# Life Cycle Assessment of Pavements (LCAP) tool user guide

January 2024

Version 2

WAKA KOTAHI
NZ TRANSPORT
AGENCY

Te Kāwanatanga o Aotearoa
New Zealand Government

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Waka Kotahi NZ Transport Agency
January 2024

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This document is available on Waka Kotahi NZ Transport Agency’s website at www.nzta.govt.nz

# Contents

# 1 Introduction

## 1.1 What is Life Cycle Assessment of Pavements (LCAP)?

Life Cycle Assessment of Pavements (LCAP) is a tool to help project teams understand the whole-of-life greenhouse gas (GHG) emissions impacts of different pavement designs, including the use of recycled materials or reuse of existing pavement layers.

The tool supports robust environmental decision making on pavement designs and allows more sustainable sourcing to be investigated, such as comparing transport distances from different aggregate sources, or using recycled or alternative materials.

Information from LCAP can be used alongside technical and cost calculations to guide pavement design choices at the detailed business case and detailed design phases, as well as for maintenance treatments.

LCAP considers the construction, maintenance and end-of-life phases of pavement design, as well as the impact on additional vehicle emissions (by estimating the impact of pavement–vehicle interactions on emissions, and the effect of maintenance-induced traffic delays).

There are 4 key modules to LCAP:

- construction
- maintenance
- use
- end of life.

The tool should be used to assist decision making on improvement projects and maintenance activities to improve the environmental performance of New Zealand’s pavements.

The research[1] used to develop the tool has produced interesting insights from comparing pavement designs, including:

- Reusing suitable layers of pavement is an effective method of reducing GHG emissions.
- Recycled crushed concrete can be transported at least 30km further than virgin aggregate and still have an equivalent or lower carbon footprint.
- Reclaimed asphalt pavement can be transported at least 500km for recycling and still have an equivalent carbon footprint to virgin asphalt pavement.
- The relative impacts of raw materials are higher when pavements have shorter design lives.

## 1.2 Alignment with other tools and methods

LCAP aligns with the principles of PAS 2080:2023 *Carbon management in buildings and infrastructure*, BS EN 17472:2022 *Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation methods* and other life cycle analysis (LCA) methods that are focused on carbon estimates of infrastructure projects.

These principles have also been applied in the Project Emissions Estimation Tool (PEET), the GHG emissions calculation tool developed by Waka Kotahi, Auckland Transport and KiwiRail, which uses standard design examples and industry research to provide a high-level estimation of GHG emissions through the life cycle of a transport infrastructure project. Both LCAP and PEET are therefore aligned with the stages and modules commonly reported in LCA carbon assessments, as shown in Figure 1.

The greatest impact from using PEET can be achieved in the planning phase of a project by highlighting areas (materials, structures and activities) with the most carbon emissions, allowing users to understand potential emissions-reducing options at an early stage. At the detailed business case and design phase,

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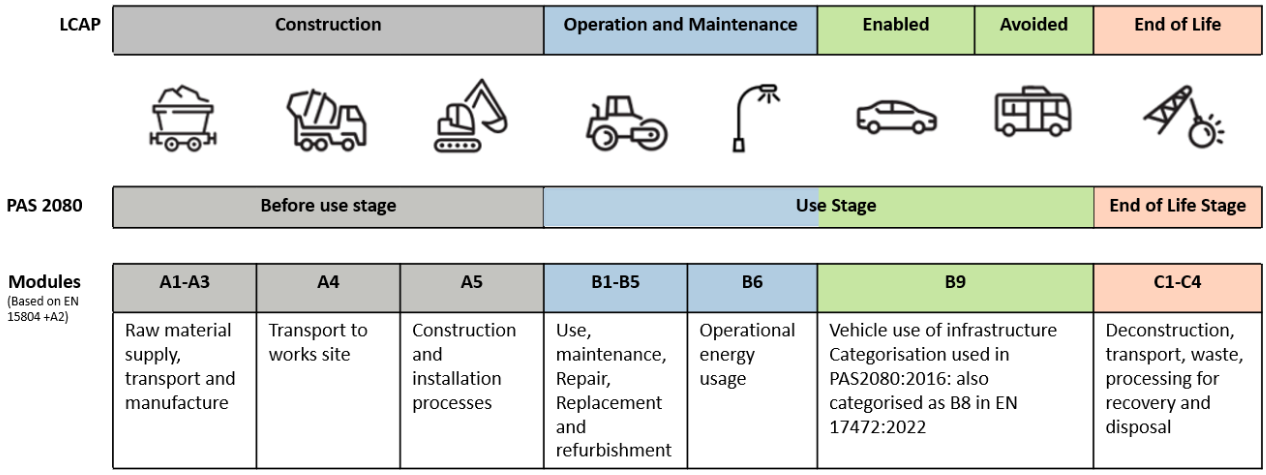
[1] Life cycle assessment of pavements: development of a calculator. Waka Kotahi NZ Transport Agency research report 695.

and during implementation, construction and maintenance, carbon emissions estimates should move from PEET to a more detailed or specific assessment tool, such as LCAP, for pavement designs.

While the emissions factors/pavement profiles used in PEET and LCAP have been aligned, the focus of the LCAP tool is for assessing GHG emissions of pavement design options for construction and operations and maintenance activities. The pavement calculations in the LCAP tool will provide more accurate and detailed GHG emissions results than PEET. LCAP provides the user with opportunities to simulate different scenarios to compare the whole-of-life impacts of pavement construction and operations and maintenance activities to enable a comparative assessment of available technologies and treatments.



| A1-A3 | A4 | A5 | B1-B5 | B6 | B9 | C1-C4 |
|---|---|---|---|---|---|---|
| Raw material supply, transport and manufacture | Transport to works site | Construction and installation processes | Use, maintenance, Repair, Replacement and refurbishment | Operational energy usage | Vehicle use of infrastructure Categorisation used in PAS2080:2016: also categorised as B8 in EN 17472:2022 | Deconstruction, transport, waste, processing for recovery and disposal |

*Figure 1: LCAP alignment with carbon management methods*

## 1.3 Version 2 updates

Updates to LCAP version 2 (LCAP v2) include the incorporation of two new tabs – LookUpTables and Change Log – to improve functionality and track changes.

In addition, this updated version allows for the inclusion of concrete road construction and foam bitumen stabiliser. Emission factors have also been updated to align with the factors in PEET, where relevant, noting the tool will continue to be updated to align with PEET and other sources of data and to improve functionality.

Changes between version 1 and version 2 are described in Appendix B.

## 1.4 Limitations

LCAP is not a replacement for detailed LCA tools or certified to international standards.

# 2 Glossary

The following is a list of terms that are used in the tool.

| Term | Definition |
|---|---|
| AADT | Annual average daily traffic |
| Annual traffic growth rate (%) | The percentage positive variation of traffic within a year |
| Asphalt (AC) | Asphalt concrete |
| Asphalt (EMOGPA) | Epoxy modified open graded porous asphalt |
| Asphalt (epoxy SMA) | Epoxy asphalt |
| Asphalt OGPA | Open-graded porous asphalt |
| Carbon emissions | GHG emissions expressed as carbon dioxide equivalents (CO2-e) |
| Charging efficiency of EVs | The proportion of electrical energy stored in the electric vehicle (EV) battery during the charging process |
| Embodied carbon | GHG emissions associated with extracting and processing construction raw materials, and manufacturing components |
| Environmental discount rate (%) | An environmental discount applied to the remaining areas of industry to adjust for efficiency improvements. |
| Heavy vehicles (%) | Percentage of the fleet which is heavy vehicle class |
| Increase in driving efficiency of vehicles (%/year) | The percentage positive change in driving efficiency, in terms of fuel consumption, within a year. For example, the expected improvements to the vehicle fleet efficiency over time. |
| IRI of surface at time of laying (m/km): | International Roughness Index, a roughness index most commonly obtained from measured longitudinal road profiles |
| LCA | Life cycle assessment |
| LCAP | Life Cycle Assessment of Pavements tool |
| Life extension $CO_2$ emissions | GHG emissions expressed as carbon dioxide equivalents (CO2-e) generated throughout the asset’s life, also referred to whole of life emissions |
| Primary scenario design life (years) | The design life is the time until pavement removal or full replacement – it includes any extension due to maintenance |
| RAP | Recycled asphalt |
| Reclaimed glass | Recovered glass from glass recycling |
| Recycled crushed concrete | Crushed concrete used as aggregate |
| Replacement $CO_2$ emissions | GHG emissions expressed as carbon dioxide equivalents (CO2-e) generated during replacement of materials as part of maintenance |
| Traffic flow rate | The number of vehicles passing a reference point per unit of time, for example vehicles per hour |
| Wearing course composition | The material mix that compose the upper layer of a roadway. Also known as a friction course or surface course. Wearing course material compositions are based on the average design mixes approved by Waka Kotahi |

# 3 LCAP tool structure

## 3.1 Tabs

The tool is an Excel spreadsheet with 13 tabs, which can be classified into 2 main categories:

1. **General users**: the purpose of these tabs is to give general background information to the user, allow for data entry and analysis. The tabs for these worksheets are coloured dark blue:
   - User Guide: This tab presents a general overview of the tool and provides for some initial high-level directions on how to use the tool.
   - Data Entry: The majority of the user interface and data input occurs in this worksheet. In this tab the user enters information surrounding the pavement composition, maintenance materials, structural pavement parameters and end-of-life treatments.
   - Maintenance & Traffic Delay: Information surrounding the maintenance schedule and the subsequent traffic delays.
   - Impact Analysis: This tab presents results for the major pavement life-cycle stages in both a table and graph. Other impacts indicators are also presented and compared at a project level to allow for a high-level trade-off assessment to be made.

