Best Practice Reference

Determination of the Embodied Carbon for Pavement Structures

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Version History

Version	Release Date	Release Notes
1.0	December 2025	Initial release of NTRO Best Practice document

Foreword

NTRO Best Practice References exist to articulate how a transport network owner or operator should require a specific, contemporary issue/challenge to be solved/resolved to ensure that it is delivering positive outcomes and meeting its statutory safety-, serviceability- and sustainability-related obligations effectively and efficiently. Rather than being totally prescriptive, NTRO Best Practice References identify the key building blocks to be followed to arrive at a desired outcome or solution and how they interrelate and combine. They are supported by NTRO and other specifications and/or test methods that set out which things must be done and specifically how they are to be done.

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Contents

Tables

Figures

1. Introduction

1.1 Purpose

The construction, maintenance and renewal of pavement infrastructure contribute significantly to greenhouse gas (GHG) emissions from pavements. High material volumes, frequent maintenance cycles and the long operational life of pavement assets result in substantial cumulative embodied carbon.

The construction, maintenance and operations of pavement infrastructure represent a significant component of our built environment and contribute substantially to the nation's GHG emissions. As the imperative to address climate change intensifies, the need for consistent, transparent and scientifically robust methods to quantify embodied carbon in pavement structures has become increasingly critical.

This Best Practice Reference has been developed to provide a harmonised framework and consistent method for the measurement, reporting and interpretation of embodied carbon across the life cycle of pavements. It is focussed on roads but is also applicable to airport and port pavements. It is intended to support practitioners, asset owners, policymakers and industry stakeholders in making informed decisions that align with Australia's sustainability goals and international climate commitments.

The methodology outlined herein reflects current best practice in life cycle assessment (LCA), tailored specifically to the unique characteristics of pavement materials, construction techniques and operational contexts within Australia. It incorporates guidance on system boundaries, data quality, emission factors and reporting formats to ensure consistency and comparability across projects and jurisdictions.

Embodied carbon estimates for pavement structures can be used for informing pavement designs and life cycle management strategies for carbon minimisation, reporting and rating purposes, or carbon accounting.

It is anticipated that this Best Practice Reference will evolve over time in response to advances in materials science, data availability and carbon accounting methodologies. Users are encouraged to remain informed of updates and to contribute to the ongoing refinement of this important work.

By adopting this Best Practice Reference, stakeholders can play a vital role in reducing the carbon emissions associated with transport infrastructure and advancing the transition to a low-carbon economy.

1.2 Scope

This Best Practice Reference specifies a consistent and transparent method for the measurement, reporting and interpretation of embodied carbon in pavement structures across their full life cycle. It addresses the absence of dedicated, nationally harmonised guidance for pavements, an infrastructure asset class with unique materials, construction methods and maintenance profiles that significantly contribute to Australia's transport sector emissions (Infrastructure and Transport Ministers 2024).

This Best Practice Reference applies to road, airport and port pavements and covers the GHG emissions arising from the extraction, manufacture, transport, construction, maintenance, repair, rehabilitation, replacement and end-of-life treatment of pavement layers. The principal GHGs of concern are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These 3 GHGs should be presented as a single metric, namely carbon dioxide equivalent (CO_2-e), using the global warming potential (GWP) factors consistent with the national GHG accounts factors (Department of Climate Change, Energy, the Environment and Water 2024a) (Table 1.1).

Table 1.1: Global warming potential over a 100-year time horizon used to convert the primary greenhouse gases into a carbon dioxide equivalent

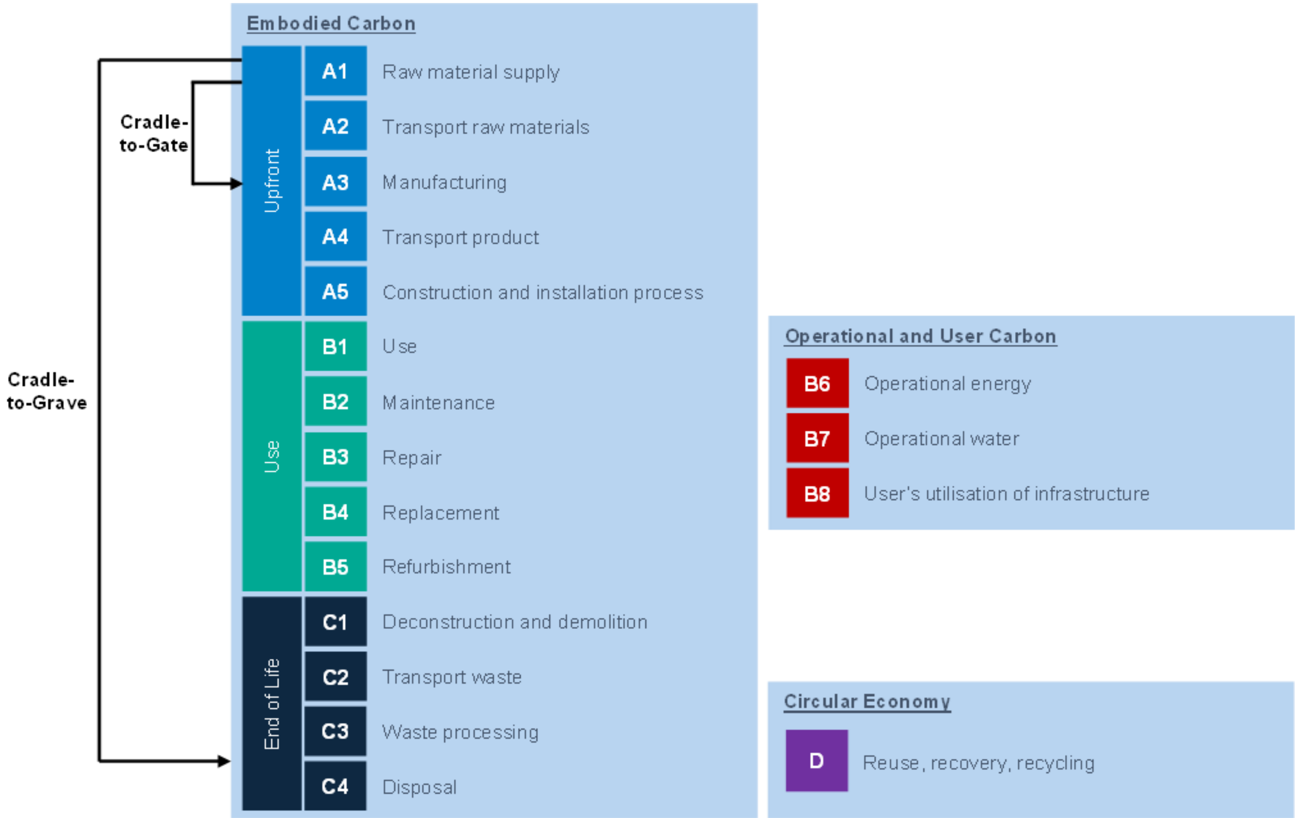
GHG	GWP (100-year)
Carbon dioxide (CO_2)	1
Methane (CH_4)	28
Nitrous oxide (N_2O)	295

Source: Department of Climate Change, Energy, the Environment and Water (2024a).

1.2.1 Life Cycle Coverage of Embodied Carbon

This Best Practice Reference adopts the modular life cycle stages defined in EN 15978:2011 and PAS 2080:2023, as adapted for Australian infrastructure by the Infrastructure and Transport Ministers *Embodied Carbon Measurement for Infrastructure – Technical Guidance* document (Infrastructure and Transport Ministers 2024) (see Figure 1.1).

Figure 1.1: Whole-of-life carbon emissions and illustration of modules



Source: Reproduced from Infrastructure and Transport Ministers (2024).

Table 1.2 summarises how the life cycle stages apply to pavements.

Table 1.2: Key terms and definitions of the different life cycle stages

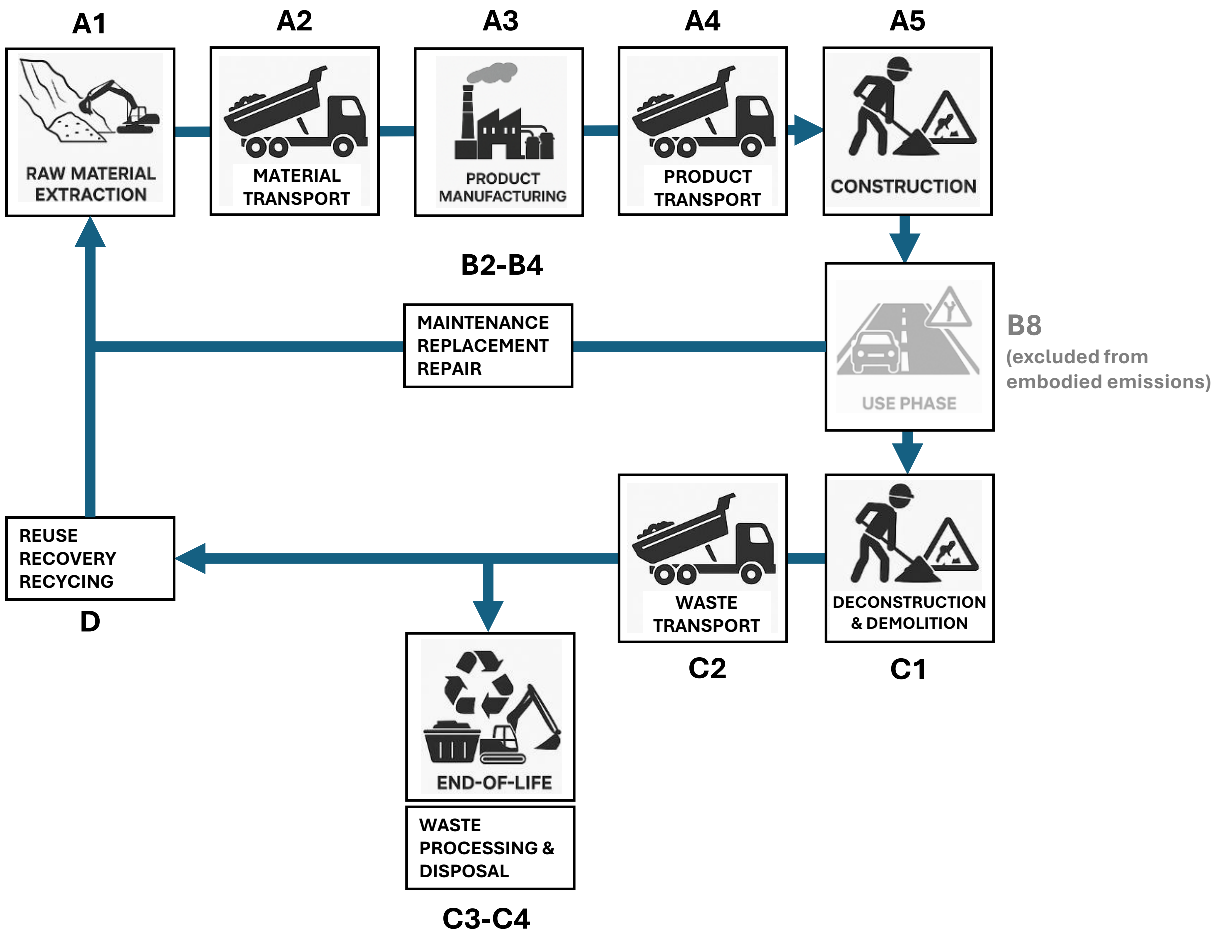
Term	Definition	Life cycle module
Upfront carbon	The carbon emissions associated with the product and construction stages up to the pavement structure's practical completion.	A1 – A5
In-use carbon	The carbon emissions associated with the processes and materials required to maintain, repair or refurbish the pavement during its operational life.	B1 – B5 *
End-of-life carbon	The carbon emissions associated with the pavement's end-of-life deconstruction or demolition and the transport and processing required to dispose of any waste materials.	C1 – C4
Embodied carbon	The carbon emissions associated with upfront carbon plus the emissions directly associated with the management of the pavement and the end of life.	A1 – A5 B1 – B5 * C1 – C4
Operational carbon	The carbon emissions associated with the energy and water usage during the pavement's operational life (e.g. lighting). Some elements of modules B1 and B2 may be included under operational carbon.	B6, B7 *
User carbon	The carbon emissions produced by users of the pavement (i.e. the emissions produced by vehicles travelling over the pavement).	B8 *
Circular economy	The potential carbon emissions that can be saved by reusing, recovering or recycling materials and components from the pavement at the end of its life.	D *

