-05	1.76E-05	5.80E-06	5.83E-06	2.61E-07	3.17E-07	1.70E-06	1.70E-06
RCC	6.94E-06	4.13E-06	6.44E-06	4.22E-06	1.43E-06	1.44E-06	2.15E-07	2.23E-07	7.45E-08	8.97E-08	2.05E-10	2.05E-10
Recycled sand	6.94E-06	4.13E-06	6.44E-06	4.22E-06	1.43E-06	1.44E-06	2.15E-07	2.23E-07	7.45E-08	8.97E-08	2.05E-10	2.05E-10

Material	NOx (kg/kg of mat.)		SOx (kg/kg of mat.)		NMVOC (kg/kg of mat.)		PM2.5 (kg/kg of mat.)		PM10 (kg/kg of mat.)		Poly aromatic hydrocarbons (PAH) (kg/kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
Rock fill	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
RCB	6.94E-06	4.13E-06	6.44E-06	4.22E-06	1.43E-06	1.44E-06	2.15E-07	2.23E-07	7.45E-08	8.97E-08	2.05E-10	2.05E-10
Select fill	1.20E-05	4.16E-06	1.01E-05	3.97E-06	9.95E-07	1.03E-06	1.98E-07	2.21E-07	1.93E-07	2.34E-07	1.02E-10	1.00E-10
Aggregates												
20 mm crushed aggregate	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
16 mm crushed aggregate	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
14 mm crushed aggregate	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
10 mm crushed aggregate	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
7 mm crushed aggregate	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
5 mm crushed aggregate	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
3 mm crushed aggregate	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
Crusher dust	3.60E-05	1.00E-05	2.97E-05	9.23E-06	1.50E-06	1.60E-06	5.04E-07	5.79E-07	6.37E-07	7.72E-07	1.54E-10	1.50E-10
Fine aggregate	1.20E-05	4.16E-06	1.01E-05	3.97E-06	9.95E-07	1.03E-06	1.98E-07	2.21E-07	1.93E-07	2.34E-07	1.02E-10	1.00E-10
Natural sand	1.20E-05	4.16E-06	1.01E-05	3.97E-06	9.95E-07	1.03E-06	1.98E-07	2.21E-07	1.93E-07	2.34E-07	1.02E-10	1.00E-10
Surface grit	1.20E-05	4.16E-06	1.01E-05	3.97E-06	9.95E-07	1.03E-06	1.98E-07	2.21E-07	1.93E-07	2.34E-07	1.02E-10	1.00E-10
Asphalt and sealing materials (excluding binders)												
RAP	8.79E-07	8.79E-07	9.34E-07	9.34E-07	3.74E-07	3.74E-07	3.08E-08	3.08E-08	1.31E-09	1.31E-09	5.04E-11	5.04E-11
Lime kiln dust	5.26E-05	5.26E-05	3.69E-05	3.69E-05	1.62E-05	1.62E-05	4.31E-06	4.31E-06	2.03E-08	2.03E-08	6.66E-11	6.66E-11
Hydrated lime	1.30E-03	1.13E-03	5.36E-04	4.04E-04	1.89E-04	1.90E-04	4.17E-05	4.22E-05	4.37E-06	5.26E-06	1.86E-09	1.83E-09
Ground limestone	1.58E-04	6.51E-05	1.12E-04	3.86E-05	1.21E-05	1.25E-05	1.09E-05	1.11E-05	2.27E-06	2.75E-06	7.26E-10	7.10E-10
EvoTherm	6.38E-03	6.38E-03	5.77E-03	5.77E-03	3.49E-03	3.49E-03	4.53E-04	4.53E-04	6.82E-05	6.82E-05	1.75E-07	1.75E-07
Sasobit	2.88E-03	2.88E-03	2.88E-03	2.88E-03	1.02E-03	1.02E-03	1.47E-04	1.47E-04	3.05E-06	3.05E-06	3.51E-09	3.51E-09
Cutting oil	1.40E-03	1.38E-03	4.12E-03	4.10E-03	1.43E-03	1.43E-03	1.08E-04	1.08E-04	5.20E-06	5.38E-06	1.76E-08	1.76E-08
Flux oil	1.42E-03	1.40E-03	4.14E-03	4.13E-03	1.42E-03	1.42E-03	1.08E-04	1.08E-04	5.43E-06	5.53E-06	1.77E-08	1.77E-08
Adhesion agent	5.05E-03	5.05E-03	4.33E-03	4.33E-03	5.88E-03	5.88E-03	2.35E-03	2.35E-03	0.00E+00	0.00E+00	3.58E-06	3.58E-06
Fibres (cellulose)	1.47E-03	1.18E-03	2.09E-03	1.86E-03	2.09E-04	2.10E-04	1.11E-04	1.12E-04	1.92E-05	2.07E-05	1.42E-08	1.42E-08
SBS copolymer	1.03E-02	1.03E-02	1.50E-02	1.50E-02	7.87E-03	7.87E-03	5.13E-04	5.13E-04	6.12E-06	6.12E-06	6.37E-08	6.37E-08

Material	NOx (kg/kg of mat.)		SOx (kg/kg of mat.)		NMVOC (kg/kg of mat.)		PM2.5 (kg/kg of mat.)		PM10 (kg/kg of mat.)		Poly aromatic hydrocarbons (PAH) (kg/kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
EVA	5.13E-03	5.13E-03	2.86E-03	2.86E-03	2.70E-03	2.70E-03	7.72E-05	7.72E-05	4.65E-05	4.65E-05	8.58E-09	8.58E-09
LDPE	8.51E-03	5.66E-03	5.27E-03	3.03E-03	1.19E-03	1.20E-03	7.86E-05	8.65E-05	8.47E-05	9.94E-05	1.11E-08	1.06E-08
HDPE	3.52E-03	3.22E-03	1.55E-03	1.31E-03	1.26E-03	1.26E-03	3.51E-05	3.59E-05	1.31E-05	1.47E-05	4.33E-09	4.28E-09
PET	5.81E-03	5.25E-03	5.64E-03	5.20E-03	2.66E-03	2.66E-03	2.57E-04	2.58E-04	6.70E-05	6.99E-05	1.03E-08	1.02E-08
Crumb rubber	1.26E-03	2.95E-04	1.02E-03	2.57E-04	1.89E-05	2.25E-05	2.24E-04	2.27E-04	2.34E-05	2.84E-05	1.95E-09	1.79E-09
Crack sealant	2.20E-03	1.78E-03	3.49E-03	3.19E-03	9.55E-04	9.40E-04	1.25E-04	1.17E-04	2.57E-06	3.12E-06	5.82E-08	4.87E-08
Binders												
C170	2.15E-03	1.82E-03	3.55E-03	3.32E-03	9.98E-04	9.82E-04	1.17E-04	1.09E-04	4.03E-09	2.72E-09	6.10E-08	5.09E-08
C320	2.15E-03	1.82E-03	3.55E-03	3.32E-03	9.98E-04	9.82E-04	1.17E-04	1.09E-04	4.03E-09	2.72E-09	6.10E-08	5.09E-08
C450	2.15E-03	1.82E-03	3.55E-03	3.32E-03	9.98E-04	9.82E-04	1.17E-04	1.09E-04	4.03E-09	2.72E-09	6.10E-08	5.09E-08
C600	2.15E-03	1.82E-03	3.55E-03	3.32E-03	9.98E-04	9.82E-04	1.17E-04	1.09E-04	4.03E-09	2.72E-09	6.10E-08	5.09E-08
EME2 binder	2.19E-03	1.83E-03	3.57E-03	3.33E-03	9.99E-04	9.82E-04	1.18E-04	1.09E-04	6.42E-07	7.76E-07	6.10E-08	5.10E-08
A10E	2.71E-03	2.36E-03	4.43E-03	4.18E-03	1.40E-03	1.39E-03	1.51E-04	1.44E-04	1.74E-06	2.03E-06	6.24E-08	5.35E-08
A15E	2.67E-03	2.32E-03	4.36E-03	4.11E-03	1.37E-03	1.35E-03	1.48E-04	1.41E-04	1.71E-06	2.00E-06	6.23E-08	5.33E-08
A20E	2.63E-03	2.27E-03	4.28E-03	4.03E-03	1.33E-03	1.31E-03	1.45E-04	1.38E-04	1.68E-06	1.97E-06	6.22E-08	5.31E-08
A25E	2.60E-03	2.29E-03	4.26E-03	4.23E-03	1.55E-03	1.56E-03	1.33E-04	1.38E-04	1.42E-06	1.71E-06	5.72E-08	4.98E-08
A35P	2.40E-03	2.07E-03	3.59E-03	3.50E-03	1.09E-03	1.10E-03	1.18E-04	1.19E-04	3.78E-06	4.08E-06	5.86E-08	5.05E-08
S10E	2.50E-03	2.13E-03	4.06E-03	3.80E-03	1.22E-03	1.21E-03	1.37E-04	1.29E-04	1.59E-06	1.88E-06	6.19E-08	5.24E-08
S15E	2.58E-03	2.22E-03	4.21E-03	3.95E-03	1.29E-03	1.28E-03	1.42E-04	1.35E-04	1.65E-06	1.94E-06	6.21E-08	5.29E-08
S20E	2.67E-03	2.32E-03	4.36E-03	4.11E-03	1.37E-03	1.35E-03	1.48E-04	1.41E-04	1.71E-06	2.00E-06	6.23E-08	5.33E-08
S25E	2.75E-03	2.41E-03	4.50E-03	4.26E-03	1.44E-03	1.42E-03	1.54E-04	1.47E-04	1.77E-06	2.07E-06	6.25E-08	5.37E-08
S35E	2.41E-03	2.06E-03	3.91E-03	3.76E-03	1.26E-03	1.25E-03	1.26E-04	1.23E-04	1.41E-06	1.71E-06	5.94E-08	5.05E-08
S9R/S9RF	2.16E-03	1.72E-03	3.39E-03	3.07E-03	9.16E-04	9.02E-04	1.29E-04	1.22E-04	3.51E-06	4.25E-06	5.59E-08	4.67E-08
S15R/S15RF/S45R	2.11E-03	1.63E-03	3.24E-03	2.89E-03	8.57E-04	8.44E-04	1.35E-04	1.29E-04	4.91E-06	5.95E-06	5.23E-08	4.38E-08
C170 5% rubber	2.20E-03	1.78E-03	3.49E-03	3.19E-03	9.55E-04	9.40E-04	1.25E-04	1.17E-04	2.57E-06	3.12E-06	5.82E-08	4.87E-08
S18RF/C170 18% rubber	2.08E-03	1.58E-03	3.16E-03	2.79E-03	8.28E-04	8.15E-04	1.39E-04	1.32E-04	5.61E-06	6.80E-06	5.06E-08	4.23E-08
CRS 170-30	8.12E-04	6.56E-04	1.25E-03	1.13E-03	3.93E-04	3.88E-04	4.21E-05	3.97E-05	1.88E-06	2.22E-06	1.98E-08	1.68E-08