   In general terms, LCAP layout for these tabs is consistent between worksheets, with:

   - descriptors on the left of the screen
   - user inputs and calculations in the middle, and
   - assumptions and notes on the right of the screen.

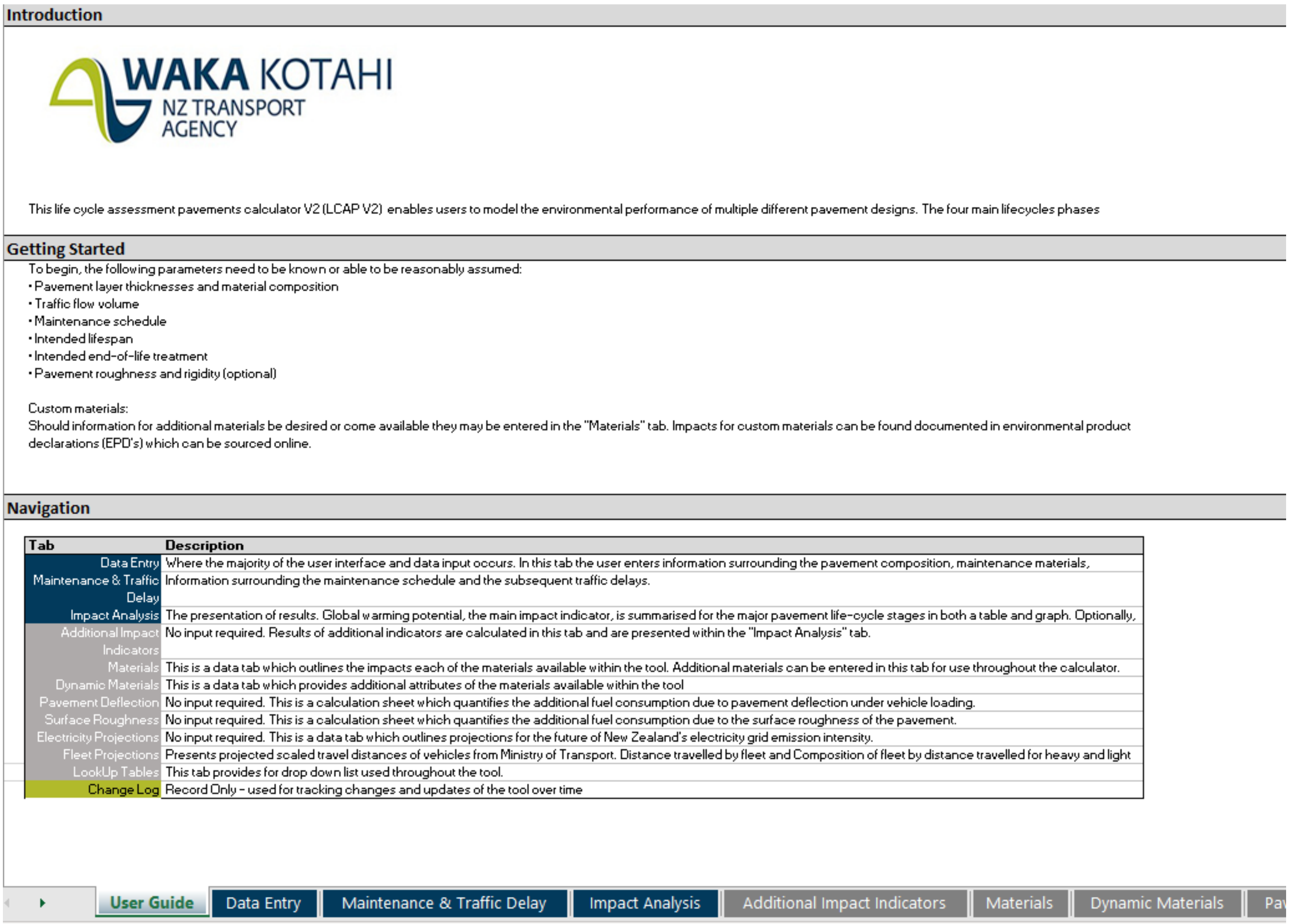
2. **Advanced users**: these worksheets provide background calculation, data support and lookups. LCAP applies emissions factors that are applicable to pavement design. Where possible these have been aligned with the Project Emissions Estimation Tool (PEET), noting that in the Materials tab there is a coding system to show where values are either aligned with PEET or derived from another source. The materials tab also allows user inputs for the addition of custom materials.

   Further lookup tabs are not intended to be edited by users but provide critical inputs for the Tool and calculations. The tabs for these worksheets are coloured grey:

   - Additional Impact Indicators: No input required. Results of additional indicators are calculated in this tab and are presented within the "Impact Analysis" tab.
   - Materials: This is a data tab which outlines the impacts each of the materials available within the tool. Additional materials can be entered in this tab for use throughout the calculator.
   - Dynamic Materials: This is a data tab which provides additional attributes of the materials available within the tool.
   - Pavement Deflection: No input required. This is a calculation sheet which quantifies the additional fuel consumption due to pavement deflection under vehicle loading.
   - Surface Roughness: No input required. This is a calculation sheet which quantifies the additional fuel consumption due to the surface roughness of the pavement.
   - Electricity projections: No input required. This is a data tab which outlines projections for the future of New Zealand's electricity grid emission intensity.
   - Fleet Projection: Presents projected scaled travel distances of vehicles from Ministry of Transport. Distance travelled by fleet and Composition of fleet by distance travelled for heavy and light vehicles.
   - Look Up Tables: This tab provides for drop down list used throughout the tool.

Additionally, the Change Log: the final tab in the LCAP tool, coloured green, is used for tracking changes and updates of the tool over time.

Figure 2 shows a general overview of the LCAP tool. Blue and grey tabs can be seen at the bottom of the screenshot.



**Introduction**

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This life cycle assessment pavements calculator V2 (LCAP V2) enables users to model the environmental performance of multiple different pavement designs. The four main lifecycles phases

**Getting Started**

To begin, the following parameters need to be known or able to be reasonably assumed:
- Pavement layer thicknesses and material composition
- Traffic flow volume
- Maintenance schedule
- Intended lifespan
- Intended end-of-life treatment
- Pavement roughness and rigidity (optional)

Custom materials:
Should information for additional materials be desired or come available they may be entered in the "Materials" tab. Impacts for custom materials can be found documented in environmental product declarations (EPD's) which can be sourced online.

**Navigation**

| Tab | Description |
|---|---|
| Data Entry | Where the majority of the user interface and data input occurs. In this tab the user enters information surrounding the pavement composition, maintenance materials, |
| Maintenance & Traffic Delay | Information surrounding the maintenance schedule and the subsequent traffic delays. |
| Impact Analysis | The presentation of results. Global warming potential, the main impact indicator, is summarised for the major pavement life-cycle stages in both a table and graph. Optionally, |
| Additional Impact Indicators | No input required. Results of additional indicators are calculated in this tab and are presented within the "Impact Analysis" tab. |
| Materials | This is a data tab which outlines the impacts each of the materials available within the tool. Additional materials can be entered in this tab for use throughout the calculator. |
| Dynamic Materials | This is a data tab which provides additional attributes of the materials available within the tool |
| Pavement Deflection | No input required. This is a calculation sheet which quantifies the additional fuel consumption due to pavement deflection under vehicle loading. |
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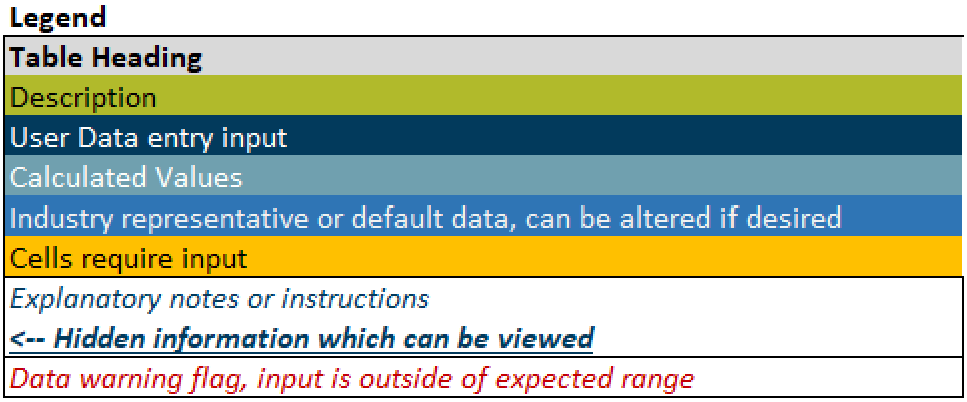
| Electricity Projections | No input required. This is a data tab which outlines projections for the future of New Zealand's electricity grid emission intensity. |
| Fleet Projections | Presents projected scaled travel distances of vehicles from Ministry of Transport. Distance travelled by fleet and Composition of fleet by distance travelled for heavy and light |
| LookUp Tables | This tab provides for drop down list used throughout the tool. |
| Change Log | Record Only - used for tracking changes and updates of the tool over time |

*Figure 2: General overview of LCAP tool*

## 3.2 Workbook legend

The workbook uses a colour-coded legend, shown in Figure 3, which applies to the entire worksheet (regardless of the tab you are on). In this context, green cells are used to provide a description of a specific element. Dark-blue cells are used to enter data by the user, while pale-blue cells are used to provide calculated values. Bright-blue cells denote an industry representative or default value and can be altered if desired.