* Notes: Some of these stages are not directly applicable to pavements, in general, or to embodied carbon, and they should be excluded from an embodied carbon assessment:

- Modules B1 and B5 are considered to not apply to pavements. It is important to ensure that B modules are clearly defined to avoid confusion.
- Modules B6 and B7 are operational carbon, not embodied carbon.
- Module B8 may be considered for certain projects, where relevant, using separate guidance (e.g. Australian Transport Assessment and Planning Steering Committee 2016).
- Module D may apply to account for recovered material flows or end-of-life recycling practices, e.g. for reclaimed asphalt pavement (RAP), but further work beyond the scope of this document is needed.

Figure 1.2 shows how the modules A to D apply to pavements.

Figure 1.2: Embodied carbon calculation process

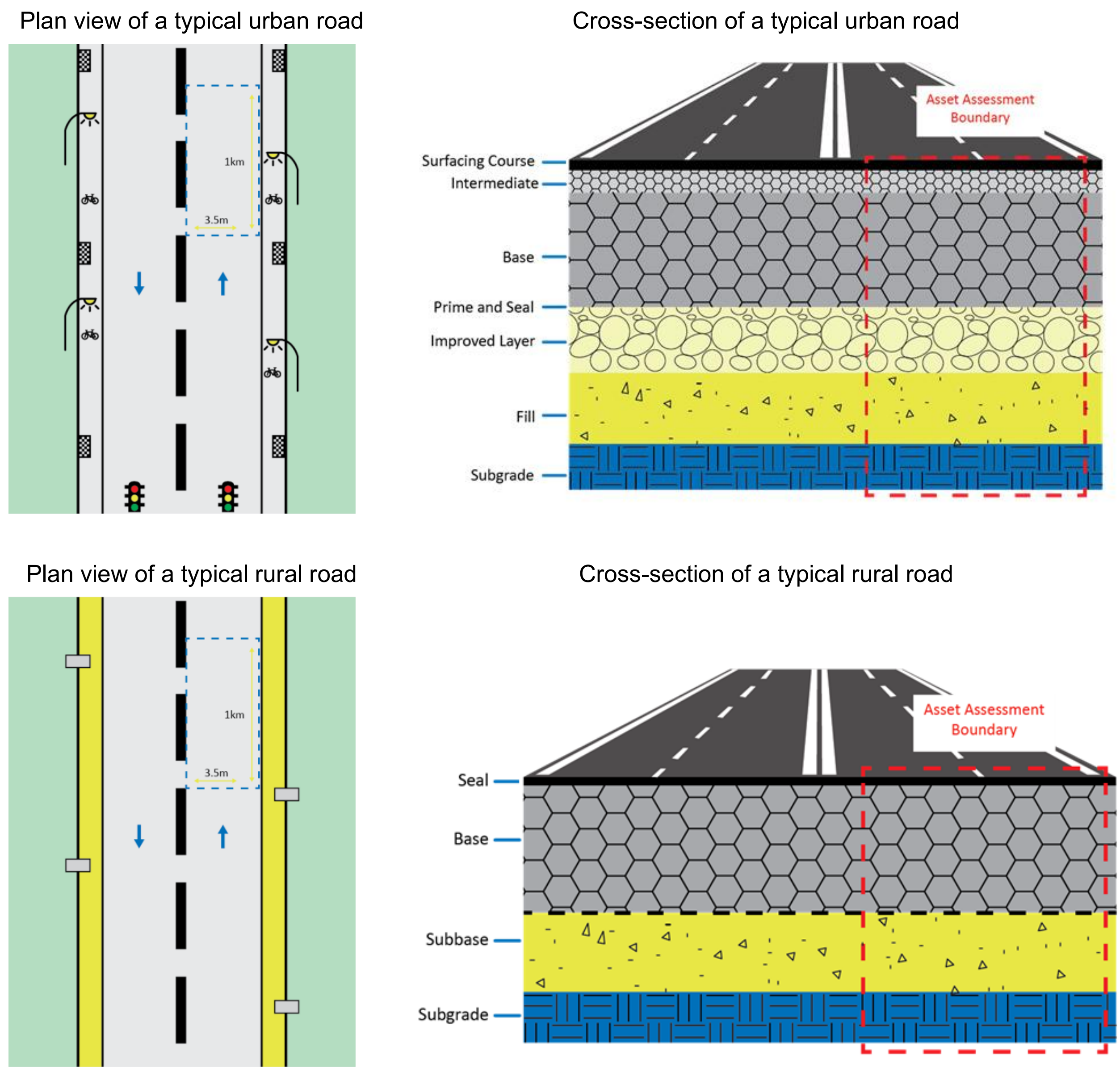


1.2.2 Types of Pavement Structures

This Best Practice Reference applies only to structural pavement layers, from above the subgrade through all base and surface layers (refer to the pavement layers in Figure 1.3). In pavement construction, the subgrade is generally considered the in situ material that forms the foundation of the pavement. Unless specific treatment (like stabilisation to improve load-bearing capacity or durability) is required, the top of the subgrade, after any necessary rolling or shaping, is accepted as the starting point for pavement works and for the consideration of embodied emissions under this Best Practice Reference.

The pavement specifically excludes ancillary civil works such as footpaths, kerbs, roadside furniture, signage, lighting, signalling and line marking. Emissions not directly attributable to the pavement's structural performance shall be excluded unless specifically required for project-specific reporting.

Figure 1.3: Typical pavements



Source: Hall et al. (2025).

1.3 Referenced documents

The following documents have been identified as key resources for the development and implementation of the Best Practice Reference for the determination of the embodied carbon of pavement structures. They provide technical guidance, datasets, tools, and methodologies relevant to embodied carbon estimation and whole-of-life carbon assessments in infrastructure projects.

Primary Guidance Documents

- *Embodied Carbon Measurement for Infrastructure – Technical Guidance* (Infrastructure and Transport Ministers 2024) – Guideline defining LCA modules, system boundaries, scopes, and measurement for infrastructure

- PAS 2080:2023 *Carbon Management in Buildings and Infrastructure* – Internationally recognised standard for managing carbon across asset life cycles
- RICS WLCA:2023 *Whole Life Carbon Assessment for the Built Environment* – Global method for life cycle carbon quantification in built assets

Tools and Case Study Resources

- SAT4P – Sustainability Assessment Tool for Pavements (Hall et al. 2025) – NTRO tool for life cycle GHG emission analysis of pavements
- Carbon Gauge Tool (Transport Authorities Greenhouse Group 2013) – TAGG tool for embodied and operational GHG calculations for roads
- Carbon Estimate and Reporting Tool (CERT) (Transport for NSW 2020) – Transport for NSW tool for consistent carbon reporting

NTRO Authored Reports and Research

- NACoE P106 (Brownjohn et al. 2019) – Report on GHG emission reductions from innovative pavement solutions
- NACoE P117 (Hall et al. 2020) – Report on developing a pavement sustainability tool for Qld (basis for SAT4P)
- NACoE S73 (O'Connor et al. 2025) – Report on integrating whole-of-life carbon for structures in the transport sector

Datasets

- EPiC Database (University of Melbourne n.d.) – Database for embodied carbon factors for construction materials (University of Melbourne).
- AusLCI – Australian National Life Cycle Inventory Database (ALCAS) (Australian Life Cycle Assessment Society n.d.) – Australian life cycle inventory (LCI) database for LCAs
- Australian Transport Assessment and Planning (ATAP) Guidelines – Parameter Values 2 and Parameter Values 5 (Australian Transport Assessment and Planning 2016, Australian Transport Assessment and Planning 2024) – Datasets for transport emission factors, fuel use, and carbon pricing

Other Guidance Documents

- *Engineers Australia Carbon Measurement Fundamentals for Engineers* (Engineers Australia 2024) – Basic carbon measurement guidance for engineers
- Austroads *Guide to Pavement Technology* – Parts 2 & 5 (Austroads 2019, Austroads 2024) – Guidance on pavement technology with sustainability aspects
- Infrastructure Australia *Guide to Assessing Greenhouse Gas Emissions* (Infrastructure Australia 2024) – Guide for GHG emission assessments in infrastructure projects
- TAGG *Greenhouse Gas Assessment Workbook for Road Projects* (Transport Authorities Greenhouse Group 2013) – Practical workbook for GHG emission calculations for roads

1.4 Terms and Definitions

Table 1.3 further defines key terms and standard units of measurement relevant to the scope and application of this Best Practice Reference. The definitions are aligned with the Transport Ministers *Embodied Carbon Measurement for Infrastructure – Technical Guidance* document (Infrastructure and Transport Ministers 2024) and relevant international standards (e.g. ISO 14040:2006, PAS 2080:2023).