Material	NOx (kg/kg of mat.)		SOx (kg/kg of mat.)		NMVOC (kg/kg of mat.)		PM2.5 (kg/kg of mat.)		PM10 (kg/kg of mat.)		Poly aromatic hydrocarbons (PAH) (kg/kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
CRS 170-48	1.20E-03	9.84E-04	1.88E-03	1.73E-03	5.72E-04	5.64E-04	6.32E-05	5.93E-05	1.87E-06	2.20E-06	3.08E-08	2.59E-08
CRS 170-60	1.46E-03	1.20E-03	2.31E-03	2.13E-03	6.92E-04	6.82E-04	7.73E-05	7.24E-05	1.87E-06	2.19E-06	3.81E-08	3.20E-08
CRS 170-70	1.67E-03	1.39E-03	2.66E-03	2.46E-03	7.92E-04	7.80E-04	8.91E-05	8.33E-05	1.87E-06	2.18E-06	4.42E-08	3.71E-08
ASS 170-60	1.46E-03	1.20E-03	2.31E-03	2.13E-03	6.92E-04	6.82E-04	7.73E-05	7.24E-05	1.87E-06	2.19E-06	3.81E-08	3.20E-08
Polymer modified bitumen emulsion	3.87E-03	3.81E-03	3.73E-03	3.68E-03	1.33E-03	1.33E-03	1.84E-04	1.84E-04	3.21E-06	3.51E-06	1.94E-08	1.94E-08
Type GP cement	3.00E-03	2.90E-03	8.29E-04	7.58E-04	1.06E-04	1.08E-04	6.61E-05	6.68E-05	5.52E-06	6.09E-06	1.04E-08	1.10E-08
Type GB cement	3.00E-03	2.90E-03	8.29E-04	7.58E-04	1.06E-04	1.08E-04	6.61E-05	6.68E-05	5.52E-06	6.09E-06	1.04E-08	1.10E-08
Type LH cement	3.00E-03	2.90E-03	8.29E-04	7.58E-04	1.06E-04	1.08E-04	6.61E-05	6.68E-05	5.52E-06	6.09E-06	1.04E-08	1.10E-08
Supplementary materials												
Slag (ground granulated blast furnace slag)	1.11E-03	1.06E-03	9.52E-04	9.19E-04	7.95E-05	8.64E-05	4.33E-05	4.61E-05	3.99E-06	4.74E-06	3.62E-08	3.93E-08
Fly ash	5.26E-05	5.26E-05	3.69E-05	3.69E-05	1.62E-05	1.62E-05	4.31E-06	4.31E-06	2.03E-08	2.03E-08	6.66E-11	6.66E-11
Quicklime	7.44E-04	6.10E-04	5.59E-04	4.53E-04	3.62E-04	3.62E-04	3.98E-05	4.01E-05	3.84E-06	4.54E-06	2.13E-09	2.11E-09
Air-entraining admixture	7.14E-03	7.14E-03	4.32E-03	4.32E-03	2.33E-03	2.33E-03	1.45E-03	1.45E-03	5.48E-05	5.48E-05	3.30E-07	3.30E-07
Water-reducing admixture	7.14E-03	7.14E-03	4.32E-03	4.32E-03	2.33E-03	2.33E-03	1.45E-03	1.45E-03	5.48E-05	5.48E-05	3.30E-07	3.30E-07
Set-retarding admixture	7.14E-03	7.14E-03	4.32E-03	4.32E-03	2.33E-03	2.33E-03	1.45E-03	1.45E-03	5.48E-05	5.48E-05	3.30E-07	3.30E-07
Set-accelerating admixture	7.14E-03	7.14E-03	4.32E-03	4.32E-03	2.33E-03	2.33E-03	1.45E-03	1.45E-03	5.48E-05	5.48E-05	3.30E-07	3.30E-07
Wetting agents	3.85E-03	3.85E-03	2.84E-03	2.84E-03	5.79E-03	5.79E-03	2.53E-04	2.53E-04	3.54E-05	3.54E-05	8.87E-08	8.87E-08
Concrete curing compound	4.97E-03	4.97E-03	5.45E-03	5.45E-03	2.35E-03	2.35E-03	2.83E-04	2.83E-04	3.69E-05	3.69E-05	1.58E-07	1.58E-07
Foaming agent	3.12E-03	3.12E-03	2.17E-03	2.17E-03	3.64E-03	3.64E-03	1.46E-03	1.46E-03	0.00E+00	0.00E+00	3.18E-06	3.18E-06
Geotextile fabric	–	–	–	–	–	–	–	–	–	–	–	–
Concrete												
Steel reinforcement	4.52E-03	4.52E-03	4.24E-03	4.24E-03	3.95E-03	3.95E-03	2.30E-03	2.30E-03	0.00E+00	0.00E+00	1.69E-06	1.69E-06
Steel fibre	4.52E-03	4.52E-03	4.24E-03	4.24E-03	3.95E-03	3.95E-03	2.30E-03	2.30E-03	0.00E+00	0.00E+00	1.69E-06	1.69E-06

A.3 EnviroPoints for Pavement Materials

Table A.3: Materials data – EnviroPoints

Material	Total (pts/kg of mat.)		Global warming (pts/kg of mat.)		Ozone depletion (pts/kg of mat.)		Acidification (pts/kg of mat.)		Eutrophication (pts/kg of mat.)		Photochemical smog (pts/kg of mat.)		Abiotic depletion – elements (pts/kg of mat.)		Abiotic depletion – fossil fuels (pts/kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
Unbound materials																
In situ material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
General/imported fill	3.81E-05	3.31E-05	2.70E-05	2.30E-05	5.64E-08	5.29E-08	1.72E-06	8.12E-07	5.09E-07	2.03E-07	8.20E-07	8.41E-07	1.17E-07	1.16E-07	7.86E-06	8.10E-06
Metal dust/quarry fines	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
Crushed limestone	3.24E-05	3.11E-05	1.73E-05	1.62E-05	6.13E-08	6.04E-08	4.87E-06	4.63E-06	1.69E-06	1.61E-06	3.26E-06	3.26E-06	1.44E-08	1.41E-08	5.22E-06	5.28E-06
Natural gravel	3.81E-05	3.31E-05	2.70E-05	2.30E-05	5.64E-08	5.29E-08	1.72E-06	8.12E-07	5.09E-07	2.03E-07	8.20E-07	8.41E-07	1.17E-07	1.16E-07	7.86E-06	8.10E-06
Crushed gravel	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
Crushed rock	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
RCG	1.44E-04	1.37E-04	1.03E-04	9.79E-05	1.49E-07	1.44E-07	5.49E-06	4.24E-06	2.45E-06	2.03E-06	1.83E-05	1.83E-05	6.71E-07	6.69E-07	1.33E-05	1.36E-05
RCC	3.67E-05	3.50E-05	2.55E-05	2.41E-05	9.79E-08	9.66E-08	1.48E-06	1.15E-06	3.50E-07	2.39E-07	1.04E-06	1.05E-06	2.62E-07	2.61E-07	7.98E-06	8.07E-06
Recycled sand	3.67E-05	3.50E-05	2.55E-05	2.41E-05	9.79E-08	9.66E-08	1.48E-06	1.15E-06	3.50E-07	2.39E-07	1.04E-06	1.05E-06	2.62E-07	2.61E-07	7.98E-06	8.07E-06
Rock fill	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
RCB	3.67E-05	3.50E-05	2.55E-05	2.41E-05	9.79E-08	9.66E-08	1.48E-06	1.15E-06	3.50E-07	2.39E-07	1.04E-06	1.05E-06	2.62E-07	2.61E-07	7.98E-06	8.07E-06
Select fill	3.81E-05	3.31E-05	2.70E-05	2.30E-05	5.64E-08	5.29E-08	1.72E-06	8.12E-07	5.09E-07	2.03E-07	8.20E-07	8.41E-07	1.17E-07	1.16E-07	7.86E-06	8.10E-06
Aggregates																
20 mm crushed aggregate	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
16 mm crushed aggregate	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
14 mm crushed aggregate	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
10 mm crushed aggregate	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
7 mm crushed aggregate	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
5 mm crushed aggregate	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
3 mm crushed aggregate	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
Crusher dust	9.44E-05	7.77E-05	6.76E-05	5.41E-05	7.33E-08	6.16E-08	4.51E-06	1.48E-06	1.46E-06	4.42E-07	1.49E-06	1.55E-06	3.80E-07	3.76E-07	1.89E-05	1.97E-05
Fine aggregate	3.81E-05	3.31E-05	2.70E-05	2.30E-05	5.64E-08	5.29E-08	1.72E-06	8.12E-07	5.09E-07	2.03E-07	8.20E-07	8.41E-07	1.17E-07	1.16E-07	7.86E-06	8.10E-06
Natural sand	3.81E-05	3.31E-05	2.70E-05	2.30E-05	5.64E-08	5.29E-08	1.72E-06	8.12E-07	5.09E-07	2.03E-07	8.20E-07	8.41E-07	1.17E-07	1.16E-07	7.86E-06	8.10E-06
Surface grit	3.81E-05	3.31E-05	2.70E-05	2.30E-05	5.64E-08	5.29E-08	1.72E-06	8.12E-07	5.09E-07	2.03E-07	8.20E-07	8.41E-07	1.17E-07	1.16E-07	7.86E-06	8.10E-06
Asphalt and sealing materials (excluding binders)																
RAP	7.77E-06	7.77E-06	5.39E-06	5.39E-06	2.73E-08	2.73E-08	2.90E-07	2.90E-07	5.56E-08	5.56E-08	2.51E-07	2.51E-07	2.80E-10	2.80E-10	1.76E-06	1.76E-06
Lime kiln dust	1.46E-04	1.46E-04	9.39E-05	9.39E-05	4.58E-07	4.58E-07	8.58E-06	8.58E-06	2.40E-06	2.40E-06	1.11E-05	1.11E-05	4.67E-09	4.67E-09	2.94E-05	2.94E-05
Hydrated lime	6.80E-03	6.70E-03	5.79E-03	5.71E-03	7.54E-06	7.46E-06	2.17E-04	1.97E-04	5.27E-05	4.61E-05	1.40E-04	1.40E-04	3.46E-06	3.43E-06	5.92E-04	5.97E-04
Ground limestone	3.80E-04	3.21E-04	2.67E-04	2.19E-04	4.30E-07	3.88E-07	2.16E-05	1.08E-05	6.84E-06	3.22E-06	9.10E-06	9.33E-06	3.02E-08	1.63E-08	7.51E-05	7.77E-05
EvoTherm	4.81E-02	4.81E-02	2.80E-02	2.80E-02	4.42E-05	4.42E-05	1.85E-03	1.85E-03	1.08E-03	1.08E-03	1.58E-03	1.58E-03	7.01E-06	7.01E-06	1.56E-02	1.56E-02
Sasobit	1.52E-02	1.52E-02	5.21E-03	5.21E-03	7.42E-06	7.42E-06	8.98E-04	8.98E-04	1.16E-04	1.16E-04	7.10E-04	7.10E-04	7.42E-08	7.42E-08	8.29E-03	8.29E-03
Cutting oil	1.31E-02	1.31E-02	3.07E-03	3.06E-03	1.21E-04	1.21E-04	1.04E-03	1.04E-03	1.51E-04	1.53E-04	9.72E-04	9.72E-04	1.88E-06	1.88E-06	7.77E-03	7.77E-03
Flux oil	1.32E-02	1.32E-02	3.11E-03	3.10E-03	1.22E-04	1.22E-04	1.05E-03	1.05E-03	1.52E-04	1.51E-04	9.72E-04	9.72E-04	1.24E-06	1.24E-06	7.81E-03	7.81E-03
Adhesion agent	3.83E-02	3.83E-02	1.17E-02	1.17E-02	3.07E-05	3.07E-05	1.91E-03	1.91E-03	5.84E-03	5.84E-03	2.81E-03	2.81E-03	9.47E-03	9.47E-03	6.51E-03	6.51E-03
Fibres (cellulose)	6.58E-02	6.57E-02	1.81E-03	1.66E-03	3.33E-06	3.20E-06	4.77E-04	4.43E-04	6.53E-05	5.39E-05	2.31E-04	2.32E-04	6.22E-02	6.22E-02	1.03E-03	1.04E-03
SBS copolymer	6.48E-02	6.48E-02	3.66E-02	3.66E-02	1.34E-05	1.34E-05	4.38E-03	4.38E-03	4.03E-04	4.03E-04	5.19E-03	5.19E-03	4.20E-05	4.20E-05	1.82E-02	1.82E-02
EVA	3.51E-02	3.51E-02	1.87E-02	1.87E-02	2.45E-05	2.45E-05	7.01E-04	7.01E-04	3.00E-04	3.00E-04	1.38E-03	1.38E-03	1.47E-05	1.47E-05	1.40E-02	1.40E-02
LDPE	4.38E-02	4.19E-02	2.55E-02	2.39E-02	2.11E-05	1.98E-05	1.04E-03	7.09E-04	3.51E-04	2.40E-04	1.14E-03	1.14E-03	3.37E-06	2.94E-06	1.58E-02	1.59E-02