Yellow cells provide for additional input if needed. Non-colour-coded cells are either explanatory notes or guiding instructions for users. Text in red identifies a warning flag, where input is outside of expected range.

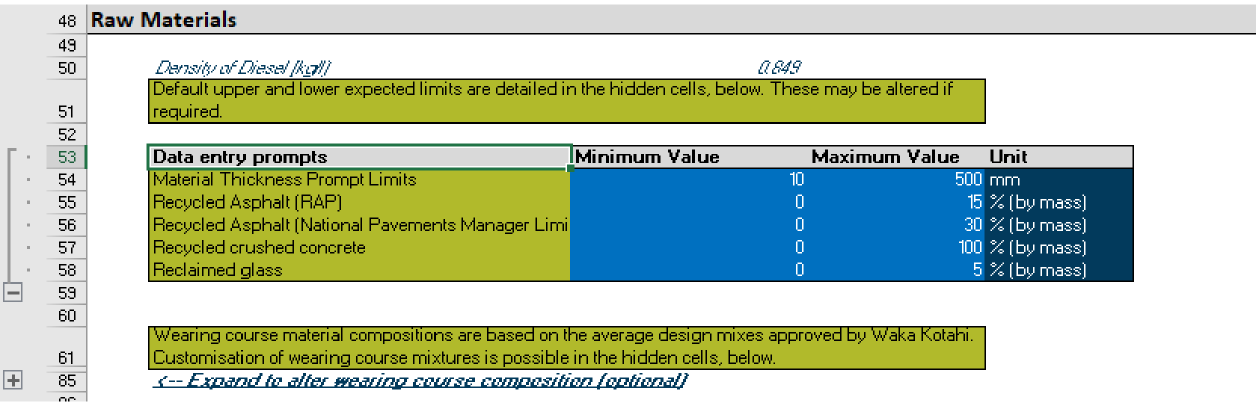


**Legend**

| **Table Heading** |
|---|
| Description |
| User Data entry input |
| Calculated Values |
| Industry representative or default data, can be altered if desired |
| Cells require input |
| *Explanatory notes or instructions* |
| ***<-- Hidden information which can be viewed*** |
| *Data warning flag, input is outside of expected range* |

*Figure 3: Workbook legend*

In addition, the tool has hidden rows that will only become visible when expanded using the plus buttons on the left of the screen. This is presented in Figure 4.



**Raw Materials**

*Density of Diesel [kg/l]* *0.849*

Default upper and lower expected limits are detailed in the hidden cells, below. These may be altered if required.

| Data entry prompts | Minimum Value | Maximum Value | Unit |
|---|---|---|---|
| Material Thickness Prompt Limits | 10 | 500 | mm |
| Recycled Asphalt (RAP) | 0 | 15 | % (by mass) |
| Recycled Asphalt (National Pavements Manager Limi | 0 | 30 | % (by mass) |
| Recycled crushed concrete | 0 | 100 | % (by mass) |
| Reclaimed glass | 0 | 5 | % (by mass) |

Wearing course material compositions are based on the average design mixes approved by Waka Kotahi. Customisation of wearing course mixtures is possible in the hidden cells, below.

*<-- Expand to alter wearing course composition (optional)*

*Figure 4: Worksheet buttons*

# 4 Using LCAP

This and the following sections provide step by step instructions on using the LCAP tool. For technical support and updates on LCAP, email environment@nzta.govt.nz with 'LCAP tool' in the subject line and you will be added to the mailing list.

## 4.1 Getting started

Download the LCAP tool from the Waka Kotahi website: Life Cycle Analysis Pavements (LCAP) tool.

To effectively use this tool, the following parameters need to be known or reasonably assumed:

1. pavement layer thicknesses and material composition
2. traffic flow rate
3. maintenance schedule
4. intended lifespan
5. intended end-of-life treatment
6. pavement roughness and rigidity (optional).

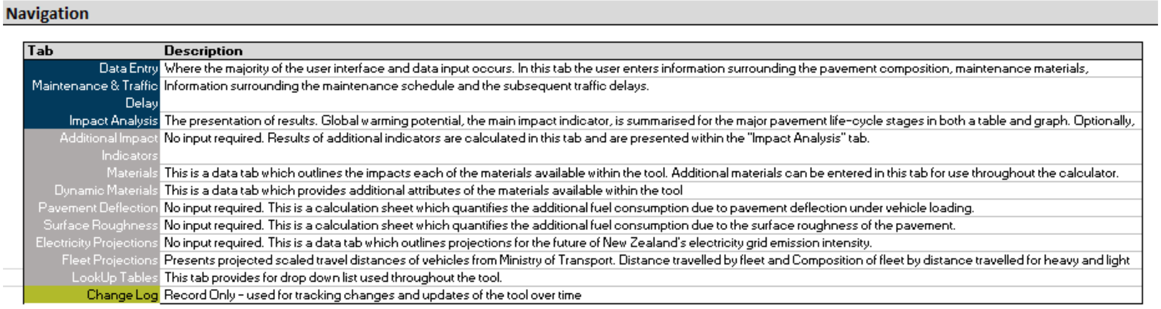
## 4.2 Navigation

In general terms, the LCAP tool follows a data entry/analysis pattern where, after reading the information in the User Guide tab, users load information in the Data Entry and Maintenance & Traffic Delay tabs. Users can then review the whole of life carbon emissions in the Impact Analysis tab. The majority of the user interface and data input occurs within these tabs. Sections within each of these tabs have been numbered to facilitate understanding and use of the tool. These numbers appear on the left-hand side of each section.

## 4.3 User Guide

The tool will open with the User Guide tab, this provides useful information on getting started, including the types of information/design parameters you will need to utilise within the tool.

The User Guide worksheet contains some important information on the tool structure, the data used in the tool, cell types, important units and definitions, as shown in Figure 5.



**Navigation**

| Tab | Description |
|---|---|
| Data Entry | Where the majority of the user interface and data input occurs. In this tab the user enters information surrounding the pavement composition, maintenance materials, |
| Maintenance & Traffic Delay | Information surrounding the maintenance schedule and the subsequent traffic delays. |
| Impact Analysis | The presentation of results. Global warming potential, the main impact indicator, is summarised for the major pavement life-cycle stages in both a table and graph. Optionally, |
| Additional Impact Indicators | No input required. Results of additional indicators are calculated in this tab and are presented within the "Impact Analysis" tab. |
| Materials | This is a data tab which outlines the impacts each of the materials available within the tool. Additional materials can be entered in this tab for use throughout the calculator. |
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| LookUp Tables | This tab provides for drop down list used throughout the tool. |
| Change Log | Record Only - used for tracking changes and updates of the tool over time |

*Figure 5: General overview User Guide tab*

## 4.4 Data Entry

To begin entering information, select the Data Entry tab. The Data Entry tab is intended to input parameters regarding a designed pavement's construction and end-of-life treatment.

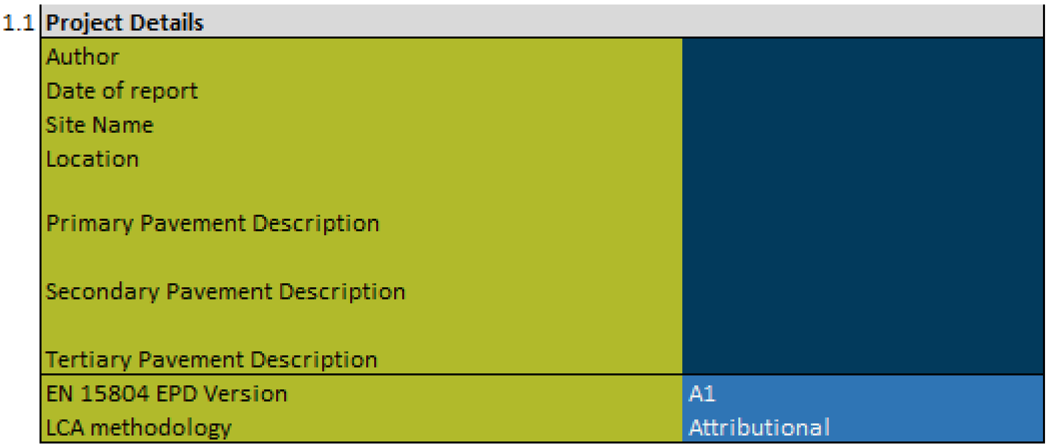
In this tab you will fills in the basic project details (including Project Details, Traffic Parameters and Pavement Parameters) before moving onto the data inputs for each scenario, beginning with raw materials and scrolling down the worksheet to complete: Maintenance Schedule & Induced Traffic Delay, Roughness Induced Pavement Vehicle Interactions, Deflection Induced Pavement Vehicle Interactions, and Replacement and End of Life Treatment.

### Project Details (1)

*Project Details (1.1)*

This information is primarily for reference. None of these fields contribute to the final calculation; however, completion of the Project Details section is recommended to provide context and support communication of the model results.

Specify up to 3 different scenarios of pavement layouts (primary, secondary and tertiary pavement description), as seen in Figure 6.