Table 1.3: Key terms and definitions used in this document

Term	Definition
Biogenic carbon	Carbon stored in biological materials (e.g. timber or biomass) that may be released during degradation or combustion. Relevant when bio-based materials are used in pavements.
Carbon emissions	The release of GHGs or carbon emissions, including CO_2, CH_4 and N_2O, expressed CO_2-e. Emissions may be direct or indirect, occurring at various stages of an asset's life cycle.
Cradle-to-gate	Includes all processes from raw material extraction (the 'cradle') through manufacturing, production and transport up to the factory or plant gate. It excludes transportation to the site, construction, use, maintenance and end-of-life phases.
Cradle-to-grave	A full LCA. Includes all stages from raw material extraction through production, transportation, construction, use, maintenance and final disposal or recycling (the 'grave').
Data quality	Refers to the accuracy, completeness and representativeness of the data used in the LCA. Critical for ensuring reliable and transparent carbon estimation. Can include primary data (measured) or secondary data (from databases).
Embodied carbon	The total GHG emissions associated with materials and construction processes throughout the life cycle stages of a pavement asset – from raw material extraction, manufacturing and transport to construction, maintenance and end-of-life treatment (modules A1 – A5, B2 – B5, C1 – C4 as per EN 15978/ISO 21930).
Environmental Product Declaration (EPD)	A third-party verified document based on the LCA, providing transparent and comparable data on the environmental impact of a product (e.g. asphalt mix or cement). EPDs are typically aligned with ISO 14025 and EN 15804+A2:2019, and ISO 21930.
Functional unit	The quantified performance output of the pavement system used as a reference for LCA comparisons. For road pavements, a common unit is '1 lane-kilometre of pavement over a 40-year design life'.
Global warming potential (GWP)	A measure of how much heat a GHG traps in the atmosphere compared to CO_2 over a specified time horizon (usually 100 years). Used to convert different GHGs into CO_2-e units for aggregation.
Life cycle assessment (LCA)	A method for evaluating the environmental impacts of a product or asset throughout its entire life cycle, including both embodied and operational phases. For pavements, this encompasses design, construction, use (vehicle emissions, maintenance) and disposal stages.
Pavement layers and terminology	Surface layer (wearing course): top layer exposed to traffic, typically asphalt or sprayed seal. Base layer: primary structural layer beneath the surface, often unbound or stabilised. Subbase and subgrade: lower layers contributing to load distribution and support. The subgrade is to be protected from traffic loads. Rehabilitation/maintenance activities: includes resealing, overlays or reconstruction, influencing the whole-of-life carbon profile.
Sankey diagram	Flow diagram that visually represents the movement of resources, energy or materials through a system. Useful for LCAs to show how inputs are distributed across outputs. The width of the arrows (flows) is proportional to the quantity being represented. Nodes represent stages or processes.
Scope 1, 2, and 3 emissions	Scope 1 emissions are direct GHG emissions from sources owned or controlled by an entity, such as fuel combustion in on-site equipment during pavement construction. Scope 2 emissions are indirect emissions from the generation of purchased electricity by the entity (needed during the pavement life cycle). Scope 3 emissions are all other indirect emissions that occur in the value chain of the entity, including emissions from the production of purchased materials, transport and waste disposal in the pavement life cycle.
System boundary	Defines the stages, processes and flows considered in the LCA of the pavement. Can range from 'cradle-to-gate' (materials only) to 'cradle-to-grave' (entire life cycle including end-of-life).

1.5 Assumptions and Background Principles

This Best Practice Reference is based on a set of core assumptions and principles to ensure that embodied carbon estimates for pavement structures are consistent, transparent and aligned with current best practice.

Where actual project-specific data is incomplete or unavailable, conservative estimates and typical default values shall be applied, with all assumptions clearly documented in the final report. Emission factors shall be sourced following a defined hierarchy, giving preference to verified EPDs where available, then to Australian life cycle inventory databases (see Sections 3 and 4.1) or other reputable sources consistent with Infrastructure and Transport Ministers (2024).

All assessments shall apply a clearly defined system boundary (e.g. cradle-to-gate, cradle-to-site or cradle-to-grave) and normalise results to an agreed functional unit, such as lane-kilometre (lane-km), over the nominated design life.

When reporting potential credits or burdens beyond the system boundary (module D), users shall ensure that recycling or reuse claims are evidence based and free of double counting. Emission factors and carbon values should be kept current with the latest GHG accounts factors (Department of Climate Change, Energy, the Environment and Water 2024a) and Infrastructure Australia (2024).

Practitioners are responsible for verifying the quality, accuracy and traceability of all data and for clearly stating any limitations or exclusions in line with the reporting requirements of this Best Practice Reference.

2. Measurement of Embodied Carbon in Pavements

2.1 When to Measure Embodied Carbon

Embodied carbon shall be measured progressively across the life cycle of a pavement asset to support informed design, procurement and maintenance decisions. Early measurement maximises opportunities to identify carbon reduction strategies, while later measurement improves accuracy by incorporating finalised project data.

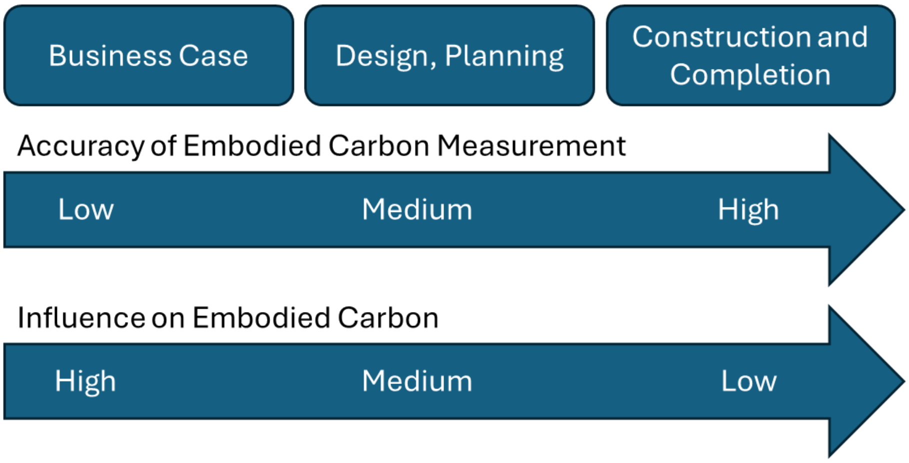
Measurement should begin at the earliest practical stage, such as during strategic planning or business case development, and should be refined as the project progresses through design, procurement, construction and handover. This staged approach ensures that embodied carbon estimates remain relevant and reliable for decision-making.

In early stages, available data may be limited. Where necessary, standard assumptions or typical values may be applied, provided they are clearly documented and replaced with project-specific information when available. Figure 2.1 illustrates the typical trade-off between the ability to influence embodied carbon outcomes and the accuracy of measurement over time.

The timing and purpose of measurement may include:

- comparing design options and materials to minimise life cycle emissions
- informing procurement requirements or sustainability assessments
- providing input to a cost-benefit analysis and funding decisions
- demonstrating performance against emissions targets or certification requirements.

Figure 2.1: Accuracy of measurement and ability to influence embodied carbon throughout the life of a pavement



Source: Adapted from Infrastructure and Transport Ministers (2024).

2.2 Context and Constraints

Historically, the absence of a consistent method for measuring embodied carbon in pavements has led to variable results, making it difficult for project owners, designers and contractors to benchmark performance or compare options on a like-for-like basis.

Local conditions introduce unique factors that influence embodied carbon estimates. Australia's extensive supply chains, variable access to local materials and long transport distances can increase upstream emissions. Regional climates affect pavement performance and maintenance frequency, which directly impact life cycle emissions. The availability of verified EPDs for key materials is improving, but coverage remains incomplete for some products and regions.

This Best Practice Reference addresses these constraints by providing a clear, modular method for defining system boundaries, selecting emission factors and structuring results in line with Infrastructure and Transport Ministers (2024) and aligned with PAS 2080:2023.

Users should remain aware of local supply chain limitations, practical opportunities for recycling and reuse (module D), and relevant sustainability frameworks (e.g. Infrastructure Sustainability (IS) rating tools) when applying this Best Practice Reference.

3. Data Requirements

3.1 Data Specifications

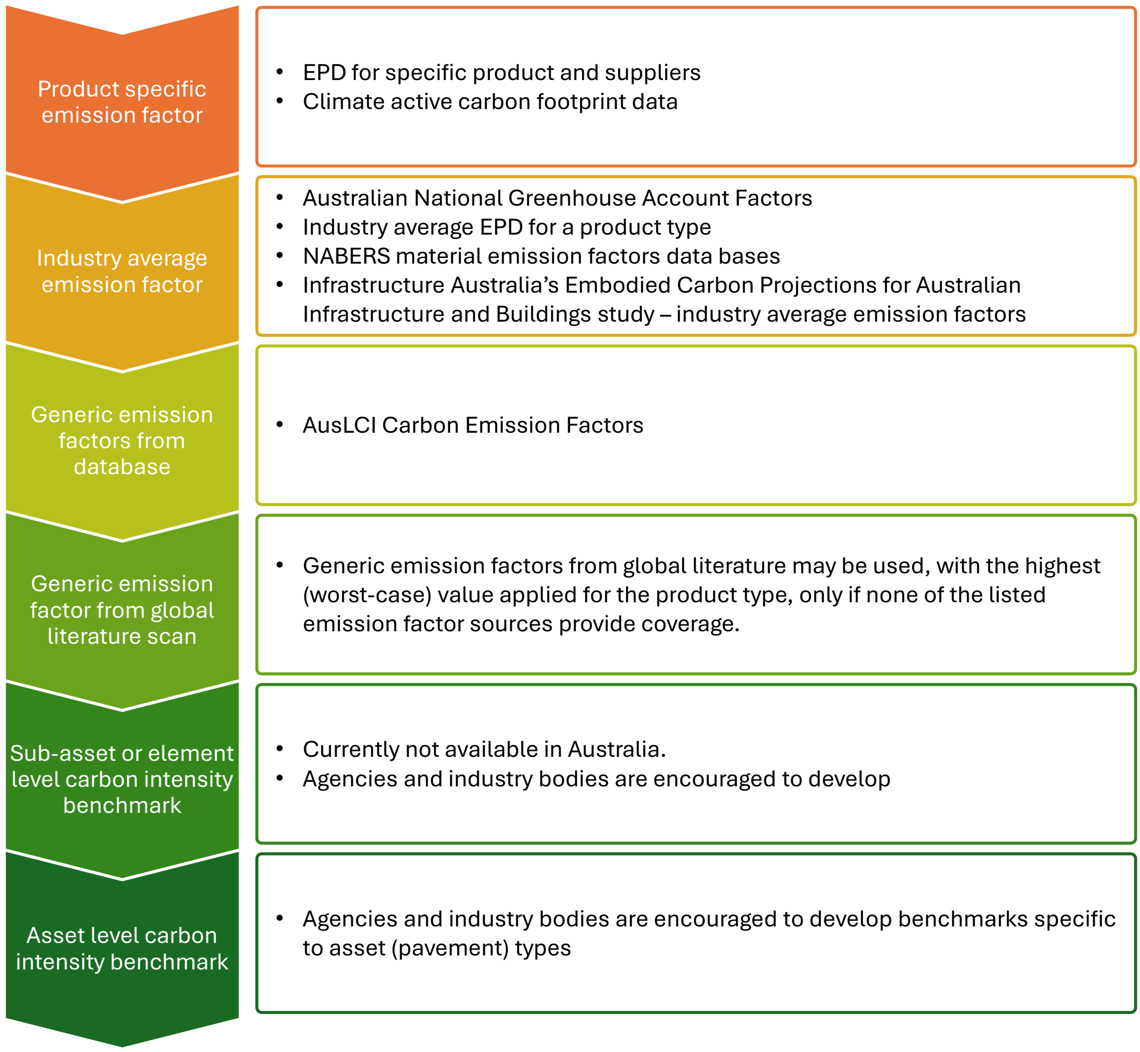
Data specification is essential to ensure that embodied carbon estimates for pavement structures are consistent, transparent and repeatable. Practitioners shall identify and document all required data inputs relevant to the materials, processes and activities across each life cycle stage (A1 – A5, B2 – B4, C1 – C4, and where used, module D).