Material	Total (pts/kg of mat.)		Global warming (pts/kg of mat.)		Ozone depletion (pts/kg of mat.)		Acidification (pts/kg of mat.)		Eutrophication (pts/kg of mat.)		Photochemical smog (pts/kg of mat.)		Abiotic depletion – elements (pts/kg of mat.)		Abiotic depletion – fossil fuels (pts/kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
HDPE	3.22E-02	3.20E-02	1.62E-02	1.60E-02	2.15E-05	2.13E-05	5.32E-04	4.97E-04	1.71E-04	1.60E-04	1.04E-03	1.04E-03	2.00E-06	1.95E-06	1.42E-02	1.42E-02
PET	3.50E-02	3.47E-02	2.00E-02	1.97E-02	1.50E-05	1.47E-05	1.34E-03	1.27E-03	2.52E-04	2.30E-04	1.56E-03	1.56E-03	7.23E-06	7.15E-06	1.18E-02	1.18E-02
Crumb rubber	2.83E-03	2.21E-03	2.06E-03	1.56E-03	4.58E-07	2.43E-08	1.42E-04	2.94E-05	5.00E-05	1.24E-05	2.89E-05	3.14E-05	2.54E-07	1.09E-07	5.56E-04	5.83E-04
Crack sealant	1.17E-02	1.14E-02	2.81E-03	2.64E-03	1.52E-04	1.52E-04	9.88E-04	8.97E-04	1.60E-04	1.39E-04	7.10E-04	6.88E-04	1.31E-05	1.29E-05	6.91E-03	6.88E-03
Binders																
C170	1.20E-02	1.17E-02	2.69E-03	2.57E-03	1.60E-04	1.60E-04	1.02E-03	9.38E-04	1.62E-04	1.44E-04	7.40E-04	7.18E-04	1.38E-05	1.36E-05	7.20E-03	7.17E-03
C320	1.20E-02	1.17E-02	2.69E-03	2.57E-03	1.60E-04	1.60E-04	1.02E-03	9.38E-04	1.62E-04	1.44E-04	7.40E-04	7.18E-04	1.38E-05	1.36E-05	7.20E-03	7.17E-03
C450	1.20E-02	1.17E-02	2.69E-03	2.57E-03	1.60E-04	1.60E-04	1.02E-03	9.38E-04	1.62E-04	1.44E-04	7.40E-04	7.18E-04	1.38E-05	1.36E-05	7.20E-03	7.17E-03
C600	1.20E-02	1.17E-02	2.69E-03	2.57E-03	1.60E-04	1.60E-04	1.02E-03	9.38E-04	1.62E-04	1.44E-04	7.40E-04	7.18E-04	1.38E-05	1.36E-05	7.20E-03	7.17E-03
EME2 binder	1.21E-02	1.18E-02	2.75E-03	2.61E-03	1.60E-04	1.60E-04	1.03E-03	9.39E-04	1.63E-04	1.44E-04	7.41E-04	7.18E-04	1.38E-05	1.36E-05	7.22E-03	7.18E-03
A10E	1.56E-02	1.53E-02	4.98E-03	4.85E-03	1.55E-04	1.54E-04	1.26E-03	1.18E-03	1.81E-04	1.62E-04	1.01E-03	9.92E-04	1.97E-05	1.95E-05	7.96E-03	7.93E-03
A15E	1.53E-02	1.50E-02	4.79E-03	4.65E-03	1.55E-04	1.55E-04	1.24E-03	1.16E-03	1.79E-04	1.61E-04	9.88E-04	9.68E-04	1.91E-05	1.90E-05	7.90E-03	7.87E-03
A20E	1.50E-02	1.47E-02	4.60E-03	4.46E-03	1.56E-04	1.55E-04	1.22E-03	1.14E-03	1.78E-04	1.59E-04	9.64E-04	9.43E-04	1.86E-05	1.84E-05	7.83E-03	7.80E-03
A25E	1.48E-02	1.50E-02	4.41E-03	4.60E-03	1.50E-04	1.52E-04	1.21E-03	1.19E-03	1.74E-04	1.58E-04	1.08E-03	1.08E-03	1.35E-05	1.84E-05	7.74E-03	7.85E-03
A35P	1.34E-02	1.35E-02	3.67E-03	3.78E-03	1.54E-04	1.55E-04	1.02E-03	9.76E-04	1.73E-04	1.56E-04	7.80E-04	7.79E-04	1.39E-05	1.76E-05	7.60E-03	7.67E-03
S10E	1.40E-02	1.52E+02	4.01E-03	3.87E-03	1.57E-04	1.52E+02	1.16E-03	1.12E-07	1.74E-04	1.62E-03	8.91E-04	6.64E-04	1.70E-05	2.04E-01	7.64E-03	9.25E-12
S15E	1.47E-02	1.67E+02	4.40E-03	4.26E-03	1.56E-04	1.67E+02	1.20E-03	1.11E-07	1.77E-04	1.68E-03	9.40E-04	6.78E-04	1.81E-05	2.15E-01	7.77E-03	9.84E-12
S20E	1.53E-02	1.82E+02	4.79E-03	4.65E-03	1.55E-04	1.82E+02	1.24E-03	1.10E-07	1.79E-04	1.75E-03	9.88E-04	6.91E-04	1.91E-05	2.27E-01	7.90E-03	1.04E-11
S25E	1.59E-02	1.98E+02	5.18E-03	5.04E-03	1.54E-04	1.98E+02	1.28E-03	1.10E-07	1.82E-04	1.81E-03	1.04E-03	7.04E-04	2.02E-05	2.38E-01	8.03E-03	1.10E-11
S35E	1.34E-02	1.40E+02	3.57E-03	3.57E-03	1.56E-04	1.40E+02	1.12E-03	1.11E-07	1.70E-04	1.59E-03	8.98E-04	6.50E-04	1.37E-05	2.08E-01	7.48E-03	8.70E-12
S9R/S9RF	1.14E-02	1.10E-02	2.79E-03	2.60E-03	1.46E-04	1.45E-04	9.53E-04	8.60E-04	1.56E-04	1.33E-04	6.81E-04	6.61E-04	1.26E-05	1.24E-05	6.65E-03	6.62E-03
S15R/S15RF/S45R	1.08E-02	9.97E+01	2.75E-03	2.54E-03	1.37E-04	9.96E+01	9.00E-04	9.67E-08	1.49E-04	1.22E-03	6.39E-04	5.40E-04	1.18E-05	1.45E-01	6.25E-03	6.37E-12
C170 5% rubber	1.17E-02	1.14E-02	2.81E-03	2.64E-03	1.52E-04	1.52E-04	9.88E-04	8.97E-04	1.60E-04	1.39E-04	7.10E-04	6.88E-04	1.31E-05	1.29E-05	6.91E-03	6.88E-03
S18RF/C170 18% rubber	1.06E-02	1.02E-02	2.73E-03	2.51E-03	1.32E-04	1.31E-04	8.74E-04	7.79E-04	1.46E-04	1.21E-04	6.17E-04	5.99E-04	1.14E-05	1.12E-05	6.05E-03	6.03E-03
CRS 170-30	4.43E-03	4.48E+01	1.21E-03	1.14E-03	5.08E-05	4.48E+01	3.49E-04	3.60E-08	6.64E-05	4.78E-04	2.61E-04	2.52E-04	6.68E-06	5.96E-02	2.49E-03	3.64E-12
CRS 170-48	6.59E-03	6.30E+01	1.69E-03	1.61E-03	7.97E-05	6.29E+01	5.33E-04	5.65E-08	9.55E-05	7.33E-04	3.94E-04	3.64E-04	9.16E-06	8.99E-02	3.79E-03	4.98E-12
CRS 170-60	8.03E-03	7.51E+01	2.02E-03	1.91E-03	9.89E-05	7.50E+01	6.55E-04	7.01E-08	1.15E-04	9.03E-04	4.83E-04	4.38E-04	1.08E-05	1.10E-01	4.65E-03	5.88E-12
CRS 170-70	9.23E-03	8.51E+01	2.29E-03	2.17E-03	1.15E-04	8.50E+01	7.58E-04	8.15E-08	1.31E-04	1.04E-03	5.57E-04	5.00E-04	1.22E-05	1.27E-01	5.37E-03	6.63E-12
ASS 170-60	8.03E-03	7.51E+01	2.02E-03	1.91E-03	9.89E-05	7.50E+01	6.55E-04	7.01E-08	1.15E-04	9.03E-04	4.83E-04	4.38E-04	1.08E-05	1.10E-01	4.65E-03	5.88E-12
Polymer modified bitumen emulsion	1.56E-02	1.55E-02	6.69E-03	6.66E-03	4.94E-05	4.93E-05	1.20E-03	1.19E-03	1.93E-04	1.90E-04	9.00E-04	9.00E-04	5.27E-05	5.27E-05	6.49E-03	6.49E-03
Type GP cement	8.08E-03	8.03E-03	6.54E-03	6.49E-03	1.13E-06	1.11E-06	4.42E-04	4.34E-04	1.18E-04	1.14E-04	1.23E-04	1.25E-04	4.55E-06	4.54E-06	8.48E-04	8.53E-04
Type GB cement	8.08E-03	8.03E-03	6.54E-03	6.49E-03	1.13E-06	1.11E-06	4.42E-04	4.34E-04	1.18E-04	1.14E-04	1.23E-04	1.25E-04	4.55E-06	4.54E-06	8.48E-04	8.53E-04
Type LH cement	8.08E-03	8.03E-03	6.54E-03	6.49E-03	1.13E-06	1.11E-06	4.42E-04	4.34E-04	1.18E-04	1.14E-04	1.23E-04	1.25E-04	4.55E-06	4.54E-06	8.48E-04	8.53E-04
Supplementary materials																
Slag (ground granulated blast furnace slag)	2.02E-03	2.01E-03	1.18E-03	1.14E-03	2.02E-06	2.14E-06	2.90E-04	3.00E-04	4.45E-05	4.24E-05	1.08E-04	1.17E-04	2.93E-07	2.73E-07	3.92E-04	4.08E-04
Fly ash	1.46E-04	1.46E-04	9.39E-05	9.39E-05	4.58E-07	4.58E-07	8.58E-06	8.58E-06	2.40E-06	2.40E-06	1.11E-05	1.11E-05	4.67E-09	4.67E-09	2.94E-05	2.94E-05
Quicklime	8.33E-03	8.24E-03	6.93E-03	6.86E-03	1.79E-05	1.78E-05	1.68E-04	1.52E-04	3.03E-05	2.51E-05	3.77E-04	3.78E-04	7.05E-08	5.03E-08	8.05E-04	8.08E-04
Air-entraining admixture	4.66E-02	4.66E-02	2.84E-02	2.84E-02	3.85E-05	3.85E-05	2.83E-03	2.83E-03	8.76E-04	8.76E-04	1.65E-03	1.65E-03	6.20E-05	6.20E-05	1.28E-02	1.28E-02
Water-reducing admixture	4.66E-02	4.66E-02	2.84E-02	2.84E-02	3.85E-05	3.85E-05	2.83E-03	2.83E-03	8.76E-04	8.76E-04	1.65E-03	1.65E-03	6.20E-05	6.20E-05	1.28E-02	1.28E-02
Set-retarding admixture	4.66E-02	4.66E-02	2.84E-02	2.84E-02	3.85E-05	3.85E-05	2.83E-03	2.83E-03	8.76E-04	8.76E-04	1.65E-03	1.65E-03	6.20E-05	6.20E-05	1.28E-02	1.28E-02
Set-accelerating admixture	4.66E-02	4.66E-02	2.84E-02	2.84E-02	3.85E-05	3.85E-05	2.83E-03	2.83E-03	8.76E-04	8.76E-04	1.65E-03	1.65E-03	6.20E-05	6.20E-05	1.28E-02	1.28E-02
Wetting agents	3.14E-02	3.14E-02	1.57E-02	1.57E-02	1.36E-05	1.36E-05	9.72E-04	9.72E-04	1.07E-03	1.07E-03	1.41E-03	1.41E-03	2.49E-04	2.49E-04	1.20E-02	1.20E-02
Concrete curing compound	2.64E-02	2.64E-02	1.52E-02	1.52E-02	7.64E-05	7.64E-05	1.47E-03	1.47E-03	2.93E-04	2.93E-04	1.23E-03	1.23E-03	6.42E-04	6.42E-04	7.48E-03	7.48E-03
Foaming agent	1.00E-02	1.00E-02	−8.25E-03	−8.25E-03	3.67E-05	3.67E-05	1.57E-03	1.57E-03	2.13E-03	2.13E-03	1.96E-03	1.96E-03	1.09E-02	1.09E-02	1.65E-03	1.65E-03