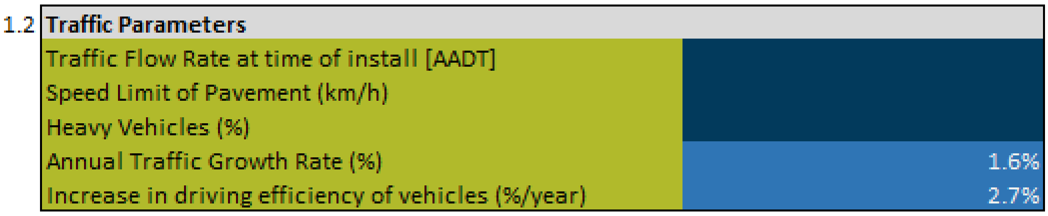


| 1.1 | Project Details | |
|---|---|---|
| | Author | |
| | Date of report | |
| | Site Name | |
| | Location | |
| | Primary Pavement Description | |
| | Secondary Pavement Description | |
| | Tertiary Pavement Description | |
| | EN 15804 EPD Version | A1 |
| | LCA methodology | Attributional |

*Figure 6: Project Details*

*Traffic Parameters (1.2)*

Traffic Parameters are the first set of variables that will cause a notable change in scenario emissions. They are shown in Figure 7.



| 1.2 | Traffic Parameters | |
|---|---|---|
| | Traffic Flow Rate at time of install [AADT] | |
| | Speed Limit of Pavement (km/h) | |
| | Heavy Vehicles (%) | |
| | Annual Traffic Growth Rate (%) | 1.6% |
| | Increase in driving efficiency of vehicles (%/year) | 2.7% |

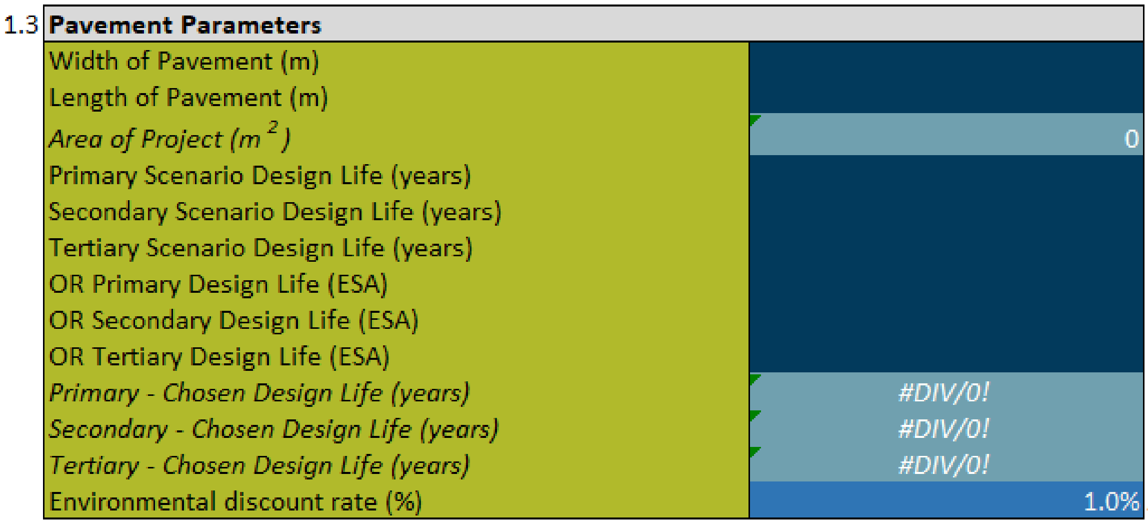
Figure 7: Traffic Parameters

The traffic flow rate at time of install (AADT), in conjunction with speed limit of pavement (km/h) and heavy vehicles (%), will be used in maintenance delay emissions calculations as well as roughness and deflection-induced emissions calculations. Depending on the selected timeframe of the project (data entered in the Impact Analysis tab) and maintenance analysis, the traffic specified for year 0 (the current year of the analysis) can grow each year based on the specified annual traffic growth rate considered.

The increase in the driving efficiency of vehicles factors in the expected improvements to the vehicle fleet efficiency as inefficient engines are phased out over time. The default of 2.7% is currently being revised in preparation for LCAP V3. Users have the option to set this to zero if they do not which to account for improvements in engine efficiency over time in their analysis. In Appendix C and D there are worked examples of how parameters are used to simulate an arterial local road. The traffic parameters in Figure 7 are from an arterial local road.

### *Pavement Parameters (1.3)*

This section allows you to specify pavement parameters, such as the dimensions and expected life span of each scenario being considered.



| 1.3 | Pavement Parameters | |
|---|---|---|
| | Width of Pavement (m) | |
| | Length of Pavement (m) | |
| | *Area of Project ($m^2$)* | 0 |
| | Primary Scenario Design Life (years) | |
| | Secondary Scenario Design Life (years) | |
| | Tertiary Scenario Design Life (years) | |
| | OR Primary Design Life (ESA) | |
| | OR Secondary Design Life (ESA) | |
| | OR Tertiary Design Life (ESA) | |
| | *Primary - Chosen Design Life (years)* | *#DIV/0!* |
| | *Secondary - Chosen Design Life (years)* | *#DIV/0!* |
| | *Tertiary - Chosen Design Life (years)* | *#DIV/0!* |
| | Environmental discount rate (%) | 1.0% |

Figure 8: Pavement Parameters

This allows different expected life spans to be assigned to each, noting that the current LCAP tool requires all 3 scenarios to use the same dimensions. The design life is the time until pavement removal or full replacement, it includes any extension due to maintenance. If you've entered the design life has been entered in years, you must leave the 'OR' (ESA) options blank. The environmental discount rate (%) can be specified to the remaining areas of industry to adjust for efficiency improvements.

This data feeds into the Impact Analysis tab to show annualised carbon emissions under each scenario.

### Raw Materials (2)

The Manufacturing Emissions (2.4) section is the main module of the spreadsheet that considers the embodied emissions associated with building pavement infrastructure. The initial 3 subsections (hidden by default): Density of Diesel (2.1), Wearing Course Composition (2.2) and Energy Inputs (2.3), can be expanded for general background calculation and data support. These cells largely contain industry representative or default data that can be altered if you have more detailed, project-specific information.

### *Manufacturing Emissions (2.4)*

Manufacturing emissions include emissions associated with the diesel burned during the laying of pavements. An input is required for each of the scenarios, which will account for the various machinery and energy used to lay the specified pavement. See Figure 9.

| 2.4 | **Manufacturing Emissions** | **- Scenario 1** | **- Scenario 2** | **- Scenario 3** |
|---|---|---|---|---|
| | Diesel Combusted During Production (litres/m$^2$) | 2.15 | 1.44 | 2.15 |

*Figure 9: Manufacturing Emissions*

Within this tab, Table 1 presents some default values based on different pavement types (see below). Note that these values have yet to be verified and are intended to be indicative only.