Minimum data requirements include:

- pavement design details: number of lanes, dimensions, layer thicknesses and product types
- material quantities by type, e.g. aggregates, binders, concrete, asphalt
- energy and fuel use associated with manufacturing, transport and site activities
- transport distances for all materials, products and waste streams
- process activity data for construction, maintenance, removal and waste treatment
- applicable emission factors expressed in CO_2-e per unit of measure.

Recognised data sources should be used. Emission factors shall be selected in accordance with the data source hierarchy (see Figure 3.1 and Infrastructure and Transport Ministers 2024). Where EPDs are available and verified, they shall be used as preferred sources of product-specific emission factors. For consistent and locally relevant values, practitioners should refer to reputable Australian datasets such as the AusLCI (Australian Life Cycle Assessment Society 2023) and EPiC (University of Melbourne n.d.) databases, and tools (see Section 4.1) such as SAT4P (Hall et al. 2025), which contains pavement-specific data for Australia.

Figure 3.1: Data hierarchy



Source: Reproduced from Infrastructure and Transport Ministers (2024).

3.2 Equipment Specifications

Direct measurement of embodied carbon relies on accurate input data rather than physical instruments. However, appropriate tools and software shall be specified and used to ensure reliable data collection, estimation and analysis. This may include:

- scales or weighbridges for verifying material quantities at point of collection or delivery
- site logs, telematics or equipment hour meters to record plant and equipment usage
- maps, GPS or geographic information system (GIS) tools for verifying transport distances
- approved LCA software tools for applying emission factors and calculating outputs.

All measurement equipment must be calibrated in accordance with recognised national standards where applicable. Emission factor databases shall be version controlled and auditable.

3.3 Operations Procedure

Practitioners shall establish and follow an operating procedure that ensures data is collected, validated and processed consistently across all stages of a project. Key considerations include:

- recording actual quantities at point of delivery or installation wherever practicable
- assigning emission factors according to the defined hierarchy and local relevance
- substituting with conservative default values only where verified data is unavailable
- documenting all assumptions, adjustments and exclusions for transparency
- validating data against supplier documentation, delivery records and construction logs
- applying version tracking for any data updates.

3.4 Data Management

Effective data management is required to maintain the quality, integrity, traceability and security of all embodied carbon data. Practitioners shall:

- store all data in secure, backed-up systems in a machine-readable format
- include key metadata such as project ID, location, reporting entity and data version
- apply version control to track updates to emission factors, assumptions and methodologies
- restrict editing rights to authorised personnel only and enable read-only access for review or audit
- maintain an audit trail for all data modifications
- retain all source documentation and references for independent verification.

4. Analysis Requirements

4.1 Software and Analysis Tools

Software and analysis tools, frameworks or spreadsheets shall be used which allow to apply consistent emission factors, system boundaries and calculation methods in line with this Best Practice Reference. The tools shall be suitable for pavement embodied emissions analysis, taking into consideration project location, complexity, size and importance. Acceptable tools include:

- dedicated pavement carbon analysis tools and frameworks, e.g. the SAT4P pavement life cycle assessment tool (Hall et al. 2025), the Australian Flexible Pavement Association's (AfPA's) sustainability framework for pavements (SF4P) (Australian Flexible Pavement Association 2018), CERT (Transport for NSW 2020) and 'Carbon Gauge' (Infrastructure NSW 2025) etc.
- LCA software and Australian databases, e.g. SimaPro (PRé Sustainability 2025), AusLCI (Australian Life Cycle Assessment Society 2023), EPiC (University of Melbourne n.d.) etc.
- spreadsheet-based methods where the project scope is simple and assumptions are transparent.

All tools shall support:

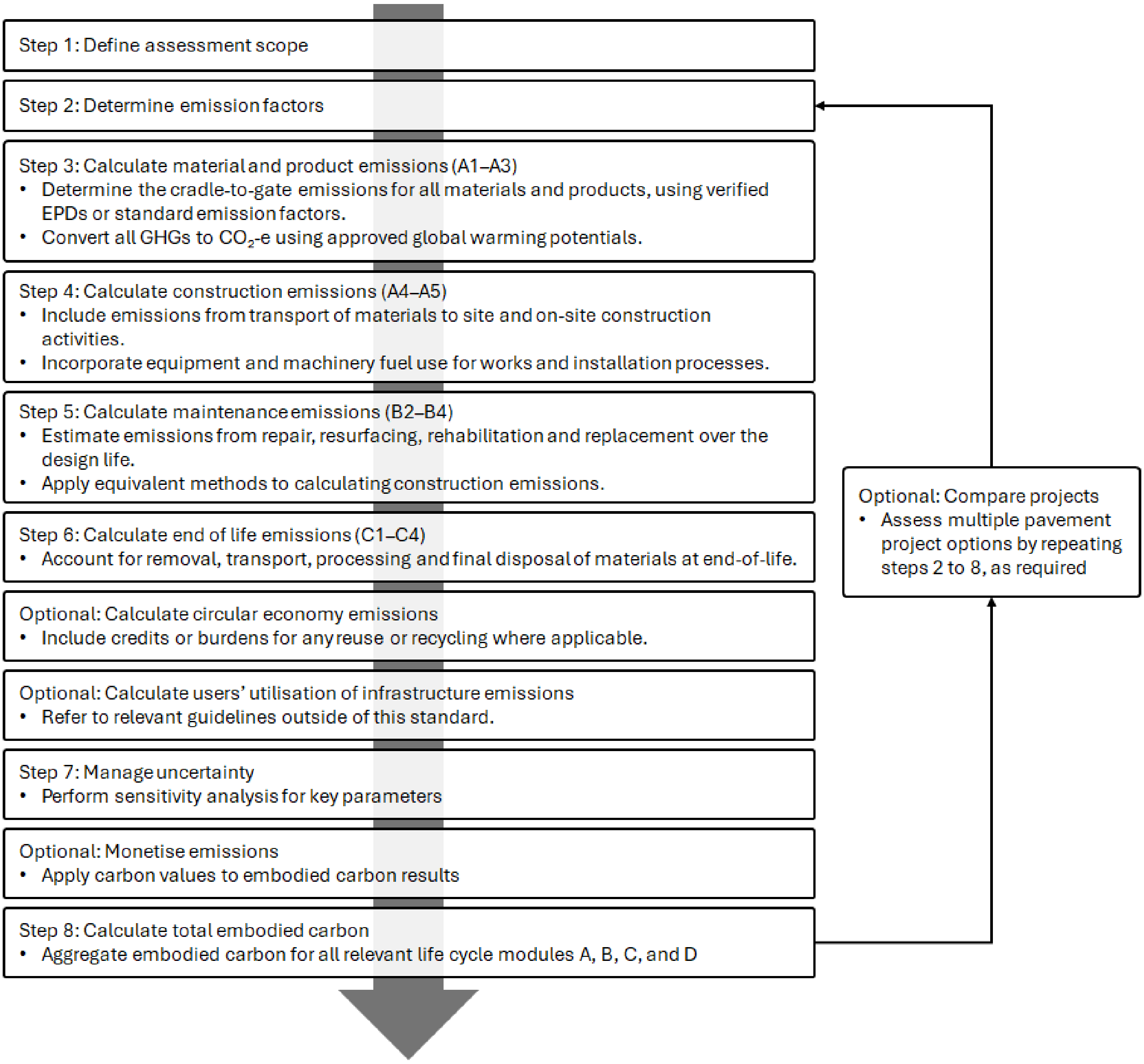
- application of life cycle modules (A1 – A5, B2 – B4, C1 – C4, D if applicable)
- version-controlled emission factors and data sources
- transparent calculation logic suitable for verification or audit.

Any tool used shall be consistent with the *Embodied Carbon Measurement for Infrastructure – Technical Guidance* document (Infrastructure and Transport Ministers 2024). Adjustments must be documented if standard settings do not align with this Best Practice Reference's requirements.

4.2 Analysis Techniques and Procedures

The following key steps (Figure 4.1) outline the analysis sequence required to quantify embodied carbon for pavement structures. The method aligns with ISO 14040:2006 and ISO 14044:2006 principles for LCA, PAS 2080:2023 carbon management for infrastructure, and relevant Australian LCI datasets such as AusLCI (Australian Life Cycle Assessment Society 2023) and the EPiC Database (University of Melbourne n.d.). Where EPDs are available and verified, they shall be used as preferred sources of product-specific emission factors.

Figure 4.1: Embodied carbon calculation process



Practitioners shall follow the data source hierarchy when applying emission factors (see Figure 3.1). All assumptions, adjustments and unit conversions shall be clearly documented.

Sections 4.2.1 to 4.2.11 step through the embodied carbon emissions calculation process. The key equations are provided. Additional equations explaining further details are provided in Appendix B.

4.2.1 Step 1: Define Assessment Scope

The first step is to clearly define the scope of the assessment and the system boundary, i.e. what are the various processes and stages across the pavement's life cycle that should be included in the assessment. For the pavement structure's embodied carbon, the assessment scope should be clearly defined as life cycle modules A1 – A5, B2 – B4 and C1 – C4. The assumptions, inclusions and exclusions within each module should also be well established. These are outlined in further detail in the following steps.

4.2.2 Step 2: Determine Emission Factors

This preparatory work of determining the emission factors is needed for calculating embodied emissions in materials and products used across all pavement construction, maintenance and end-of-life stages.