Material	Total (pts/kg of mat.)		Global warming (pts/kg of mat.)		Ozone depletion (pts/kg of mat.)		Acidification (pts/kg of mat.)		Eutrophication (pts/kg of mat.)		Photochemical smog (pts/kg of mat.)		Abiotic depletion – elements (pts/kg of mat.)		Abiotic depletion – fossil fuels (pts/kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
Geotextile fabric	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Concrete																
Steel reinforcement	2.55E-02	2.55E-02	1.31E-02	1.31E-02	3.05E-05	3.05E-05	1.43E-03	1.43E-03	3.00E-04	3.00E-04	3.26E-03	3.26E-03	2.92E-03	2.92E-03	4.49E-03	4.49E-03
Steel fibre	2.55E-02	2.55E-02	1.31E-02	1.31E-02	3.05E-05	3.05E-05	1.43E-03	1.43E-03	3.00E-04	3.00E-04	3.26E-03	3.26E-03	2.92E-03	2.92E-03	4.49E-03	4.49E-03

A.4 Embodied Energy and Water Consumption Factors for Pavement Materials

Table A.4: Materials data – energy and water consumption factors

Material	Embodied energy (MJ/kg of mat.)		Embodied diesel use (kg/kg of mat.)		Embodied natural gas use (GJ/kg of mat.)		Embodied electricity use (kWh/kg of mat.)		Water usage (m^3eq./kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
Unbound materials										
In situ material	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
General/imported fill	5.36E-02	5.80E-02	3.62E-04	3.60E-04	3.12E-06	1.20E-05	3.07E-03	3.09E-03	1.40E-03	1.39E-03
Metal dust/quarry fines	1.29E-01	1.43E-01	3.67E-04	3.59E-04	1.01E-05	3.96E-05	1.01E-02	1.02E-02	1.38E-03	1.37E-03
Crushed limestone	3.57E-02	3.69E-02	4.33E-04	4.33E-04	1.48E-06	3.81E-06	9.40E-04	9.43E-04	2.55E-05	2.44E-05
Natural gravel	5.36E-02	5.80E-02	3.62E-04	3.60E-04	3.12E-06	1.20E-05	3.07E-03	3.09E-03	1.40E-03	1.39E-03
Crushed gravel	1.29E-01	1.43E-01	3.67E-04	3.59E-04	1.01E-05	3.96E-05	1.01E-02	1.02E-02	1.38E-03	1.37E-03
Crushed rock	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
RCG	8.96E-02	9.56E-02	7.19E-06	3.83E-06	4.02E-06	1.62E-05	4.14E-03	4.15E-03	2.00E-03	2.00E-03
RCC	5.44E-02	5.61E-02	8.00E-04	7.99E-04	1.39E-06	4.61E-06	1.20E-03	1.21E-03	1.59E-05	1.45E-05
Recycled sand	5.44E-02	5.61E-02	8.00E-04	7.99E-04	1.39E-06	4.61E-06	1.20E-03	1.21E-03	1.59E-05	1.45E-05
Rock fill	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
RCB	5.44E-02	5.61E-02	8.00E-04	7.99E-04	1.39E-06	4.61E-06	1.20E-03	1.21E-03	1.59E-05	1.45E-05
Select fill	5.36E-02	5.80E-02	3.62E-04	3.60E-04	3.12E-06	1.20E-05	3.07E-03	3.09E-03	1.40E-03	1.39E-03
Aggregates										
20 mm crushed aggregate	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
16 mm crushed aggregate	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
14 mm crushed aggregate	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
10 mm crushed aggregate	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
7 mm crushed aggregate	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
5 mm crushed aggregate	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
3 mm crushed aggregate	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
Crusher dust	1.29E-01	1.43E-01	3.56E-04	3.48E-04	9.77E-06	3.92E-05	1.00E-02	1.01E-02	1.38E-03	1.37E-03
Fine aggregate	5.36E-02	5.80E-02	3.62E-04	3.60E-04	3.12E-06	1.20E-05	3.07E-03	3.09E-03	1.40E-03	1.39E-03