*Table 1: Defaults for Manufacturing Emissions*

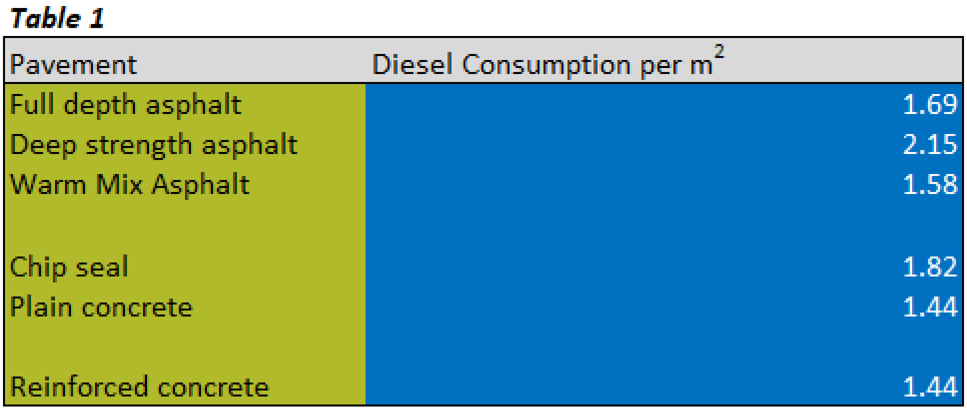


***Table 1***

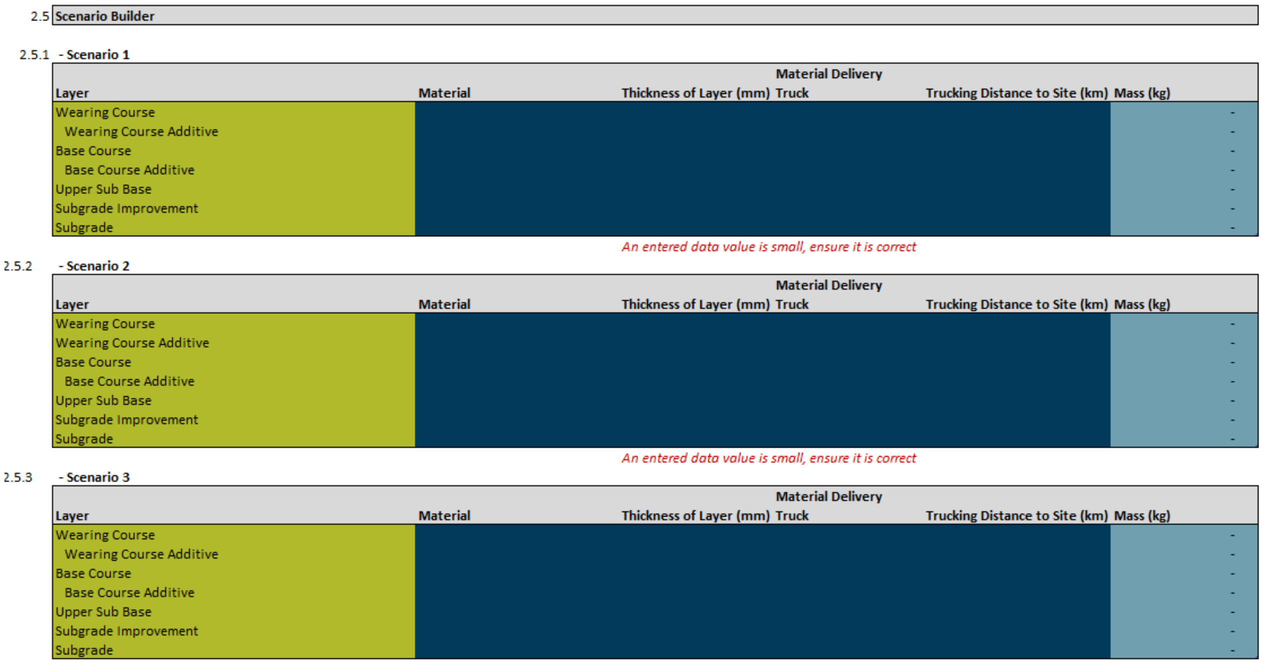
| Pavement | Diesel Consumption per m$^2$ |
|---|---|
| Full depth asphalt | 1.69 |
| Deep strength asphalt | 2.15 |
| Warm Mix Asphalt | 1.58 |
| Chip seal | 1.82 |
| Plain concrete | 1.44 |
| Reinforced concrete | 1.44 |

### *Scenario Builder (scenarios 1–3) (2.5)*

In this module you can specify up to 3 cross sectional pavement layouts, including details on:

- material
- thickness of layer (mm)
- truck (vehicle used for delivery of the material)
- trucking distance to site (km) (transport distance from quarry to site).

This is shown in Figure 10.



2.5 **Scenario Builder**

2.5.1 **- Scenario 1**

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | | | | | - |
| Wearing Course Additive | | | | | - |
| Base Course | | | | | - |
| Base Course Additive | | | | | - |
| Upper Sub Base | | | | | - |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

*An entered data value is small, ensure it is correct*

2.5.2 **- Scenario 2**

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | | | | | - |
| Wearing Course Additive | | | | | - |
| Base Course | | | | | - |
| Base Course Additive | | | | | - |
| Upper Sub Base | | | | | - |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

*An entered data value is small, ensure it is correct*

2.5.3 **- Scenario 3**

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | | | | | - |
| Wearing Course Additive | | | | | - |
| Base Course | | | | | - |
| Base Course Additive | | | | | - |
| Upper Sub Base | | | | | - |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

*Figure 10: Scenario Builder input*

See Appendix C and D for worked examples of how to build pavement layers for scenario testing.

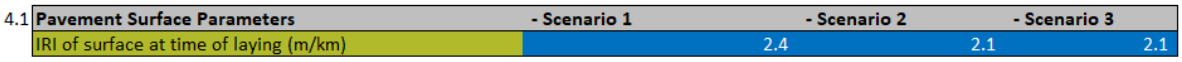
### Maintenance Schedule & Induced Traffic Delay (3)

This is a reference section that directs you to the Maintenance & Traffic Delay tab for further inputs.

### Roughness Induced Pavement Vehicle Interactions (4)

#### *Pavement Surface Parameters (4.1)*

This section provides for further inputs relative to roughness for each scenario considered and allows you to explore the effect on vehicle emissions of reducing pavement roughness. See Figure 11.



| 4.1 Pavement Surface Parameters | - Scenario 1 | - Scenario 2 | - Scenario 3 |
|---|---|---|---|
| IRI of surface at time of laying (m/km) | 2.4 | 2.1 | 2.1 |

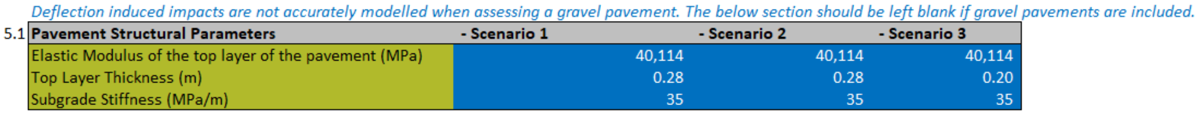
*Figure 11: Roughness induced pavement vehicle interactions*

### Deflection Induced Pavement Vehicle Interactions (5)

This section provides for general modelling of pavement. Note that deflection-induced impacts are not accurately modelled when assessing an unsealed or gravel pavement – because of this, the section should be left blank if these pavements are included.

#### *Pavement Structural Parameters (5.1)*

The tool includes variables that will determine the stiffness of the top surface of the pavement, which will affect the efficiency of the vehicles driving on them. The model used in the current LCAP tool indicates that the impact of deflection for heavy vehicles, across the range of weak to stiff pavements, is similar in magnitude of that for roughness of around 4 IRI for heavy vehicles. For light vehicles there is no predicted impact of deflections on emissions. This is shown in Figure 12.



*Deflection induced impacts are not accurately modelled when assessing a gravel pavement. The below section should be left blank if gravel pavements are included.*

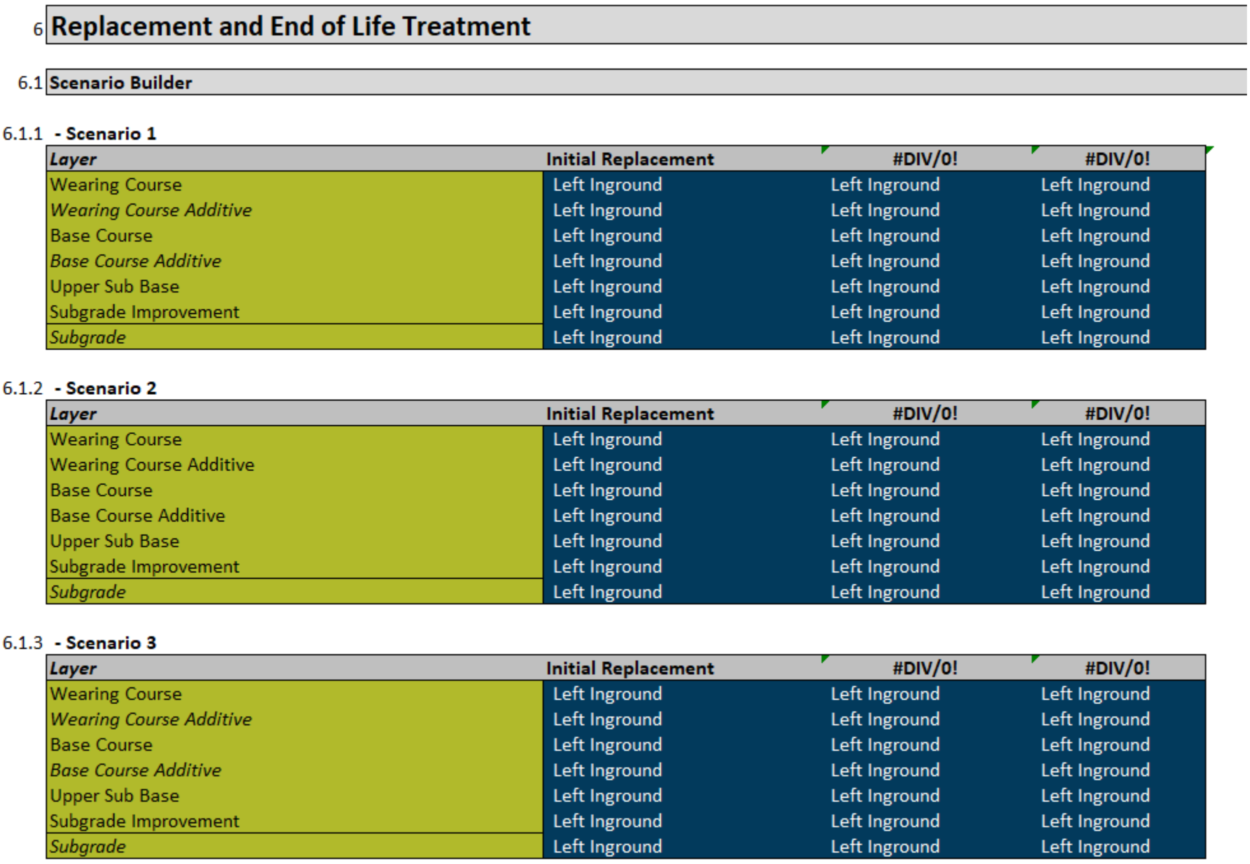
| 5.1 Pavement Structural Parameters | - Scenario 1 | - Scenario 2 | - Scenario 3 |
|---|---|---|---|
| Elastic Modulus of the top layer of the pavement (MPa) | 40,114 | 40,114 | 40,114 |
| Top Layer Thickness (m) | 0.28 | 0.28 | 0.20 |
| Subgrade Stiffness (MPa/m) | 35 | 35 | 35 |

*Figure 12: Pavement Structural Parameters*

**Note:** Both the models for roughness and deflection and their interactions with vehicles are unchanged from the initial release of LCAP v1 and have yet to be reviewed and updated. It is expected that by the time LCAP v3 is released both models will have been reviewed and calibrated against the New Zealand vehicle operating costs model (NZVOC) and the highway development and management model version 4 (HDM-4). It is also expected that texture induced vehicle emissions will be included in v3. It should be noted that the deflection parameters used in the model are still not well understood and that this module should be used with caution or disabled in the Impact Analysis tab.