Emission factors (labelled EF) are measured in kg CO_2-e per unit of measurement. They need to cover both direct (scope 1) and indirect (scope 2 and 3) emissions, as outlined in the Australian National GHG Accounts Factors (Department of Climate Change, Energy, the Environment and Water 2024a).

Emission factors need to be determined for:

- materials and products (made from pavement materials, e.g. asphalt)
- construction, maintenance and removal processes
- pavement end-of-life and circular economy (reuse, recycling, recovery) processes
- fuels and energy.

Determining emission factors for materials and products can be expressed by Equation 1:

$$EF = \sum_i EF_i \qquad (1)$$

where

EF = the emission factor

EF_i = the emission factors for individual steps i in the value chain of a material or product, or for individual elements of a process

Databases like AusLCI (Australian Life Cycle Assessment Society 2023) can be used to determine relevant emission factors, or emission factors are provided within SAT4P (Hall et al. 2025). Where a product has an EPD available and verified, the cradle-to-gate emission factor specified in the EPD should be used.

Materials and products emission factors

Emission factors for materials or products are the sums of all individual emissions created along the chain from raw material extraction (or reuse/recovery/recycling processes) to the availability of the materials or products at the local supplier (in Australia). They should cover the material extraction, shipping/transport and the product manufacturing processes, if applicable.
Example: kg CO_2-e per tonne of asphalt.

Process emission factors

Emission factors for construction and maintenance processes are the sum of all emissions associated with a process, such as emissions from fuel or energy use, and from use of other consumables.
Example: kg CO_2-e per hour of operation of an asphalt paver.

Fuel and energy emission factors

Emission factors for transport fuels and energy are standard values and are generally available from relevant sources, e.g. Department of Climate Change, Energy, the Environment and Water (2024a). Important emission factors for liquid fuels and electricity use are provided in 0.
Example: kg CO_2-e per kWh of electricity or per GJ of diesel consumed.

4.2.3 Step 3: Calculate Material and Product Emissions (A1 – A3)

The production stage encompasses all emissions associated with the creation of construction materials and products, commonly referred to as 'cradle-to-gate' emissions. This includes emissions generated from raw material extraction, processing, transport of raw materials, operation of machinery and manufacturing activities (modules A1 to A3).

Emissions are typically calculated based on the energy consumption (e.g. diesel, electricity, natural gas) per tonne or volume of material or product produced. This applies to all relevant aggregates used across pavement layers, including components incorporated into asphalt production. Additionally, transport emissions prior to the final product leaving the manufacturing facility are included within this stage.

These emissions (energy consumption, transport etc.) can be aggregated into a single emission factor EF for individual materials and products (Step 2), e.g. CO_2-e per kg of bitumen, and then applied in this step.

Pavement aggregates typically found in the subbase and/or basecourse are either crushed rock or limestone, depending on the pavement design. Asphalt and seal layers are dependent on manufacturing specifications. Typical standardised asphalt components are as shown in Table 4.1.

Table 4.1: Components of typical Australian pavement types

Pavement type	Components
Asphalt	Coarse aggregate
	Fine aggregate
	Filler
	Bitumen (binder)
Spray seal	Coarse aggregate
	Fine aggregate
	Sprayed bitumen

Material or product emissions are calculated using Equation 2:

$$t\ CO_2e = \sum_{materials\ \&\ products} \frac{EF \times Q}{1000} \qquad 2$$

where

Q = the material or product quantity (e.g. mass or volume)

EF = the emission factor for a material or product (Step 2), e.g. kg CO_2-e per quantity

Material (or product) emissions need to be aggregated (summed up) across all pavement layers and all materials or products in each layer. Layers may contain multiple materials or products.

Quantities are determined by the project scope and can be expressed per road-km, per lane-km or per area (m^2) of pavement. Factors such as lane width, layer thickness, compaction density and material interactions (e.g. mixing of liquid binders and solid aggregates) impact the quantities required for a project. Appropriate unit conversions need to be applied depending on the typical units used for different materials or products (e.g. L, m^3, kg, tonnes).

4.2.4 Step 4: Calculate Construction Process Emissions (A4 – A5)

Construction emissions can be split into 2 categories: emissions from the transport of materials or products (module A4) to the project site and from installation of the product (module A5). Transport emissions mainly originate from fuel or energy use of haulage vehicles. Product installation emissions mainly consist of fuel or energy use from on-site plants and equipment.

The calculation of plant and equipment utilisation for pavement should include the following (Table 4.2).

Table 4.2: Plant and equipment utilisation

Equipment type	Role in pavement construction
Graders	Trimming and shaping of subgrade, subbase and base layers
Compactors/rollers	Compaction of subbase, basecourse and asphalt layers
Water trucks (for compaction)	Moisture conditioning during layer compaction
Dump trucks/tippers	Hauling subbase/base aggregates and asphalt from stockpile
Asphalt paver	Placement of asphalt layers
Bitumen sprayer/distributor	Application of primer and tack coat between layers

Note: Plant and equipment that is associated with general earthworks should be excluded from the pavement embodied carbon calculation, such as dust suppression and cut-to-fill activities.

The transport and process emissions can be calculated using Equation 3:

$$t\,CO_2e = \sum_{transport\ trips} \frac{EF \times FC \times D}{1000} + \sum_{processes} \frac{EF \times Q}{1000} \quad (3)$$

where

EF = the emission factor for transport fuels/energy or (construction/maintenance etc.) processes

FC = the fuel or energy consumption of haulage vehicles

D = the haulage distance

Q = the quantity that applies to individual processes
The emissions across all transport trips and processes need to be aggregated (summed up) across the project.

For transport, the fuel consumption can be measured in L, kg or kWh per km depending on the fuel type of the vehicles. The amounts of materials or products needed and the vehicles' payloads will determine the number of trips required. Empty return trips need to be included, if applicable, and the payload of each vehicle influences the vehicle's fuel consumption during a trip.

For construction processes, the quantities can be expressed per unit of volume of product/material (m^3), per paved area (m^2) or per unit of time for operation of machinery (hours). Construction processes may involve both the construction of new pavements as well as the removal of old pavements, if required.

4.2.5 Step 5: Calculate Maintenance Process Emissions (B2 – B4)

Maintenance process emissions (modules B2 to B4) typically result from pavement resurfacing, rehabilitation, repair (e.g. potholes) and other minor tasks (e.g. renewal of linemarking). Emissions from pavement upgrades over the course of the pavement life, such as road/lane widening, may also count towards operational/maintenance emissions.

Like for the initial pavement construction, pavement maintenance procedures involve raw material extraction, pavement product manufacturing, pavement removal and construction processes, as well as the transport of materials and products to and from the site. Consequently, the steps to calculate embodied emissions for pavement operation (use) follow the steps for calculating material/product emissions and construction process emissions, i.e. the equations provided in Steps 3 and 4 apply accordingly.

For further details, refer to Appendix B.

4.2.6 Step 6: Calculate End-of-life Emissions (C1 – C4)

The emissions associated with the pavement's end-of-life (modules C1 to C4) are composed of emissions from deconstruction activities, transport of materials and waste management.

The formulas in Steps 3 and 4 apply accordingly, covering deconstruction processes (equivalent to construction processes under Step 4, module A5), transport of materials from site to disposal or recycling/recovery facilities, and any waste management or treatment processes (equivalent to material/product manufacturing processes under Step 3, module A3).

Some materials or pavement components may remain on-site and become part of the new pavement. This may lead to reduced overall emissions, as transport emissions and emissions for new raw material extraction and product manufacturing processes (upfront modules A, see Figure 1.1) can be reduced. Specifically, the quantities Q and number of haulage trips in Equations 2 and 3 will be reduced in this case, leading to decreased emissions.

An example is RAP which, in some cases, can be milled and reused directly on-site, for example for temporary roads or base layers. This minimises transportation and processing costs.

For further details, refer to Appendix B.

4.2.7 Optional: Calculate Circular Economy Emissions (D)

This Best Practice Reference recognises the importance of circular economy outcomes (module D), which account for potential benefits or burdens beyond the system boundary through reuse, recovery or recycling of materials (Infrastructure and Transport Ministers 2024).

Users should include circular economy emissions under module D where robust data is available on recovered material flows or end-of-life recycling practices. Calculate circular economy emissions following the equations for material/product or process emissions under Steps 3 and 4.

An example is RAP which, more commonly, is transported to an asphalt manufacturing plant where it is crushed, screened and blended with virgin materials to produce new asphalt. Equations 2 and 3 can be applied in this case for new materials and recycling/reuse processes.

However, it is acknowledged that consistent, verifiable data for module D may be limited in the Australian context. As industry practices mature, reporting of module D should be progressively integrated and clearly documented alongside core life cycle modules.

4.2.8 Optional: Calculate Users' Utilisation of Infrastructure Emissions (B8)

Road user emissions are outside the scope of this Best Practice Reference. They are not considered embodied carbon. There are, however, important implications from the design and construction of the pavement that can impact road user emissions and are worth considering:

- The pavement condition will have an impact on road user emissions. Deteriorated pavements with high surface roughness may lead to increased vehicle fuel/energy consumption and vehicle wear and tear. This will result in additional emissions from fuel/energy consumption and vehicle maintenance materials and processes. Maintaining good quality roads is a way for road operators to help reduce road user emissions.
- Road user emissions typically account for the vast majority of emissions from a road over its service life. The share of the user emissions strongly depends on the number of vehicles using the road (measured in annual average daily traffic, AADT), on the types of vehicles (light or heavy vehicles) and on the vehicles' fuel/energy consumptions. Road user emissions are expected to decline in the coming years and decades with the uptake of low and zero emission vehicles (LZEVs).

There may be cases or projects where road user emissions need to be considered or reported. To estimate vehicle fuel consumption, or to estimate the environmental impact of vehicle traffic on the roads, users of this Best Practice Reference should refer to other guidance documents, in particular SAT4P (Hall et al. 2025) and the *Australian Transport Assessment and Planning Guidelines: PV2 Road Parameter Values* (Australian Transport Assessment and Planning 2016), which outline data and methodologies to estimate road user emissions based on road parameters (e.g. surface roughness, incline/decline) and vehicle parameters (e.g. fuel/energy consumption, vehicle mass).

4.2.9 Step 7: Manage Uncertainty

Input data and assumptions are subject to uncertainty. Where applicable, the calculation of emissions should be supported by a sensitivity analysis of key inputs (e.g. material quantities, transport distances, pavement maintenance frequencies), in particular during the early project stages/business case stage when data accuracy is low (see Figure 2.1). This is typically done by applying a per cent factor to key input variables (e.g. ±x%). It is up to the practitioners to determine reasonable factors based on experience and available data.

The reported results need to reflect the uncertainty, e.g. by providing low, medium and high estimates.