Material	Embodied energy (MJ/kg of mat.)		Embodied diesel use (kg/kg of mat.)		Embodied natural gas use (GJ/kg of mat.)		Embodied electricity use (kWh/kg of mat.)		Water usage (m^3eq./kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
Natural sand	5.36E-02	5.80E-02	3.62E-04	3.60E-04	3.12E-06	1.20E-05	3.07E-03	3.09E-03	1.40E-03	1.39E-03
Surface grit	5.36E-02	5.80E-02	3.62E-04	3.48E-04	3.12E-06	3.92E-05	3.07E-03	1.01E-02	1.40E-03	1.39E-03
Asphalt and sealing materials (excluding binders)										
RAP	1.20E-02	1.20E-02	2.26E-04	2.26E-04	4.28E-08	4.28E-08	2.45E-05	2.45E-05	6.52E-07	6.52E-07
Lime kiln dust	2.00E-01	2.00E-01	3.79E-03	3.79E-03	4.85E-07	4.85E-07	3.79E-04	3.79E-04	1.06E-05	1.06E-05
Hydrated lime	3.98E+00	4.08E+00	2.20E-03	2.15E-03	9.41E-05	2.86E-04	7.00E-02	7.06E-02	6.04E-01	6.04E-01
Ground limestone	5.11E-01	5.63E-01	5.34E-04	5.05E-04	3.56E-05	1.40E-04	3.60E-02	3.62E-02	1.09E-04	6.11E-05
EvoTherm	1.08E+02	1.08E+02	4.66E-02	4.66E-02	6.98E-02	6.98E-02	1.29E+00	1.29E+00	3.80E-03	3.80E-03
Sasobit	5.67E+01	5.67E+01	1.48E-02	1.48E-02	3.09E-03	3.09E-03	5.68E-02	5.68E-02	6.22E-03	6.22E-03
Cutting oil	5.29E+01	5.29E+01	8.30E-03	8.29E-03	1.16E-04	1.42E-04	9.57E-02	9.69E-02	2.80E-03	3.48E-03
Flux oil	5.32E+01	5.32E+01	1.01E+00	1.01E+00	1.27E-04	1.49E-04	1.00E-01	1.00E-01	2.82E-03	2.81E-03
Adhesion agent	6.59E+01	6.59E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.86E+00	5.86E+00
Fibres (cellulose)	9.43E+00	9.60E+00	2.00E-02	1.99E-02	2.31E-03	2.65E-03	3.38E-01	3.38E-01	6.46E-03	6.31E-03
SBS copolymer	1.24E+02	1.24E+02	3.08E-03	3.08E-03	1.70E-02	1.70E-02	1.13E-01	1.13E-01	2.17E-01	2.17E-01
EVA	9.72E+01	9.72E+01	3.94E-02	3.94E-02	7.20E-02	7.20E-02	8.98E-01	8.98E-01	1.60E-02	1.60E-02
LDPE	1.09E+02	1.10E+02	4.14E-02	4.06E-02	7.49E-02	7.80E-02	1.47E+00	1.47E+00	3.21E-03	1.73E-03
HDPE	9.86E+01	9.87E+01	2.66E-02	2.65E-02	8.23E-02	8.27E-02	2.09E-01	2.09E-01	9.08E-04	7.51E-04
PET	8.08E+01	8.11E+01	2.28E-02	2.26E-02	2.18E-02	2.25E-02	1.22E+00	1.22E+00	1.30E-02	1.27E-02
Crumb rubber	3.78E+00	4.32E+00	6.67E-04	3.66E-04	3.60E-04	1.45E-03	3.71E-01	3.72E-01	9.14E-04	4.10E-04
Crack sealant	4.71E+01	4.69E+01	1.07E-03	1.04E-03	1.40E-04	2.56E-04	4.68E-02	4.69E-02	1.56E-01	1.54E-01
Binders										
C170	4.90E+01	4.88E+01	1.01E-07	3.82E-08	1.06E-04	1.02E-04	6.37E-05	3.83E-05	1.64E-01	1.63E-01
C320	4.90E+01	4.88E+01	1.01E-07	3.82E-08	1.06E-04	1.02E-04	6.37E-05	3.83E-05	1.64E-01	1.63E-01
C450	4.90E+01	4.88E+01	1.01E-07	3.82E-08	1.06E-04	1.02E-04	6.37E-05	3.83E-05	1.64E-01	1.63E-01
C600	4.90E+01	4.88E+01	1.01E-07	3.82E-08	1.06E-04	1.02E-04	6.37E-05	3.83E-05	1.64E-01	1.63E-01
EME2 binder	4.91E+01	4.89E+01	1.77E-05	9.39E-06	1.16E-04	1.41E-04	1.02E-02	1.02E-02	1.64E-01	1.63E-01
A10E	5.42E+01	5.40E+01	1.20E-03	1.19E-03	1.05E-03	1.11E-03	2.85E-02	2.86E-02	1.73E-01	1.72E-01
A15E	5.38E+01	5.36E+01	1.19E-03	1.17E-03	9.67E-04	1.03E-03	2.79E-02	2.80E-02	1.72E-01	1.71E-01

Material	Embodied energy (MJ/kg of mat.)		Embodied diesel use (kg/kg of mat.)		Embodied natural gas use (GJ/kg of mat.)		Embodied electricity use (kWh/kg of mat.)		Water usage (m^3eq./kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
A20E	5.33E+01	5.31E+01	1.17E-03	1.16E-03	8.83E-04	9.45E-04	2.74E-02	2.74E-02	1.72E-01	1.70E-01
A25E	5.26E+01	5.33E+01	1.05E-03	1.03E-03	1.15E-04	1.76E-04	2.25E-02	2.26E-02	1.54E-01	1.60E-01
A35P	5.18E+01	5.24E+01	3.27E-03	3.26E-03	3.79E-03	3.85E-03	6.81E-02	6.82E-02	1.57E-01	1.61E-01
S10E	5.20E+01	5.18E+01	1.13E-03	1.11E-03	6.31E-04	6.93E-04	3.17E-02	2.57E-02	1.69E-01	1.68E-01
S15E	5.29E+01	5.27E+01	1.16E-03	1.14E-03	7.99E-04	8.61E-04	3.28E-02	2.69E-02	1.71E-01	1.70E-01
S20E	5.38E+01	5.36E+01	1.19E-03	1.17E-03	9.67E-04	1.03E-03	3.39E-02	2.80E-02	1.72E-01	1.71E-01
S25E	5.47E+01	5.45E+01	1.22E-03	1.20E-03	1.14E-03	1.20E-03	3.51E-02	2.91E-02	1.74E-01	1.73E-01
S35E	5.08E+01	5.11E+01	1.04E-03	1.02E-03	1.22E-04	1.83E-04	2.84E-02	2.85E-02	1.59E-01	1.62E-01
S9R/S9RF	4.52E+01	4.51E+01	1.10E-03	1.05E-03	1.53E-04	3.23E-04	6.53E-02	6.55E-02	1.49E-01	1.48E-01
S15R/S15RF/S45R	4.25E+01	4.24E+01	1.13E-03	1.07E-03	1.66E-04	3.91E-04	8.38E-02	8.41E-02	1.39E-01	1.38E-01
C170 5% rubber	4.71E+01	4.69E+01	1.07E-03	1.04E-03	1.40E-04	2.56E-04	4.68E-02	4.69E-02	1.56E-01	1.54E-01
S18RF/C170 18% rubber	4.12E+01	4.11E+01	1.15E-03	1.08E-03	1.73E-04	4.31E-04	9.49E-02	9.53E-02	1.35E-01	1.33E-01
CRS 170-30	1.70E+01	1.69E+01	1.34E-03	1.32E-03	1.09E-03	1.15E-03	3.70E-02	3.76E-02	5.00E-02	4.96E-02
CRS 170-48	2.58E+01	2.57E+01	1.34E-03	1.32E-03	1.11E-03	1.17E-03	3.70E-02	3.74E-02	7.93E-02	7.86E-02
CRS 170-60	3.17E+01	3.16E+01	1.34E-03	1.32E-03	1.12E-03	1.18E-03	3.69E-02	3.73E-02	9.88E-02	9.80E-02
CRS 170-70	3.66E+01	3.64E+01	1.34E-03	1.32E-03	1.13E-03	1.19E-03	3.69E-02	3.72E-02	1.15E-01	1.14E-01
ASS 170-60	3.17E+01	3.16E+01	1.34E-03	1.32E-03	1.12E-03	1.18E-03	3.69E-02	3.73E-02	9.88E-02	9.80E-02
Polymer modified bitumen emulsion	4.32E+01	4.33E+01	1.34E-03	1.32E-03	1.08E-03	1.14E-03	5.80E-02	5.81E-02	5.09E-02	5.08E-02
Type GP cement	5.72E+00	5.80E+00	7.69E-03	7.66E-03	1.24E-03	1.37E-03	9.59E-02	9.61E-02	1.04E-03	9.83E-04
Type GB cement	5.72E+00	5.80E+00	7.69E-03	7.66E-03	1.24E-03	1.37E-03	9.59E-02	9.61E-02	1.04E-03	9.83E-04
Type LH cement	5.72E+00	5.80E+00	7.69E-03	7.66E-03	1.24E-03	1.37E-03	9.59E-02	9.61E-02	1.04E-03	9.83E-04
Supplementary materials										
Slag (ground granulated blast furnace slag)	2.69E+00	2.85E+00	1.79E-03	1.76E-03	9.91E-04	1.15E-03	6.47E-02	6.51E-02	3.47E-04	2.76E-04
Fly ash	2.00E-01	2.00E-01	3.79E-03	3.79E-03	4.85E-07	4.85E-07	3.79E-04	3.79E-04	1.06E-05	1.06E-05
Quicklime	5.46E+00	5.54E+00	1.89E-03	1.85E-03	6.38E-05	2.16E-04	6.25E-02	6.27E-02	4.52E-04	3.81E-04
Air-entraining admixture	8.88E+01	8.88E+01	4.35E-02	4.35E-02	6.34E-02	6.34E-02	1.02E+00	1.02E+00	8.16E-03	8.16E-03
Water-reducing admixture	8.88E+01	8.88E+01	4.35E-02	4.35E-02	6.34E-02	6.34E-02	1.02E+00	1.02E+00	8.16E-03	8.16E-03