### Replacement and End of Life Treatment (6)

This section provides alternatives for initial pavement replacement, considering either leaving or removing the material from site. This section allows you to consider recycling options on site and at recycling facilities. See Figure 13.



6 **Replacement and End of Life Treatment**

6.1 **Scenario Builder**

6.1.1 **- Scenario 1**

| *Layer* | Initial Replacement | #DIV/0! | #DIV/0! |
|---|---|---|---|
| Wearing Course | Left Inground | Left Inground | Left Inground |
| *Wearing Course Additive* | Left Inground | Left Inground | Left Inground |
| Base Course | Left Inground | Left Inground | Left Inground |
| *Base Course Additive* | Left Inground | Left Inground | Left Inground |
| Upper Sub Base | Left Inground | Left Inground | Left Inground |
| Subgrade Improvement | Left Inground | Left Inground | Left Inground |
| *Subgrade* | Left Inground | Left Inground | Left Inground |

6.1.2 **- Scenario 2**

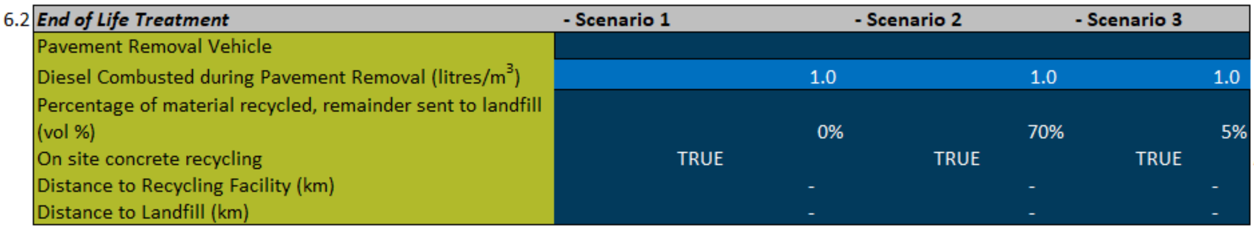
| *Layer* | Initial Replacement | #DIV/0! | #DIV/0! |
|---|---|---|---|
| Wearing Course | Left Inground | Left Inground | Left Inground |
| Wearing Course Additive | Left Inground | Left Inground | Left Inground |
| Base Course | Left Inground | Left Inground | Left Inground |
| Base Course Additive | Left Inground | Left Inground | Left Inground |
| Upper Sub Base | Left Inground | Left Inground | Left Inground |
| Subgrade Improvement | Left Inground | Left Inground | Left Inground |
| *Subgrade* | Left Inground | Left Inground | Left Inground |

6.1.3 **- Scenario 3**

| *Layer* | Initial Replacement | #DIV/0! | #DIV/0! |
|---|---|---|---|
| Wearing Course | Left Inground | Left Inground | Left Inground |
| *Wearing Course Additive* | Left Inground | Left Inground | Left Inground |
| Base Course | Left Inground | Left Inground | Left Inground |
| *Base Course Additive* | Left Inground | Left Inground | Left Inground |
| Upper Sub Base | Left Inground | Left Inground | Left Inground |
| Subgrade Improvement | Left Inground | Left Inground | Left Inground |
| *Subgrade* | Left Inground | Left Inground | Left Inground |

*Figure 13: Replacement and End of Life Treatment*

The final module allows you to consider the end-of-life option for the scenarios – what happens after 50 years. This is completed in the Data Entry tab, in the form shown in Figure 14.



| 6.2 *End of Life Treatment* | - Scenario 1 | - Scenario 2 | - Scenario 3 |
|---|---|---|---|
| Pavement Removal Vehicle | | | |
| Diesel Combusted during Pavement Removal (litres/m$^3$) | 1.0 | 1.0 | 1.0 |
| Percentage of material recycled, remainder sent to landfill (vol %) | 0% | 70% | 5% |
| On site concrete recycling | TRUE | TRUE | TRUE |
| Distance to Recycling Facility (km) | - | - | - |
| Distance to Landfill (km) | - | - | - |

*Figure 14: End of Life Treatment*

The current tool only allows for ‘removed’ or ‘left in ground’ as the options for end of life, and considers multiple ends of life to be reached before the project horizon ends. The tool is currently limited to only account for 3 end of life options for each scenario.

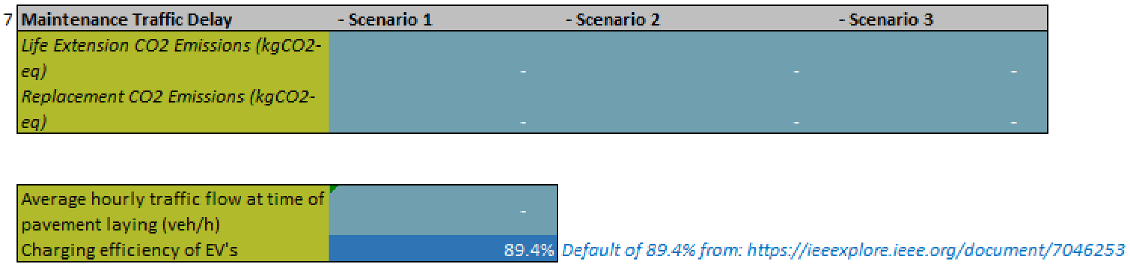
The tool also allows the distance to landfill and recycling facilities to be specified, as well as the expected percentage of materials that should be recycled. Note that the use of recycled materials may result in carbon savings; in future versions of this tool this will be included as an option that can be selected during scenario building in the raw materials sections, such as an option to specify RAP percentage in AC.

## 4.5 Maintenance & Traffic Delay

The Maintenance & Traffic Delay tab allows for inputs for maintenance schedule, key materials and associated traffic delays.

### Maintenance Traffic Delay (7)

A number of assumptions and limitations are detailed at the top of the tab before a summary of life extension $CO_2$-e and replacement $CO_2$-e emissions are displayed. See Figure 15.



| 7 Maintenance Traffic Delay | - Scenario 1 | - Scenario 2 | - Scenario 3 |
|---|---|---|---|
| *Life Extension CO2 Emissions (kgCO2-eq)* | - | - | - |
| *Replacement CO2 Emissions (kgCO2-eq)* | - | - | - |

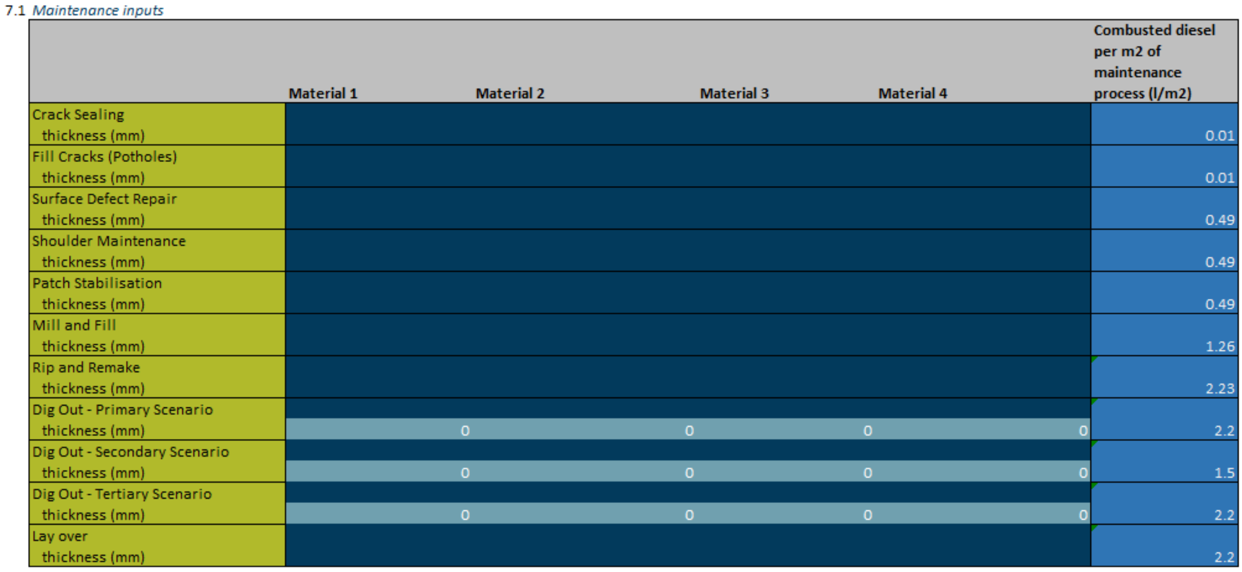
| | | |
|---|---|---|
| Average hourly traffic flow at time of pavement laying (veh/h) | - | |
| Charging efficiency of EV's | 89.4% | *Default of 89.4% from: https://ieeexplore.ieee.org/document/7046253* |

*Figure 15: Maintenance Traffic Delay summary*

In this analysis tab, you can select the type of work to be considered, materials, form of maintenance and area of work. Typical maintenance activity and materials (1-4) inputs are shown in Figure 16.

*Maintenance Inputs (7.1)*

In this section, select materials from dropdown menus for each applicable row. Once the material has been selected, you should input the thickness considered, in millimetres. See Figure 16.