4.2.10 Optional: Carbon Valuation

To support economic evaluation, the emissions and embodied carbon estimates may be converted to a monetary value (carbon costs) using a published carbon value. It is recommended to use carbon values reported by Infrastructure Australia (2024) (refer to 0). The carbon value can be considered as the damage cost of carbon emissions. Carbon costs are calculated as outlined in Equation 4:

$$Carbon\ Costs\ (\$) = Carbon\ Value\ \left(\frac{\$}{t\ CO_2e}\right) \times Embodied\ Carbon\ (t\ CO_2e) \quad (4)$$

The *Australian Transport Assessment and Planning Guidelines: PV5 Environmental Parameter Values* (Australian Transport Assessment and Planning 2024) provide cost parameters ($ per vehicle-km) that can be considered for assigning a monetary value to road user emissions (optional module B8).

All cost values shall be converted into the appropriate project currency (AUD) if required.

4.2.11 Optional: Compare Projects

Comparative analyses can be performed by following Steps 1 to 7 (and optional steps) for multiple pavement project options, e.g. to explore alternative materials or processes. A comparative analysis may be considered for the following:

- use of recycled or low-carbon materials (e.g. reclaimed asphalt, geopolymer concrete)
- design approaches that reduce material volumes or extend service life
- alternative construction methods that reduce fuel or electricity consumption
- reduced transport distances for materials and equipment.

When results are compared across options or projects, system boundaries, assumptions and functional units shall be equivalent.

A comparative analysis must not be confused with a sensitivity analysis (Step 7), which aims to assess uncertainty by determining the sensitivity of the results by varying key drivers (input data).

4.3 Step 8: Findings

The total embodied carbon result shall be determined by aggregating the emissions for all relevant life cycle modules A, B, C and D as shown in Equation 5, including emissions for material and products, all construction and maintenance processes, all haulage and waste disposal trips, and all recycling/recovery processes:

$$Total\ t\ CO_2e = \sum_{Modules\ A,B,C,D} t\ CO_2e \quad (5)$$

The findings must include:

- the declared system boundary (e.g. cradle-to-gate, cradle-to-grave)
- functional unit and design life assumptions
- a breakdown of emissions by life cycle stage (A1 – A5, B2 – B4, C1 – C4, D)
- any credits or burdens beyond the system boundary, reported separately.

Findings shall be presented in a clear, auditable and machine-readable format, supported by summary tables, charts or figures consistent with Section 5 (Required Outcomes). Key metadata, including the project ID, declared scope, functional unit and version shall be included. The final results shall be stored securely and remain accessible for internal review or third-party verification.

4.4 Bias and Transparency

Practitioners shall take reasonable steps to ensure the validity, accuracy and transparency of all analysis results. Key requirements include:

- documenting all data sources, emission factors and assumptions used
- disclosing any data gaps, conservative estimates or known limitations
- applying version control to all emission factors, calculation methods and results
- maintaining an auditable record of all analysis steps and modifications
- ensuring that where multiple options are compared, the same functional unit, system boundary and calculation approach are applied consistently to avoid bias.

All assumptions, exclusions and data limitations shall be clearly documented to enable independent verification.

5. Required Outcomes

5.1 Key Output(s)

This Best Practice Reference requires the reporting of embodied carbon emissions associated with pavement structures over their full life cycle. All results shall be presented in a consistent, auditable and clearly interpretable format that supports decision-making across the design, delivery, maintenance and reporting phases.

5.1.1 Mandatory Results

All embodied carbon assessments performed under this Best Practice Reference shall include the following:

- project details including type and location (urban/rural, climate zone) and pavement details (design life, pavement configuration, key materials)
- system boundary (cradle-to-gate, cradle-to-site, cradle-to-grave)
- declared functional unit and assessment scope inclusions and exclusions (e.g. B8 or D)
- life cycle stage breakdown (A1 – A3, A4 – A5, B2 – B4, C1 – C4, optional B8 and D)
- results of total embodied carbon and embodied carbon per function unit
- data sources, data quality and uncertainty commentary
- sensitivity analysis results (ranges and key drivers)
- supporting tables and figures (e.g. charts, diagrams, data tables)
- recommendations for carbon reduction, where applicable.

Embodied carbon results shall be expressed in tonnes of CO_2-e (tCO_2-e) and normalised to a clearly defined functional unit – typically one lane-kilometre of pavement over a 40-year design life – or an alternative agreed design life suitable for the project. If a different functional unit is used, it shall be explicitly stated, justified and applied consistently. In addition, embodied carbon results shall be disaggregated and reported for each life cycle stage in accordance with EN 15978 and the *Embodied Carbon Measurement for Infrastructure – Technical Guidance* document (Infrastructure and Transport Ministers 2024), as outlined in Section 4.2 (modules A to D):

A clear summary results table shall be included, showing total embodied carbon results and the contribution of each life cycle stage. Visual representations may include:

- bar charts comparing life cycle stage contributions
- Sankey diagrams to illustrate carbon flows through the asset's life cycle.

Supporting data tables shall be provided in an appendix, detailing:

- emission factors used and their sources
- material quantities and assumptions
- declared system boundaries and any exclusions.

Sensitivity shall be presented numerically and graphically, if feasible. Data quality levels (primary, secondary, default) shall be disclosed for major inputs, and any assumptions, exclusions or known limitations shall be clearly documented.

5.1.2 Optional Results

If emissions are converted into a monetary value (see Section 4.2.10), the following shall be reported:

- the carbon value ($/t$CO_2$-e) used and its sources (e.g. Infrastructure Australia central value)
- the total monetary impact value ($)
- any comparison of options based on both carbon and cost performance.

If an options analysis is performed (see Section 4.2.11), the options and their differences must be outlined clearly, e.g. in a table format. All results as listed above must be described for all options.

5.2 Commentary

Reports shall include brief commentary to explain the options considered, key decisions made and any practical recommendations for reducing embodied carbon impacts. Where multiple design or procurement options have been assessed, the commentary shall summarise how these alternatives compare, referencing the same functional unit and boundary.

Practitioners should note any implications for related programs or policies, such as procurement targets, sustainability ratings or broader organisational carbon reduction strategies and infrastructure programs. Commentary shall focus on supporting decision-makers to understand the results and apply them meaningfully in context.

6. Reporting

6.1 Purpose of Reporting

Reporting under this Best Practice Reference provides a transparent record of embodied carbon estimates, enabling project stakeholders to understand, compare and verify results throughout the asset's life cycle. Reporting serves to:

- provide evidence of embodied carbon outcomes for a given pavement structure
- enable comparison of carbon performance between options or over time
- support integration with other reporting systems (e.g. cost-benefits analysis, IS rating tools)
- promote transparency and traceability in assessment processes.

6.2 Reporting Components

Reports must clearly identify the project scope, data sources, assumptions and any limitations relevant to interpretation. Reports shall be clear; comprehensive; transparent and suitable for decision-making, external review, certification or public disclosure, as required for the target audience. They shall align with the required format and content defined in Sections 3 to 5.

The minimum reporting requirements in accordance with this Best Practice Reference are summarised in Table 6.1.

Table 6.1: Reporting requirements

Reporting component		Details
Project overview and context	Mandatory	• Project name, location, type and scope • Pavement design type and functional unit used • Declared design life and traffic loading assumptions
Data sources and quality	Mandatory	• Emission factors used and their sources (e.g. EPDs, AusLCI) • Quality of the data (e.g. high-confidence primary data vs assumptions) • Any data limitations or known exclusions
Assessment scope and system boundary	Mandatory	• Life cycle stages included (modules A to D) • Rationale for exclusions, if any • Geographic and temporal boundaries
Methodology summary	Mandatory	• Reference to this Best Practice Reference and any tools used (e.g. SAT4P, Carbon Gauge) • Calculation procedures followed (refer to Section 4) • Outline of any assumptions made during the calculations
Embodied carbon results (modules A1 – A4, B2 – B4, C1 – C4)	Mandatory	• Total embodied carbon (tCO_2-e) for each life cycle stage • Sensitivity analysis results and key drivers of uncertainty • Carbon reduction strategies evaluated, if applicable
Circular economy and user GHG emission results (modules B8, D)	If required	
Visualisation and representation	Recommended	• Summary tables with numerical results, and supporting diagrams where relevant • Emissions profiles over time (if applicable)
Carbon valuation	If required	• Monetary value of embodied carbon impact based on current carbon pricing • Reference to pricing framework (refer to 0)
Comparative analysis	If required	• Summary of alternative pavement designs or material options assessed

Reporting component		Details
		• Differences between results of embodied carbon estimates for each option
Appendices	As required	• Data tables • Emission factor references and assumptions • Material and process inventories • Sensitivity analysis details

6.3 Reporting Format

Reports shall be prepared in a professional, editable format (e.g. Microsoft Word) with all figures, tables and data sources clearly cited. An editable digital version with data table or spreadsheet is recommended where the assessment will be subject to verification or review.

Where results are to be shared externally (e.g. with funding bodies, certification programs or public reports), the report shall clearly indicate which data are confidential or commercially sensitive, provide sufficient detail for independent review without disclosing proprietary methods or costs, and include a declaration of conformity to this Best Practice Reference.

7. Application and Implementation of Outcomes

This Best Practice Reference shall be applied by practitioners in a way that integrates measurement of embodied carbon into routine design, construction and asset management processes. Typical practical steps include:

- establishing responsibilities for carbon measurement and reporting within project teams
- aligning embodied carbon measurement tasks with design milestones and approvals
- using results to inform design changes or procurement specifications
- reviewing results to identify lessons learned and share improvements across projects.

The application of this Best Practice Reference should align with any relevant organisational carbon policies, sustainability frameworks or jurisdictional requirements.

7.1 Applications

Embodied carbon results generated under this Best Practice Reference are intended to:

- inform sustainable infrastructure design and delivery decisions
- enable data-driven choices across planning, procurement, construction and maintenance
- contribute to meeting and tracking emissions reduction targets
- support compliance with regulatory, funding or reporting requirements related to climate risk and carbon performance.

Key practical applications supported by this Best Practice Reference include, but are not limited to, the areas shown in Table 7.1. These support whole-of-life carbon estimation, sustainability reporting, benchmarking and benefit-cost analysis.