Material	Embodied energy (MJ/kg of mat.)		Embodied diesel use (kg/kg of mat.)		Embodied natural gas use (GJ/kg of mat.)		Embodied electricity use (kWh/kg of mat.)		Water usage (m^3eq./kg of mat.)	
	Qld	WA	Qld	WA	Qld	WA	Qld	WA	Qld	WA
Set-retarding admixture	8.88E+01	8.88E+01	4.35E-02	4.35E-02	6.34E-02	6.34E-02	1.02E+00	1.02E+00	8.16E-03	8.16E-03
Set-accelerating admixture	8.88E+01	8.88E+01	4.35E-02	4.35E-02	6.34E-02	6.34E-02	1.02E+00	1.02E+00	8.16E-03	8.16E-03
Wetting agents	8.37E+01	8.37E+01	3.08E-03	3.08E-03	1.70E-02	1.70E-02	1.13E-01	1.13E-01	2.74E-03	2.74E-03
Concrete curing compound	5.35E+01	5.35E+01	1.46E-02	1.46E-02	1.31E-02	1.31E-02	6.93E-01	6.93E-01	1.03E-02	1.03E-02
Foaming agent	3.11E+01	3.11E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.98E+00	1.98E+00
Geotextile fabric	–	–	–	–	–	–	–	–	–	–
Concrete										
Steel reinforcement	2.38E+01	2.38E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.31E+00	7.31E+00
Steel fibre	2.38E+01	2.38E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.31E+00	7.31E+00

Note: Data for embodied natural gas, diesel and electricity factors were produced in 2021 but were not updated during the 2024 data update.

A.5 Process Emissions Data

A.5.1 Construction and Maintenance Fuel Use and Emissions Data

Table A.5: Scope and full cycle emissions data for fuels

Fuel type	Unit	Scope 1 emissions	Scope 2 emissions	Scope 3 emissions	Full cycle emissions
Petrol	[tCO_2eq/kL]	2.313E+00	–	5.882E-01	2.901E+00
Diesel	[tCO_2eq/kL]	2.717E+00	–	0.6678	3.3852
Electricity (Qld)	[tCO_2eq/kWh]	–	7.300E-04	1.500E-04	8.800E-04
Electricity (WA)	[tCO_2eq/kWh]	–	5.300E-04	4.000E-05	5.700E-04
Natural gas – Metro (Qld)	[tCO_2eq/GJ]	5.153E-05	–	8.800E-06	6.03E-05
Natural gas – Metro (WA)	[tCO_2eq/GJ]	5.153E-05	–	4.100E-06	5.56E-05

Source: Department of Climate Change, Energy, the Environment and Water (2023).

Table A.6: Product manufacturing data – energy use and emissions

Product	Material density (t/m^3)	Natural gas (MJ/m^3 of mat.)	Diesel (L/m^3 of mat.)	Electricity (kWh/m^3 of mat.)	Scope 1 emissions (tCO_2eq/m^3 of mat.)	Scope 2 emissions (tCO_2eq/m^3 of mat.)	Scope 3 emissions (tCO_2eq/m^3 of mat.)
Hot mix asphalt (Qld)	2.35	705.00	0.52	14.10	3.773E-02	1.029E-02	8.664E-03

Product	Material density (t/m³)	Natural gas (MJ/m³ of mat.)	Diesel (L/m³ of mat.)	Electricity (kWh/m³ of mat.)	Scope 1 emissions (tCO_2eq/m^3 of mat.)	Scope 2 emissions (tCO_2eq/m^3 of mat.)	Scope 3 emissions (tCO_2eq/m^3 of mat.)
Hot mix asphalt (WA)					3.773E-02	7.473E-03	3.800E-03
Warm mix asphalt (Qld)	2.35	528.75	0.52	14.10	2.865E-02	1.029E-02	7.113E-03
Warm mix asphalt (WA)					2.865E-02	7.473E-03	3.077E-03
Concrete (Qld)	2.40	0.00	22.70	4.36	1.598E-03	3.183E-03	1.047E-03
Concrete (WA)					1.598E-03	2.311E-03	5.671E-04

Source: AusLCI (2011).

Table A.7: Removal processes data – diesel fuel use and emissions

Removal process	Unit of measure	Fuel usage [L/UoM]	Scope 1 emissions [tCO_2eq/UoM]	Scope 3 emissions [tCO_2eq/UoM]	Full cycle emissions [tCO_2eq/UoM]
Excavating	[m³]	1.5085	4.099E-03	1.007E-03	5.107E-03
Grading	[m³]	1.3852	3.764E-03	9.250E-04	4.689E-03
Profiling	[m³]	1.7996	4.890E-03	1.202E-03	6.092E-03

Source: Skolnik et al. (2013); Transport Authorities Greenhouse Group (2013); Wirtgen Gmbh (2022).

Table A.8: Pavement construction and maintenance processes data – diesel fuel use and emissions

Pavement construction/maintenance process	Unit of measure	Fuel usage [L/UoM]	Scope 1 emissions [tCO_2eq/UoM]	Scope 3 emissions [tCO_2eq/UoM]	Full cycle emissions [tCO_2eq/UoM]
Jointed reinforced concrete pavement (JRCP)/continuously reinforced concrete pavement (CRCP) – placement in construction	[m³]	2.0220	5.495E-03	1.350E-03	6.845E-03
JRCP/CRCP – placement in maintenance	[m³]	2.9113	7.912E-03	1.944E-03	9.856E-03
Plain concrete pavement (PCP)/steel fibre reinforced polymer (SFRP) – placement in construction	[m³]	2.0220	5.495E-03	1.350E-03	6.845E-03
PCP/SFRP – placement in maintenance	[m³]	2.9114	7.912E-03	1.944E-03	9.856E-03
Crack sealing	[m²]	2.0220	5.495E-03	1.350E-03	6.845E-03
Hot mix asphalt – placement	[m³]	2.9114	7.912E-03	1.944E-03	9.856E-03
Hot mix asphalt – placement including material transfer vehicle	[m³]	0.0305	8.288E-05	8.288E-05	1.658E-04
Warm mix asphalt – placement	[m³]	2.4534	6.667E-03	1.638E-03	8.305E-03
In situ stabilisation (bitumen) < 200 mm	[m³]	3.3856	9.200E-03	2.261E-03	1.146E-02
In situ stabilisation (bitumen) > 200 mm	[m³]	2.4534	6.667E-03	1.638E-03	8.305E-03

Pavement construction/maintenance process	Unit of measure	Fuel usage [L/UoM]	Scope 1 emissions [tCO_2eq/UoM]	Scope 3 emissions [tCO_2eq/UoM]	Full cycle emissions [tCO_2eq/UoM]
In situ stabilisation (cement) < 200 mm	[m³]	2.7473	7.466E-03	1.835E-03	9.300E-03
In situ stabilisation (cement) > 200 mm	[m³]	2.3998	6.521E-03	1.603E-03	8.124E-03
In situ stabilisation (lime) – layers < 200 mm	[m³]	1.9043	5.175E-03	1.272E-03	6.447E-03
In situ stabilisation (lime) – layers > 200 mm	[m³]	1.7179	4.668E-03	1.147E-03	5.815E-03
Microsurfacing/slurry sealing	[m³]	1.9043	5.175E-03	5.175E-03	1.035E-02
Prime	[m²]	1.7179	4.668E-03	1.147E-03	5.815E-03
Single/single seal	[m²]	3.9161	1.064E-02	2.615E-03	1.326E-02
Double/double seal	[m²]	0.0090	2.448E-05	6.015E-06	3.049E-05
Geotextile reinforced seal	[m²]	0.0319	8.658E-05	2.128E-05	1.079E-04
Cement-stabilised material – placement	[m³]	0.0656	1.782E-04	4.380E-05	2.221E-04
Plant-mix foamed bitumen stabilised materials – placement (> 200 mm)	[m³]	0.0656	1.782E-04	4.380E-05	2.221E-04
Plant-mix foamed bitumen stabilised materials – placement (< 200 mm)	[m³]	1.9329	5.253E-03	1.291E-03	6.543E-03
Unbound granular material – placement with grader	[m³]	1.9621	5.332E-03	1.310E-03	6.642E-03
Unbound granular material – placement with paver	[m³]	2.6906	7.312E-03	1.797E-03	9.108E-03

Source: Caterpillar (2019); Road Dryer (2019); Skolnik et al. (2013); Transport Authorities Greenhouse Group (2013).