7.1 *Maintenance inputs*

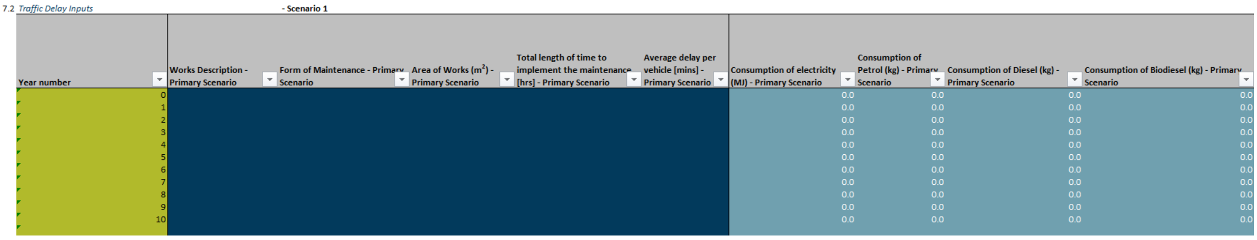
| | Material 1 | Material 2 | Material 3 | Material 4 | Combusted diesel per m2 of maintenance process (l/m2) |
|---|---|---|---|---|---|
| Crack Sealing<br>thickness (mm) | | | | | 0.01 |
| Fill Cracks (Potholes)<br>thickness (mm) | | | | | 0.01 |
| Surface Defect Repair<br>thickness (mm) | | | | | 0.49 |
| Shoulder Maintenance<br>thickness (mm) | | | | | 0.49 |
| Patch Stabilisation<br>thickness (mm) | | | | | 0.49 |
| Mill and Fill<br>thickness (mm) | | | | | 1.26 |
| Rip and Remake<br>thickness (mm) | | | | | 2.23 |
| Dig Out - Primary Scenario<br>thickness (mm) | 0 | 0 | 0 | 0 | 2.2 |
| Dig Out - Secondary Scenario<br>thickness (mm) | 0 | 0 | 0 | 0 | 1.5 |
| Dig Out - Tertiary Scenario<br>thickness (mm) | 0 | 0 | 0 | 0 | 2.2 |
| Lay over<br>thickness (mm) | | | | | 2.2 |

*Figure 16: Maintenance inputs*

*Traffic Delay Inputs (7.2)*

This section considers the selection of the primary scenario under the works description column. Once you have selected the type of work, you need to select the form of maintenance – either life extension or replacement.

You then need to establish the area of works (m²), considering this as the total annual total area of works for the provided maintenance process. Then select the total length of time to implement the maintenance (hrs), followed by the total length of time for the project where traffic may be disrupted and the average delay per vehicle (mins). This is shown in Figure 17.



7.2 *Traffic Delay Inputs* - Scenario 1

| Year number | Works Description - Primary Scenario | Form of Maintenance - Primary Scenario | Area of Works (m²) - Primary Scenario | Total length of time to implement the maintenance [hrs] - Primary Scenario | Average delay per vehicle [mins] - Primary Scenario | Consumption of electricity (MJ) - Primary Scenario | Consumption of Petrol (kg) - Primary Scenario | Consumption of Diesel (kg) - Primary Scenario | Consumption of Biodiesel (kg) - Primary Scenario |
|---|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 1 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 2 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 3 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 4 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 6 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 7 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 8 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 9 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| 10 | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |

*Figure 17: Maintenance and Impacts of Traffic Delay*

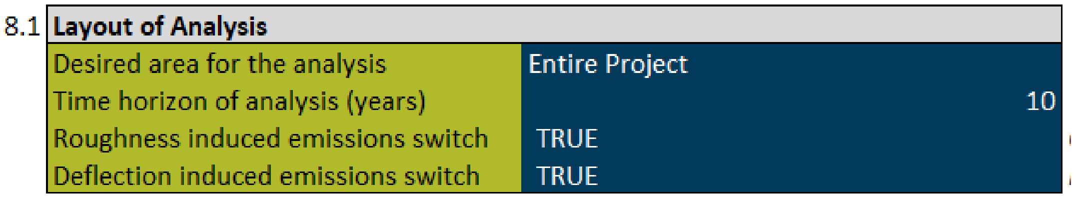
## 4.6 Impact Analysis

The Impact Analysis tab presents the results.

### Impact Analysis (8)

*Layout of Analysis (8.1)*

Initially you can select the area of assessment desired from a dropdown menu. Assessment can be done at entire project level, per m², or per km of lane. Once that has been defined, you must select the time horizon for analysis in years. Finally, this section considers a roughness and deflection switch to include or exclude those elements from the assessment by selecting true or false. This is shown in Figure 18.



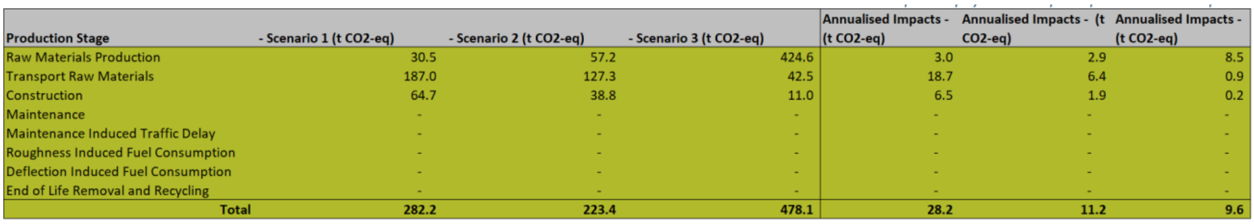
8.1 **Layout of Analysis**

| | |
|---|---|
| Desired area for the analysis | Entire Project |
| Time horizon of analysis (years) | 10 |
| Roughness induced emissions switch | TRUE |
| Deflection induced emissions switch | TRUE |

*Figure 18: Layout of analysis*

GHG emissions, expressed in $CO_2$-e, are the main indicator for the climate change impact category, and are summarised for the major pavement life-cycle stages in both a table and graph. Optionally, the impacts can be viewed at each individual process step. Selected nuisance factors and other impact indicators are also presented and compared at a project level to allow for a high-level trade-off assessment to be made, ensuring any benefits achieved by one environmental indicator are not being transferred to another (for example a decrease in global warming potential but a subsequent large increase in eutrophication potential).

This tab then goes into a detailed breakdown of each component (by production stage). This tab compares the input data to provide you with a detailed summary for the whole-of-life carbon emissions associated with each design scenario. See Figure 19.



| Production Stage | - Scenario 1 (t CO2-eq) | - Scenario 2 (t CO2-eq) | - Scenario 3 (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) |
|---|---|---|---|---|---|---|
| Raw Materials Production | 30.5 | 57.2 | 424.6 | 3.0 | 2.9 | 8.5 |
| Transport Raw Materials | 187.0 | 127.3 | 42.5 | 18.7 | 6.4 | 0.9 |
| Construction | 64.7 | 38.8 | 11.0 | 6.5 | 1.9 | 0.2 |
| Maintenance | - | - | - | - | - | - |
| Maintenance Induced Traffic Delay | - | - | - | - | - | - |
| Roughness Induced Fuel Consumption | - | - | - | - | - | - |
| Deflection Induced Fuel Consumption | - | - | - | - | - | - |
| End of Life Removal and Recycling | - | - | - | - | - | - |
| **Total** | **282.2** | **223.4** | **478.1** | **28.2** | **11.2** | **9.6** |

*Figure 19: Impact analysis example*

Note that in this example only the first 3 stages (materials production, transport and construction*)* are showing for each scenario. These represent the embodied carbon of an infrastructure project, or the carbon required to source and install a piece of infrastructure on the network. Appendix C provides a worked example for embodied carbon.

Appendix D provides a second worked example, focusing on other modules of LCAP, that shows whole-of-life pavement emissions.

**Note:** Available materials in the LCAP scenario builder are still under development, as is the user interface of the scenario builder itself. These updates will be part of the v3 release expected in mid-2024. Upcoming changes are listed in Appendix A.

# Appendix A: Upcoming changes with LCAP v3

Modules under review within LCAP v2 and plans for LCAP v3 (expected mid-2024) include:

- updating the user interface of the Data Entry tab to allow for more layers and inputs for additives and stabilisation instead of current rigid layer type definitions
- updating the Maintenance & Traffic Delay tab to allow for all materials
- reviewing the traffic delay, deflection and roughness induced carbon modules
- reviewing fleet and electricity projection modules
- reviewing density calculation of dynamic materials (currently estimated through mass balance proportioning)
- updating to new asphaltic concrete (AC) emission factors from recent New Zealand environmental product declarations (EPDs)
- updating format and structure of the materials and dynamic material tables to be more user-friendly
- adding texture-induced vehicle emissions.