Table 7.1: Application areas for pavement embodied carbon estimates

Application area	Description
Strategic planning and option assessment	• Compare pavement types, materials or design strategies based on total life cycle carbon impact • Support feasibility studies and business cases with quantified environmental impact data • Identify low-carbon pathways early in project development
Benchmarking and benefit-cost analysis	• Use embodied carbon estimates as an input to compare design or procurement options, evaluate life cycle cost implications, and support investment decision-making
Procurement and contracting	• Embed embodied carbon thresholds, reporting requirements or weightings into procurement specifications • Support performance-based contracts that incentivise low-carbon solutions • Align with IS or PAS 2080:2023-compliant procurement practices
Design development	• Optimise material selection, geometry and layer configurations to minimise embodied emissions • Incorporate recycled or locally sourced materials • Evaluate trade-offs between durability, structural performance and carbon outcomes
Construction and delivery	• Benchmark actual carbon performance against design estimates • Track material quantities and construction emissions during delivery • Adjust methods on site to reduce emissions where feasible (e.g. haul distances, fuel use, plant efficiency)
Operation and asset management	• Integrate carbon data into pavement management systems (PMS) • Inform rehabilitation and maintenance scheduling with carbon objectives • Support whole-of-life carbon performance tracking
Regulatory and external reporting	• Comply with sustainability and climate disclosure obligations • Report to funding bodies, regulators or infrastructure rating schemes

	• Contribute to corporate or agency-wide sustainability reporting

7.2 Implementation Considerations

For effective implementation, project teams and asset owners should:

- define clear roles and responsibilities for carbon estimation, review and reporting
- provide training or guidance to designers, contractors and asset managers on applying this Best Practice Reference
- align embodied carbon tasks with data collection, quality control and delivery frameworks
- update emission factors and assumptions regularly based on new data and evolving standards.

Where appropriate, results should be incorporated into project evaluation, risk assessment and decision-making processes alongside traditional technical, financial and safety criteria.

7.3 Integration with Other Programs and Tools

The application of this Best Practice Reference is designed to complement:

- life cycle cost analysis (LCCA) and benefit-cost analysis (BCA) frameworks
- broader sustainability frameworks, including the IS rating scheme
- circular economy initiatives through measurement of module D outcomes (reuse, recovery, recycling).

Tools and databases (see Section 4.1) can be used to perform embodied carbon calculations and help to comply with the requirements outlined in this Best Practice Reference.

8. Monitoring and Evaluation of Implementations

Monitoring and evaluation ensure that embodied carbon results remain meaningful and verifiable and support continuous improvement across the full pavement asset's life cycle. Practitioners shall:

- verify consistency between predicted and actual embodied carbon outcomes by comparing estimated and actual material quantities, construction methods and transport activities
- record any significant variances and update life cycle emissions accordingly
- maintain clear records and documentation to enable internal review or third-party verification
- store all input data, factors and calculation records securely and in line with organisational data governance requirements.

8.1 Monitoring Objectives and Requirements

The objectives of monitoring are to:

- confirm alignment between calculated and actual embodied carbon outcomes
- identify any deviations, improvements or lessons learned during project delivery
- enhance the accuracy of future assessments and refine design, procurement and construction practices
- enable transparent reporting to stakeholders, funding bodies and regulators
- support organisational innovation and decarbonisation targets.

All projects applying this Best Practice Reference shall establish procedures for post-assessment monitoring, including:

- tracking as-built data: actual material quantities, equipment use, transport distances and fuel types
- recalculating emissions based on verified data and updating total emissions and stage breakdowns if the scope, boundary or assumptions change
- maintaining supporting documentation for audits and reviews, using standard reporting templates where practical.

8.2 Performance Review and Continuous Improvement

Embodied carbon performance shall be evaluated against:

- project-specific design benchmarks or contract requirements
- relevant internal carbon targets and historical project baselines
- industry best practice and national decarbonisation goals.

Where significant over- or under-performance occurs, project teams should undertake root cause analysis to identify drivers (e.g. conservative estimates, scope changes, material availability). Learnings shall be documented and fed into post-completion reviews, lessons learned processes and future planning activities.

Organisations applying this Best Practice Reference should periodically review and update emission factors, EPDs, data sources and modelling assumptions to maintain alignment with current best practice. Where appropriate, carbon values should be applied for economic assessments, and optional life cycle modules (modules B8 and D) should be reassessed and included in future estimates where relevant.

Participation in industry benchmarking, collaborative research and knowledge sharing is encouraged to support continuous improvement.

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Appendix A Data Tables

Emission conversion factors for liquid fuel combustion

Direct (scope 1) and indirect (scope 3) emission factors for the consumption of liquid fuels, including certain petroleum-based products for stationary energy purposes are shown in the tables below.

Table A.1: Emission factors for fuel types

Fuel type	Scope 1 emission factors	Scope 3 emission factors	Energy content
	(CO_2-e/GJ)	(CO_2-e/GJ)	(GJ/kL)
Diesel oil	70.2	17.3	38.6
Liquefied petroleum gas	60.6	20.2	25.7
Petroleum-based greases	3.5	18	38.8
Biodiesel	0.28	–	34.6

Source: Department of Climate Change, Energy, the Environment and Water (2024a).

Indirect (scope 2 and scope 3) emissions from consumption of purchased electricity from a grid

Table A.2: Emission factors for Australian electricity grids

State, territory or grid description	Scope 2 emission factors	Scope 3 emission factors
	(kg CO_2-e/kWh)	(kg CO_2-e/kWh)
New South Wales and Australian Capital Territory	0.66	0.04
Victoria	0.77	0.09
Queensland	0.71	0.10
South Australia	0.23	0.05
Western Australia – South West Interconnected System (SWIS)	0.51	0.06
Western Australia – North Western Interconnected System (NWIS)	0.61	0.09
Tasmania	0.15	0.03
Northern Territory – Darwin Katherine Interconnected System (DKIS)	0.56	0.07
National	0.63	0.07

Source: Department of Climate Change, Energy, the Environment and Water (2024a).

Projected grid electricity emissions

Table A.3: Baseline scenario indirect scope 2 and 3 emissions

Table 47 Indirect scope 2 and 3[72] combined emissions factors in the baseline scenario, tonnes CO_2-e per MWh

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Australia, all grid connected	0.63	0.58	0.53	0.43	0.29	0.19	0.18	0.15	0.14	0.14	0.09	0.08	0.08	0.07	0.07	0.06
National Electricity Market	0.63	0.58	0.53	0.44	0.29	0.18	0.18	0.15	0.13	0.13	0.08	0.07	0.07	0.06	0.06	0.05
NSW/ACTACT	0.55	0.50	0.43	0.36	0.23	0.16	0.16	0.14	0.09	0.09	0.08	0.07	0.06	0.06	0.06	0.03
Queensland	0.74	0.67	0.62	0.55	0.37	0.19	0.20	0.15	0.16	0.17	0.14	0.13	0.12	0.11	0.12	0.11
South Australia	0.24	0.25	0.23	0.23	0.17	0.11	0.09	0.06	0.07	0.07	0.07	0.07	0.06	0.05	0.06	0.06
Victoria	0.84	0.77	0.75	0.56	0.38	0.27	0.24	0.20	0.20	0.19	0.02	0.02	0.01	0.01	0.01	0.01
Tasmania	0.22	0.21	0.21	0.04	0.04	0.02	0.04	0.04	0.05	0.06	0.01	0.01	0.01	0.01	0.01	0.01
Western Australia's Wholesale Electricity Market	0.56	0.53	0.48	0.34	0.26	0.14	0.13	0.14	0.14	0.13	0.13	0.12	0.12	0.12	0.11	0.14
North West Interconnected System	0.71	0.68	0.66	0.64	0.62	0.60	0.55	0.51	0.47	0.42	0.38	0.34	0.30	0.25	0.19	0.17
Darwin-Katherine Interconnected System	0.61	0.56	0.47	0.44	0.44	0.43	0.39	0.39	0.39	0.38	0.38	0.38	0.38	0.37	0.37	0.37

Source: Department of Climate Change, Energy, the Environment and Water (2024b).

Infrastructure Australia carbon valuation

Table A.4: Recommended carbon values

Table 1 – Recommended carbon values per tCO_2-e emissions (AUD $2023)

Year	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032
Low	44	56	62	69	76	87	107	124	144
Central	56	66	76	88	104	123	148	171	192
High	66	77	95	107	132	152	180	210	227

Year	FY2033	FY2034	FY2035	FY2036	FY2037	FY2038	FY2039	FY2040	FY2041
Low	159	166	172	184	191	193	206	210	212
Central	209	222	234	244	254	264	273	282	291
High	258	262	280	293	308	319	329	340	351

Year	FY2042	FY2043	FY2044	FY2045	FY2046	FY2047	FY2048	FY2049	FY2050
Low	215	228	246	267	272	274	276	284	287
Central	300	309	318	326	335	344	354	363	377
High	361	370	375	380	403	421	429	437	469

Source: Infrastructure Australia (2024).

Appendix B Detailed Equations

The equations below should be used as needed in the step-by-step guide (Section 4.2) to calculate embodied emissions.

B.1 Module A1: Material Extraction Emissions (Calculating Emission Factors $\boldsymbol{EF}$)

Material extraction calculations will be required for each distinct material used within the pavement layers (e.g. aggregates, crushed rock, sand, filler, bitumen etc.). Emissions should be calculated separately per material to ensure accurate life cycle quantification.

B.1.1 Fuel and Electricity Use for a Raw Material

Calculate the volume of fuel F or amount of electricity E consumed for each plant or equipment in the extraction and stockpiling of a raw material within the extraction (module A1) boundary. Estimate fuel and electricity usage based on operating hours and consumption rates for all plant and equipment for the extraction, based on the tonnes or cubic metres of material.

$$F = FC \times H \times Q \qquad \text{A1}$$

or

$$E = EC \times H \times Q$$

where

F = fuel used by individual equipment/plant (kL)

E = electricity used by individual equipment/plant (kWh)

FC = equipment/plant fuel consumption (kL/h*t, kL/h*m^3)

EC = equipment/plant electricity consumption (kWh/h*t, kWh/h*m^3)

H = time/hours worked by individual equipment/plant (h)

Q = material quantity (t, m^3)

B.1.2 Fuel and Electricity Emissions for a Raw Material

Calculate emissions for extraction and stockpiling of a raw material based on fuel use, fuel-specific emission factors and energy content, or electricity use and grid-specific emission factors, and aggregate over all plants and equipment used.

$$t\ CO_2e\ (Fuels) = \sum_{plants\ \&\ equipment} \frac{F \times EF_F \times EN_F}{1000} \quad \text{A2}$$

or

$$t\ CO_2e\ (Electricity) = \sum_{plants\ \&\ equipment} \frac{E \times EF_E}{1000}$$

where

$t\ CO_2e\ (Fuels)$	=	emissions from fuel use for extraction of a raw material (tCO_2-e)
$t\ CO_2e\ (Electricity)$	=	emissions from electricity use for extraction of a raw material (tCO_2-e)
F	=	fuel used by individual equipment/plant (kL)
E	=	electricity used by individual equipment/plant (kWh)
EF_F	=	fuel-specific emission factor (kg CO_2-e/GJ)
EF_E	=	grid-specific emission factor (kg CO_2-e/kWh)
EN_F	=	fuel-specific energy content (GJ/kL)

Notes:

- EF_F is determined by the fuel type used for each plant and equipment; if unknown, it should be assumed that the plant and equipment will be diesel.
- If multiple fuel types are used for an individual plant or equipment, then F must be calculated separately for each fuel type.
- Where electricity is sourced from multiple grids or includes renewable supply agreements (e.g. power purchase agreements), emissions should be calculated separately for each source using the applicable grid emission factor EF_E and then summed to determine total emissions.