Table A.9: Equipment data – diesel fuel use and emissions

Machinery type	Unit of measure	Fuel usage [L/UoM]	Scope 1 emissions [tCO_2eq/UoM]	Scope 3 emissions [tCO_2eq/UoM]	Full cycle emissions [tCO_2eq/UoM]	Description
Excavator (digger, trackhoe)	[h]	17.00	4.62E-02	1.14E-02	5.75E-02	Crawler Class 100, medium application, 300 h/month
Crane (Hydraulic)	[h]	26.33	7.16E-02	1.76E-02	8.91E-02	Crane 50 t, medium application, 300 h/month
Backhoe loader (backhoe)	[h]	10.00	2.72E-02	6.68E-03	3.39E-02	4WD Class 2 to Class 5, medium application, 300 h/month
Concrete slipform paver	[h]	26.50	7.20E-02	1.77E-02	8.97E-02	Concrete slipform paver
Dozer D6	[h]	19.00	5.16E-02	1.27E-02	6.43E-02	Cat, Class D6, medium application, 300 h/month
Dozer D9	[h]	43.00	1.17E-01	2.87E-02	1.46E-01	Class 300C (D9 size), medium application, 300 h/month
Grader (road grader, blade, maintainer, motor grader)	[h]	17.00	4.62E-02	1.14E-02	5.75E-02	Class 110, medium application, 300 h/month
Haul truck 25 t	[h]	26.33	7.16E-02	1.76E-02	8.91E-02	Cat 25 t articulated, medium application, 300 h/month
Haul truck 40 t	[h]	41.67	1.13E-01	2.78E-02	1.41E-01	Cat 40 t articulated, medium application, 300 h/month

Machinery type	Unit of measure	Fuel usage [L/UoM]	Scope 1 emissions [tCO_2eq/UoM]	Scope 3 emissions [tCO_2eq/UoM]	Full cycle emissions [tCO_2eq/UoM]	Description
Lighting tower	[h]	1.95	5.30E-03	1.30E-03	6.60E-03	Individual lighting tower (4 x 1,000 W lights)
Loader, skid steer (track type)	[h]	5.33	1.45E-02	3.56E-03	1.81E-02	Loader, medium application, 300 h/month
Loader, wheeled	[h]	15.00	4.08E-02	1.00E-02	5.08E-02	Class 50WL, medium application, 300 h/month
Material handlers (excavator with grapple)	[h]	10.00	2.72E-02	6.68E-03	3.39E-02	Medium application, 300 h/month
Material transfer vehicle	[h]	39.67	1.08E-01	2.65E-02	1.34E-01	MTV Shuttle Buggy SB2500, 300 h/month at 67% loading
Mobilisation	[h]	22.71	6.17E-02	1.52E-02	7.69E-02	Truck Tractor and Lowboy Trailer
Paver	[h]	23.80	6.47E-02	1.59E-02	8.06E-02	Roadtec RP170 300 h/month @ 70% loading
Portable screening and crushing plant	[h]	37.83	1.03E-01	2.53E-02	1.28E-01	Medium Application, 300 h/month
Road dryer	[h]	66.50	1.81E-01	4.44E-02	2.25E-01	Road Dryer RD-1200XT, reported fuel consumption of 57–76 L/hr
Roller, steel	[h]	16.00	4.35E-02	1.07E-02	5.42E-02	Steel roller, medium application, 300 h/month
Scraper	[h]	48.33	1.31E-01	3.23E-02	1.64E-01	Caterpillar TS220, 300 kW, medium application, 300 h/month
Site office – electricity generation	[h]	12.92	3.51E-02	8.63E-03	4.37E-02	Diesel generator, 500 m^2 office, 240 h/month (12 h/day, 5 days/week, 4 weeks/month)
Stabiliser soil	[h]	57.00	1.55E-01	3.81E-02	1.93E-01	450 kW, 2,440 x 500 mm working width and depth, medium application, 300 h/month
Sweeper truck	[h]	15.14	4.11E-02	1.01E-02	5.13E-02	Assumed similar to Truck Service/Mechanic
Traffic management	[h]	4.37	1.19E-02	2.92E-03	1.48E-02	Assume two 4x4 vehicles (utes), use Site Vehicles – Medium Project
Truck service/mechanic	[h]	15.14	4.11E-02	1.01E-02	5.13E-02	Truck Service/Mechanic
Vibrating roller (asphalt, soil)	[h]	16.00	4.35E-02	1.07E-02	5.42E-02	Class VR35, medium application, 300 h/month
Water pump	[h]	1.67	4.54E-03	1.12E-03	5.65E-03	6” pump running continuously for dewatering (720 h/month – 30 days/month)
Water truck	[h]	18.93	5.14E-02	1.26E-02	6.41E-02	Truck Water
Stationary batching plant (concrete)	[h]	30.00	8.15E-02	2.00E-02	1.02E-01	60 m^3/hour, 0.5 litres diesel/m^3 of concrete, 300 h/month
Stationary diesel pump	[h]	7.67	2.08E-02	5.12E-03	2.60E-02	30 kW motor, 300 h/month
Site vehicles – small project	[h]	2.17	5.90E-03	1.45E-03	7.35E-03	Project size < $2m, 2 Hilux utes, assume all vehicles are diesel
Site vehicles – medium project	[h]	4.37	1.19E-02	2.92E-03	1.48E-02	Project size $2–10m, 4 Hilux utes, assume all vehicles are diesel
Site vehicles – large project	[h]	11.33	3.08E-02	7.57E-03	3.84E-02	Project size $10–100m, 10 Hilux utes, assume all vehicles are diesel
Generator – Small	[h]	11.36	3.09E-02	7.58E-03	3.84E-02	Cat 35 kW generator

Machinery type	Unit of measure	Fuel usage [L/UoM]	Scope 1 emissions [tCO_2eq/UoM]	Scope 3 emissions [tCO_2eq/UoM]	Full cycle emissions [tCO_2eq/UoM]	Description
Generator – Large	[h]	22.71	6.17E-02	1.52E-02	7.69E-02	Cat 150 kW generator
W200 Fi Profiler	[h]	47.00	1.28E-01	3.14E-02	1.59E-01	Cold Milling Machine, fuel consumption in field mix
Volvo MT2000 Milling Machine	[h]	37.85	1.03E-01	2.53E-02	1.28E-01	Half Lane Milling Machine
Bitumen tanker	[h]	18.93	5.14E-02	1.26E-02	6.41E-02	Assumed same as Water Truck
Bitumen truck	[h]	12.49	3.39E-02	8.34E-03	4.23E-02	Assumed same as Water Truck at low application (x0.66)
Crew truck	[h]	9.99	2.72E-02	6.67E-03	3.38E-02	Assumed same as Truck Service/Mechanic at low application (x0.66)
Emulsions and aggregate trucks	[h]	12.47	3.39E-02	8.33E-03	4.22E-02	Assumed same as 3-axle rigid truck at low application (x0.66)
Rigid truck	[h]	18.93	5.14E-02	1.26E-02	6.41E-02	3-Axle rigid truck, assumed same as Water Truck
Sprayer	[h]	18.93	5.14E-02	1.26E-02	6.41E-02	Assumed same as Water Truck
Spreader truck	[h]	12.49	3.39E-02	8.34E-03	4.23E-02	Assumed same as Water Truck at low application (x0.66)
Power curber	[h]	15.14	4.11E-02	1.01E-02	5.13E-02	Curb and gutter machine, Power Curber 5700B
Roller, padfoot	[h]	15.15	4.12E-02	1.01E-02	5.13E-02	CAT CP76B Vibrating padfoot roller, approximately 17 t operating weight, medium application
Roller, multi-tyre	[h]	12.00	3.26E-02	8.01E-03	4.06E-02	CAT CW16 multi-tyre roller (max op weight 15 t), medium application
Brushing utility vehicle	[h]	1.09	2.95E-03	7.25E-04	3.67E-03	Assume one 4x4 vehicle (utes), use half of Site Vehicles – Small Project
Sawcut trolley	[h]	3.52	9.56E-03	2.35E-03	1.19E-02	Estimate, from [TRB13] concrete saw (petrol). Used [TAG13] Loader, Skid Steer (Track Type), low application (x0.66)

Source: Caterpillar (2019); JLG Industries (2013), Road Dryer (2019), Skolnik et al. (2013); Transport Authorities Greenhouse Group (2013); Wirtgen Gmbh (2022).

A.5.2 Haulage Emissions Data

Table A.10: Haulage GHG emissions data – Queensland

Vehicle type	Scope 1 emissions [tCO_2eq per 1 tonne moved 1 km]	Scope 3 emissions [tCO_2eq per 1 tonne moved 1 km]	Total emissions [tCO_2eq per 1 tonne moved 1 km]	Scope 1 (return) empty vehicle emissions [tCO_2eq/km]	Scope 3 (return) empty vehicle emissions [tCO_2eq/km]	Total (return) empty vehicle emissions [tCO_2eq/km]
Two-axle truck	8.612E-05	2.132E-05	1.074E-04	4.177E-04	1.032E-04	5.210E-04
Three-axle truck	6.135E-05	1.513E-05	7.648E-05	6.596E-04	1.627E-04	8.222E-04
Four-axle truck	6.135E-05	1.513E-05	7.648E-05	6.596E-04	1.627E-04	8.222E-04

Vehicle type	Scope 1 emissions [tCO_2eq per 1 tonne moved 1 km]	Scope 3 emissions [tCO_2eq per 1 tonne moved 1 km]	Total emissions [tCO_2eq per 1 tonne moved 1 km]	Scope 1 (return) empty vehicle emissions [tCO_2eq/km]	Scope 3 (return) empty vehicle emissions [tCO_2eq/km]	Total (return) empty vehicle emissions [tCO_2eq/km]
Three-axle articulated	5.808E-05	1.431E-05	7.240E-05	7.253E-04	1.787E-04	9.040E-04
Four-axle articulated	5.481E-05	1.350E-05	6.831E-05	7.910E-04	1.948E-04	9.857E-04
Five-axle articulated	4.596E-05	1.132E-05	5.728E-05	8.748E-04	2.154E-04	1.090E-03
Six-axle articulated	4.734E-05	1.166E-05	5.900E-05	9.640E-04	2.374E-04	1.201E-03
B-Double	3.974E-05	9.786E-06	4.953E-05	1.127E-03	2.775E-04	1.404E-03
Double road train	3.969E-05	9.774E-06	4.947E-05	1.411E-03	3.474E-04	1.758E-03
Triple road train	3.557E-05	8.759E-06	4.433E-05	1.646E-03	4.052E-04	2.051E-03

Source: Australian Transport Assessment and Planning (ATAP) Steering Committee (2016) and NTRO analysis.

Table A.11: Haulage GHG emissions data – Western Australia

Vehicle type	Scope 1 emissions [tCO_2eq per 1 tonne moved 1 km]	Scope 3 emissions [tCO_2eq per 1 tonne moved 1 km]	Total emissions [tCO_2eq per 1 tonne moved 1 km]	Scope 1 (return) empty vehicle emissions [tCO_2eq/km]	Scope 3 (return) empty vehicle emissions [tCO_2eq/km]	Total (return) empty vehicle emissions [tCO_2eq/km]
Two-axle truck	8.588E-05	2.123E-05	1.071E-04	4.165E-04	1.028E-04	5.193E-04
Three-axle truck	6.121E-05	1.508E-05	7.629E-05	6.577E-04	1.621E-04	8.198E-04
Four-axle truck	6.121E-05	1.508E-05	7.629E-05	6.577E-04	1.621E-04	8.198E-04
Three-axle articulated	5.794E-05	1.427E-05	7.221E-05	7.229E-04	1.780E-04	9.010E-04
Four-axle articulated	5.467E-05	1.346E-05	6.813E-05	7.881E-04	1.940E-04	9.821E-04
Five-axle articulated	4.585E-05	1.128E-05	5.713E-05	8.719E-04	2.146E-04	1.087E-03
Six-axle articulated	4.722E-05	1.162E-05	5.884E-05	9.607E-04	2.364E-04	1.197E-03
B-Double	3.963E-05	9.752E-06	4.938E-05	1.122E-03	2.762E-04	1.398E-03
Double road train	3.956E-05	9.736E-06	4.930E-05	1.404E-03	3.455E-04	1.750E-03
Triple road train	3.544E-05	8.721E-06	4.416E-05	1.636E-03	4.027E-04	2.039E-03

Source: Australian Transport Assessment and Planning (ATAP) Steering Committee (2016) and NTRO analysis.

A.5.3 Waste Disposal Emissions Data

Table A.12: Waste disposal GHG emissions data

Material	Scope 1 disposal emissions [tCO_2eq/tonne]	Scope 3 disposal emissions [tCO_2eq/tonne]	Full cycle disposal emissions [tCO_2eq/tonne]
All disposed materials	0.0024	0.0000	0.0024

Source: AusLCI (2011).

A.5.4 State-specific Disposal Costs

Table A.13: State-specific disposal costs

State	Region	Levy rate 2024–25 [$/tonne]	Landfill gate fees (2024) [$/tonne]	Annual growth rate [$/tonne/year]
Queensland	Metro (12 SEQ LGAs)	$115.00	$273.40	$10.00
	Regional	$94.00	$207.00	$10.00
	Non-levy zone	$ –	$113.00	$10.00
Western Australia	Metropolitan	$85.00	$183.63	$6.00
	Southwest	$ –	$98.63	$3.50
	Great Southern	$ –	$98.63	$3.50
	Wheatbelt	$ –	$98.63	$3.50
	Kalgoorlie-Esperance	$ –	$98.63	$3.50
	Midwest-Gascoyne	$ –	$98.63	$3.50
	Pilbara	$ –	$98.63	$3.50
	Kimberley	$ –	$98.63	$3.50

Source: Queensland Government (2024); Department of Water and Environmental Regulation (2024).

Appendix B Generating Reference Data

This appendix details the methods used to generate the emissions, energy consumption and environmental impact data for the materials and processes used in SAT4P. Details are provided for calculation of:

- other air-borne emissions
- energy use
- water use
- EnviroPoints.

B.1 Other Air-borne Pollutants

B.1.1 Material Emissions

Similar to the generation of GHG emissions outputs, other air-borne emissions are calculated by applying emission factors to material quantities. This process requires the development of state-specific emission factors for every material and every reportable air-borne pollutant (as identified in Section 8.1.2). This method is closely aligned with the update of the materials database for state-specific GHG emission factors (explained in Section 8.1.2).

Material emission factors were generated in SimaPro using AusLCI and ecoinvent data sources. The key steps undertaken were:

1. Develop an air-borne emissions worksheet and data template in the SAT4P materials database.
2. Develop an analysis method within SimaPro (consisting of the relevant substance flows) that will identify emissions outputs for each air-borne pollutant.
3. Apply the analysis method in SimaPro to generate the relevant emissions data tables.
4. Upload the data into a new worksheet template in SAT4P (based on the GHG materials database).
5. Update the SAT4P's material database (for other air-borne pollutants) to identify data sources and assumptions.
6. Generate material emissions output tables for each air-borne pollutant.

B.1.2 Process and Use Phase Emissions

Similarly to the generation of GHG emissions outputs, process and use phase emissions are generated by applying an appropriate calculation (sourced from the National Pollutant Inventory Guide, Department of the Environment 2015) to fuel consumption and energy usage totals. The estimation of lifecycle fuel consumption and energy usage (see energy use model enhancement in Section B.2) is a precondition of these calculation. The key steps undertaken were:

1. Source and document relevant air-pollution calculations or factors – available in the National Pollution Inventories.
2. Document assumptions about fuel quality (i.e. a single sulphur content assumption for diesel fuel), vehicle standards (i.e. assumed Euro 4 for light vehicles and IV for heavy vehicles) machinery engine capacities, types and load in SAT4P.
3. Document the electricity generation by fuel type for each state, i.e. the proportion of electricity generated by coal, gas, renewables – available in Australian Energy Statistics, Table O Electricity generation by fuel type 2018–19 and 2019 (Department of the Environment and Energy 2019).
4. Apply proportions to electricity usage estimates (generated in the energy use model enhancement).
5. Apply appropriate air-pollution calculations or emission factors to fuel consumption and electricity use estimates (generated in the energy use model enhancement) to generate air-borne emissions results for lifecycle processes and use phase.
6. Generate process and use phase emissions outputs for each air-borne pollutant.

B.1.3 Total Lifecycle Air-borne Emissions

Combining the material and process emissions and the use phase emissions estimates involves the following key steps:

1. Aggregate the outputs from each lifecycle phase for each air-borne pollutant.
2. Develop new output tables within SAT4P output worksheets and build functions to populate them.
3. Test and verify the workings of the enhancement. Testing and verification involved internal developer testing, presentation of results to Main Roads and TMR and an independent third-party review of the model workings and outputs by an LCA and SimaPro expert.
4. Refine and finalise.
5. Incorporate functionality into the web-based tool.

B.2 Energy Data

B.2.1 Upstream Energy Use in Material Extraction and Production

Material extraction and production energy use outputs were generated in SimaPro using AusLCI and ecoinvent data sources. This method is closely linked with the update of materials database for state-specific GHG emissions factors.

The key steps were:

1. Develop an energy use worksheet and data template within the SAT4P materials database.
2. Develop an energy use method within SimaPro (i.e. total primary energy content using the higher heating value (HHV) demand assessment method) to quantify total primary energy usage outputs from fuel consumption and electricity use.
3. Apply the analysis method in SimaPro to generate the relevant energy use data tables.
4. Upload the resulting data into a new worksheet template within SAT4P.
5. Convert energy consumption to energy content (GJ) and aggregate (where there are multiple energy sources).
6. Update SAT4P's material database to reflect the data sources and assumptions.

B.2.2 Process and Use Phase Energy Use

Process and use phase fuel consumption and energy usage were previously estimated within SAT4P as interim datasets for calculating the GHG emissions. However, these interim datasets did not distinguish energy usage as separate output values.

The pre-existing energy consumption data that was available included:

- construction and maintenance process energy consumption in terms of kL of diesel per unit of measure (e.g. hours, m^2, m^3, etc)
- asphalt production (manufacturing) energy consumption in terms of kL of diesel, MJ of gas and kWh of electricity per m^3 (where the volume is determined by user-defined road length, width and layer thickness)
- vehicle fuel usage (for material haulage and in the use phase) in terms of L/100 km of petrol and diesel and other fuels (whereby CNG and LPG vehicles fuel consumption and EV electricity usage have been converted to equivalent litres of diesel/petrol).

The key steps undertaken were:

1. Develop a calculation formula to generate fuel consumption and electricity usage outputs for each lifecycle phase in the new data worksheet template.
2. Convert energy consumption unit to energy content (GJ) and aggregate (where there are multiple energy sources).

3. Document the electricity generation by fuel type for each state, i.e. the proportion of electricity generated by coal, gas, renewables – available in Australian Energy Statistics (Department of the Environment and Energy 2019).
4. Apply proportions to electricity usage outputs to estimate electricity consumption by energy source.
5. Update the SAT4P's material database to reflect the data sources and assumptions.

B.2.3 Total Lifecycle Energy Usage

Combining the upstream and use phase energy use was undertaken through the following key steps:

1. Aggregate the outputs from each lifecycle phase for each energy source.
2. Develop new output tables in the SAT4P output worksheets and build functions to populate them.
3. Test and verify the workings of the enhancement. Testing and verification will involve internal developer testing, presentation of results to Main Roads and TMR and an independent third-party review of the model workings and outputs by an LCA and SimaPro expert.
4. Refine and finalise.
5. Incorporate the functionality into the web-based tool.

B.3 Water Data

B.3.1 Upstream Water Use in Material Extraction and Production

Material extraction and production water use outputs were generated in SimaPro using AusLCI and ecoinvent data sources. This method is closely linked with the update of the materials database for state-specific GHG emission factors. The key steps were:

1. Develop a water use worksheet and data template within the SAT4P materials database.
2. Develop a water use method within SimaPro (based on an adjusted water scarcity method that considers gross freshwater use, regardless of its source) that will identify gross water usage outputs in the extraction and production of materials.
3. Apply the analysis method in SimaPro to generate the relevant water use data tables.
4. Upload the data into a new worksheet template within SAT4P.
5. Update the SAT4P's material database to reflect the data sources and assumptions.

B.4 EnviroPoints Data

EnviroPoint values were generated in SimaPro using AusLCI and ecoinvent data sources following the ISC's EnviroPoints methodology (Infrastructure Sustainability Council of Australia 2018). This method is closely linked with the update of the materials database for state-specific GHG emission factors. The key steps included:

1. Develop an EnviroPoints data template within the SAT4P materials database.
2. Use SimaPro and the EN 15804:2012 + A1:2013 assessment method to generate state-specific mid-point EnviroPoint values for every material in the materials database.
3. Apply the normalisation factors to each mid-point value for every material in the materials database. Normalisation factors for each EnviroPoint category are available as fixed values in the IS Materials Calculator. Application of normalisation factors converts the mid-point values into a percentage of the annual average global per capita impact (for that category).
4. Apply the fixed value weighting factors.
5. Aggregate the individual EnviroPoints to determine the total EnviroPoints indexed value.
6. Develop new outputs in the worksheets (automatically calculated).
7. Test and verify the workings of the enhancement. Testing and verification involved internal developer testing, presentation of results to Main Roads and TMR and an independent third-party review of the model workings and outputs by an LCA and SimaPro expert.
8. Refine and finalise.

9. Incorporate the functionality into the web-based tool.