B.1.3 Total Emissions for a Raw Material

The total emissions for extraction of an individual raw material are:

$$t\ CO_2e\ (Extraction) = t\ CO_2e\ (Fuels) + t\ CO_2e\ (Electricity) \quad \text{A3}$$

where

$t\ CO_2e\ (Extraction)$	=	emissions from fuel and electricity use for extraction of a raw material (tCO_2-e)

Alternatively, if ready-to-use emission factors are available from relevant databases, tools or EPDs, the following equation can be used for calculating the emissions for extraction of a material, instead of basing the emissions calculation on fuel and electricity use for raw material extraction as outlined above.

The same applies to products (under module A3) if an emission factor is available for that product, e.g. asphalt leaving an asphalt plant, accounting for all emissions under A1 to A3.

$$t\ CO_2e\ (Extraction) = \frac{EF \times Q}{1000} \qquad \text{A4}$$

where

$t\ CO_2e\ (Extraction)$	=	emissions from fuel and electricity use for extraction of a raw material (tCO_2-e)
EF	=	emission factor for a specific material, covering all plant/equipment needed to extract that material (kg CO_2-e/t, kg CO_2-e/m^3)
Q	=	material quantity (t, m^3)

B.2 Modules A2, A4, C2: Transportation Emissions

Transportation emissions account for emissions associated with any transportation (haulage) tasks, in particular:

- transportation of raw materials from the exit of extraction site to the entry point of the product manufacturing/processing facility (module A2)
- transportation of products from the exit of the manufacturing/processing facility to the pavement construction site (module A4)
- transportation of pavement waste products after pavement decommissioning (module C2).

All relevant transport modes used across the supply chain must be included, such as road freight (trucks), rail, marine shipping, or a combination of modes. Emissions must be calculated for each leg of the journey, using mode-appropriate methods and fuel data, to ensure complete and accurate LCA of material movements.

B.2.1 Fuel and Electricity Consumption for Transport (Haulage)

Estimate fuel use using load, distance travelled and vehicle fuel efficiency per kilometre (for road vehicles):

A5

$$F = F(haulage) + F(empty) = \frac{Q}{C} \times FE_L \times D + \frac{Q}{C} \times FE_E \times D$$

or

$$E = E(haulage) + E(empty) = \frac{Q}{C} \times EE_L \times D + \frac{Q}{C} \times EE_E \times D$$

where

F, $F(haulage)$ and $F(empty)$	=	fuel used for transport of a material or product (L)
E, $E(haulage)$ and $E(empty)$	=	electricity used for transport of a material or product (kWh)
Q	=	total quantity of an individual material required (t, m^3)
C	=	load capacity (max. payload) of a vehicle (t, m^3)

FE_L and FE_E	=	vehicle fuel efficiency for loaded or empty trips (L/km)
EE_L and EE_E	=	vehicle energy (electricity) efficiency for loaded or empty trips (kWh/km)
D	=	transport distance (km)

Estimate fuel use using load, distance travelled and vehicle fuel efficiency per kilometre (for marine shipping, rail locomotives or long-haul equipment operating on time-based duty cycles where distance-based fuel efficiency is not available or practicable):

$$F = \frac{Q}{C} \times FE_H \times H \tag{A6}$$

or

$$E = \frac{Q}{C} \times EE_H \times H$$

where

F	=	fuel used for transport of a material or product (L)
E	=	fuel used for transport of a material or product (kWh)
Q	=	total quantity of an individual material required (t, m^3)
C	=	load capacity (max. payload) of a vehicle (t, m^3)
FE_H	=	vehicle fuel efficiency per hour (L/h)
EE_H	=	vehicle energy (electricity) efficiency per hour (kWh/h)
H	=	transport time/hours (h)

Notes:

- The factor $\frac{Q}{C}$ represents the number of vehicles needed to complete the transport task for a material or product. The factor will need to be rounded up, e.g. if $\frac{Q}{C}$ is less than 1 (quantity smaller than load capacity of the vehicle), then 1 vehicle will be needed (e.g. 1 truck). Alternatively, the fuel use of the vehicle can be apportioned based on the material or product quantity (e.g. materials transported on freight trains or vessels).
- If applicable, fuel consumptions for empty vehicle (return) trips need to be added, e.g. vehicles may transport materials to a construction site and return empty to the plant to pick up the next lot of material. Fuel efficiencies of loaded vehicles FE_L may differ from fuel efficiencies of empty vehicles FE_E.

B.2.2 Emissions from Transport Fuel end Electricity Use

Convert transport fuel and electricity use into carbon emissions:

$$t\ CO_2e\ (Transport\ Fuel) = \sum_{trips} \frac{\mathrm{F} \times EF_F \times EN_F}{1000} \qquad \text{A7}$$

or

$$t\ CO_2e\ (Transport\ Electricity) = \sum_{trips} \frac{\mathrm{E} \times EF_E}{1000}$$

where

$t\ CO_2e\ (Transport\ Fuel)$	=	emissions from transport fuel use (tCO_2-e)
$t\ CO_2e\ (Transport\ Electricity)$	=	emissions from electricity use (tCO_2-e)
F	=	fuel used by individual vehicle type (kL)
E	=	electricity used by individual vehicle type (kWh)
EF_F	=	fuel-specific emission factor (kg CO_2-e/GJ)
EF_E	=	grid-specific emission factor (kg CO_2-e/kWh)
EN_F	=	fuel-specific energy content (GJ/kL)

Note: If electric vehicles (EVs) are used for any part of the transport, emissions must be calculated based on electricity consumption and the relevant electricity grid emission factor for the project location. This also applies where EVs are powered by renewable energies.

B.2.3 Total Transport Emissions

Calculate total transport emissions:

$$t\ CO_2e\ (Transport) = t\ CO_2e\ (Transport\ Fuel) + t\ CO_2e\ (Transport\ Electricity) \qquad \text{A8}$$

where

$t\ CO_2e\ (Transport)$	=	emissions from fuel and electricity use for transport (haulage) tasks (tCO_2-e)

Alternatively, the *Australian Transport Assessment and Planning Guidelines: PV2 Road Parameter Values* (Australian Transport Assessment and Planning 2016) provide guidance on calculating vehicle emissions based on vehicle mass and payload, which can be considered for calculating transport emissions.

B.3 Modules A3, A5, C1, C3, C4, D: Process Emissions

Process emissions account for emissions associated with any process, in particular:

- product manufacturing processes of raw materials into a product (module A3), e.g. creating crushed rock from larger rocks
- construction processes during pavement construction (module A5), e.g. operation of a grader
- deconstruction processes during pavement deconstruction (and renewal), e.g. operation of a pavement milling machine
- pavement waste product treatment and disposal (modules C3, C4).

The calculation of process emissions is similar to raw material extraction emissions.

Manufacturing process calculations will be required for each distinct product used within the pavement layers (e.g. aggregates, crushed rock, sand, filler, bitumen etc.), for each construction process, deconstruction process or waste treatment and disposal process. Emissions should be calculated separately per product and process to ensure accurate life cycle quantification.

B.3.1 Fuel and Electricity Use for Processes

Calculate the volume of fuel F or amount of electricity E consumed for each plant or equipment in each process boundary (A3, A5, C1, C3, C4). Estimate fuel and electricity usage based on operating hours and consumption rates for all plant and equipment for the extraction of a single tonne or cubic metre of material.

A9

$$F = FC \times H$$

or

$$E = EC \times H$$

where

F	=	fuel used by individual equipment/plant (kL)
E	=	electricity used by individual equipment/plant (kWh)
FC	=	equipment/plant fuel consumption (kL/h)
EC	=	equipment/plant electricity consumption (kWh/h)
H	=	time/hours worked by individual equipment/plant (h)

B.3.2 Fuel and Electricity Emissions for Processes

Calculate emissions for processes based on fuel use, fuel-specific emission factors and energy content, or electricity use and grid-specific emission factors, and aggregate over all processes:

A10

$$t\ CO_2e\ (Fuels) = \sum_{processes} \frac{F \times EF_F \times EN_F}{1000}$$

or

$$t\ CO_2e\ (Electricity) = \sum_{processes} \frac{E \times EF_E}{1000}$$

where

$t\ CO_2e\ (Fuels)$	=	emissions from fuel use for a process (tCO_2-e)
$t\ CO_2e\ (Electricity)$	=	emissions from electricity use for a process (tCO_2-e)
F	=	fuel used by individual process (kL)
E	=	electricity used by individual process (kWh)
EF_F	=	fuel-specific emission factor (kg CO_2-e/GJ)
EF_E	=	grid-specific emission factor (kg CO_2-e/kWh)

EN_F = fuel-specific energy content (GJ/kL)

Notes:

- EF_F is determined by the fuel type used for each product or process; if unknown, it should be assumed that the plant and equipment will be diesel.
- If multiple fuel types are used for an individual product or process, then F must be calculated separately for each fuel type.
- Where electricity is sourced from multiple grids or includes renewable supply agreements (e.g. power purchase agreements), emissions should be calculated separately for each source using the applicable grid emission factor EF_E and then summed to determine total emissions.

B.4 Modules B2, B3, B4: Maintenance, Repair and Replacement Emissions

Calculating emissions from maintenance, repair and replacement activities follows the calculations as outlined above, taking into consideration that maintenance activities repeat some of the steps involving:

- additional materials extraction for pavement repair, resurfacing or rehabilitation (module A1)
- additional transportation tasks for moving materials from material extraction sites to product manufacturing facilities and to the pavement site, as well as transportation tasks for moving waste materials away from the pavement site (modules A2, A4, C2)
- additional processes for pavement product manufacturing and waste management (modules A3, C3, C4)
- additional processes for pavement removal and reconstruction (modules A5, C1).

B.5 Module B8: Utilisation of Infrastructure Emissions

Calculate the environmental impact of vehicle traffic on the roads by following other guidance documents that outline data and methodologies to estimate road user emissions based on road parameters (e.g. surface roughness, incline/decline) and vehicle parameters (e.g. fuel/energy consumption, vehicle mass), in particular:

- SAT4P (Hall et al. 2025)
- *Australian Transport Assessment and Planning Guidelines: PV2 Road Parameter Values* (Australian Transport Assessment and Planning 2016).