# Appendix B: Change log between LCAP v1 and v2

| Date change recorded | Version | Change type | Change |
|---|---|---|---|
| Aug-23 | 2 | Bug fix | Dropdown lists changed to reference table in LookUpTables tab. |
| Aug-23 | 2 | Bug fix | Fixes to Maintenance & Traffic Delay tab. Cells show error if no material defined. Added 0 column into materials table to remedy. |
| Aug-23 | 2 | Emissions table change | Updated GWP A1 values to match against those in PEET. |
| Aug-23 | 2 | Materials added | Ability to construct concrete roads added. This includes adding lean cement (20Mpa cement) and surface concrete (50MPa concrete) into options. |
| Aug-23 | 2 | Materials added | Pure foam 3% water added into materials table. |
| Aug-23 | 2 | Bug fix | Fixes to Maintenance & Traffic Delay tab. Raw materials impacts table calling to wrong materials in table. Corrected. |
| Aug-23 | 2 | Materials added | All trucks added to emissions table. Added as material delivery truck option. |
| Aug-23 | 2 | Added tabs | Added Change Log tab to keep track of changes to versions. |
| Aug-23 | 2 | Added tabs | Added LookUpTables tab to store drop down list options. |
| Aug-23 | 2 | Bug fix | Fixed roughness output formula to only populate when roughness induced emissions flag is set to true. |
| Sep-23 | 2 | Emissions table change | Diesel combustion adjusted using PEET from 3.64kg CO2-e/unit to 3.036kg CO2-e/unit |
| Sep-23 | 2 | Emissions table change | Diesel combustion (vehicle) adjusted using PEET from 3.65kg CO2-e/unit to 3.036kg CO2-e/unit |
| Sep-23 | 2 | Emissions table change | Petrol combustion adjusted using PEET from 3.71kg CO2-e/unit to 3.109kg CO2-e/unit |
| Sep-23 | 2 | Emissions table change | Bio-diesel combustion adjusted using PEET from 0.483kg CO2-e/unit to 0.04kg CO2-e/unit |
| Sep-23 | 2 | Emissions table change | All trucks added from PEET (0.000135kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Foam bitumen (3% H2O) added from ISC (0.372kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Hydraulic lime added from PEET (0.8335kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Water adjusted using PEET from 0.000043kg CO2-e/unit to 0.000031 kgCO2e/unit |
| Sep-23 | 2 | Emissions table change | Aggregate added from PEET (0.00455kg CO2-e/unit) |

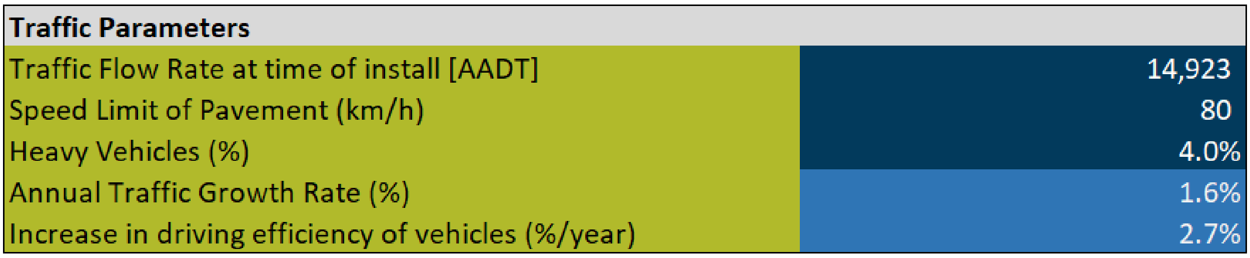
| | | | |
|---|---|---|---|
| Sep-23 | 2 | Emissions table change | Ballast added from PEET (0.00435kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Natural sand added from PEET (0.003875kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Sealing chip added from PEET (0.00452kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | RipRap added from PEET (0.004156kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Topsoil added from PEET (0.004156kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Basalt added from PEET (0.003875kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Portland cement added from PEET (0.945kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Recycled crushed concrete 2 added from PEET (0.000827kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Recycled crushed glass added from PEET (0.00246kg CO2-e/unit) |
| Sep-23 | 2 | Emissions table change | Aggregate (hard rock) adjusted using PEET (0.0038kg CO2-e/unit to 0.00455kg CO2-e/unit) |
| Sep-23 | 2 | Materials added | Epoxy chipseal added |
| Sep-23 | 2 | Materials added | Asphalt (epoxy SMA) added |
| Sep-23 | 2 | Materials added | Asphalt (EMOGPA) updated |
| Sep-23 | 2 | Value changed | Epoxy components adjusted to correct ratios. Correct ratios seen in Dynamic Materials tab cells AF2:AH5 |

# Appendix C: Worked example 1 – embodied carbon

This is a worked example for the main module of the spreadsheet that accounts for the embodied emissions associated with building pavement infrastructure.

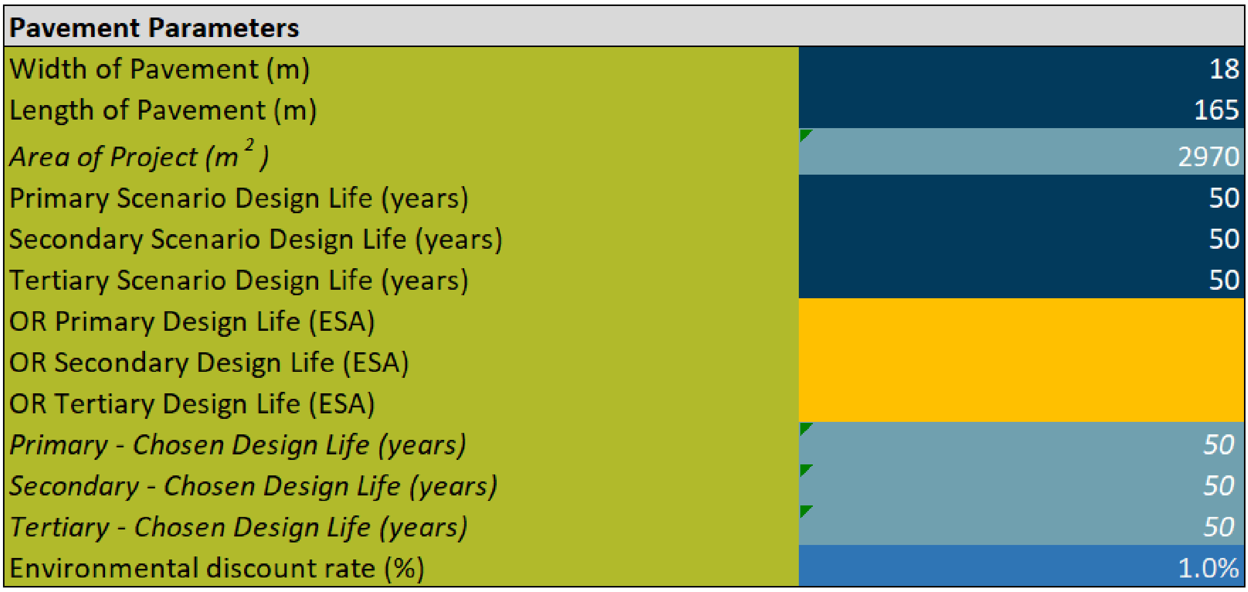
## C.1. Set up parameters

The following figures show the input parameters for traffic, pavement and manufacturing emissions that will be used for worked example 1.



| Traffic Parameters | |
|---|---|
| Traffic Flow Rate at time of install [AADT] | 14,923 |
| Speed Limit of Pavement (km/h) | 80 |
| Heavy Vehicles (%) | 4.0% |
| Annual Traffic Growth Rate (%) | 1.6% |
| Increase in driving efficiency of vehicles (%/year) | 2.7% |

*Figure A-1: Traffic parameters for worked example 1*



| Pavement Parameters | |
|---|---|
| Width of Pavement (m) | 18 |
| Length of Pavement (m) | 165 |
| *Area of Project ($m^2$)* | 2970 |
| Primary Scenario Design Life (years) | 50 |
| Secondary Scenario Design Life (years) | 50 |
| Tertiary Scenario Design Life (years) | 50 |
| OR Primary Design Life (ESA) | |
| OR Secondary Design Life (ESA) | |
| OR Tertiary Design Life (ESA) | |
| *Primary - Chosen Design Life (years)* | *50* |
| *Secondary - Chosen Design Life (years)* | *50* |
| *Tertiary - Chosen Design Life (years)* | *50* |
| Environmental discount rate (%) | 1.0% |

*Figure A-2: Pavement parameters for worked example 1*

| Manufacturing Emissions | - Scenario 1 | - Scenario 2 | - Scenario 3 |
|---|---|---|---|
| Diesel Combusted During Production (litres/$m^2$) | 1.69 | 1.69 | 1.44 |

*Figure A-3: Manufacturing emission assumptions for worked example 1*

## C.2. Scenario builder

In this module users will specify up to three cross-sectional pavement layouts, including details on:

- material type
- thickness
- transport vehicle
- transport distance (quarry to site).

- Scenario 1

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | Asphalt (AC) | 40 | Truck (7.5-16t) | 50 | 273,240 |
| Wearing Course Additive | | | | | - |
| Base Course | | | | | - |
| Base Course Additive | Foam Bitumen Stabilisation | 200 | Truck (7.5-16t) | 50 | 993,908 |
| Upper Sub Base | Aggregate (Hard Rock) | 400 | Truck (7.5-16t) | 50 | 2,019,600 |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

- Scenario 2

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | Asphalt (AC) | 40 | Truck (7.5-16t) | 50 | 273,240 |
| Wearing Course Additive | | | | | - |
| Base Course | Asphalt (AC) | 240 | Truck (7.5-16t) | 50 | 1,639,440 |
| Base Course Additive | | | | | - |
| Upper Sub Base | Aggregate (Hard Rock) | 360 | Truck (7.5-16t) | 50 | 1,817,640 |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

- Scenario 3

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | Concrete | 190 | Truck (7.5-16t) | 50 | 1,354,320 |
| Wearing Course Additive | | | | | - |
| Base Course | Concrete (Lean Mix) | 150 | Truck (7.5-16t) | 50 | 1,069,200 |
| Base Course Additive | | | | | - |
| Upper Sub Base | Aggregate (Hard Rock) | 260 | Truck (7.5-16t) | 50 | 1,312,740 |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

*Figure A-4: Scenario builder worked example 1.*

In the example in Figure A-4, 3 scenarios are considered. It should be noted that these have been designed to support the loading of a very high stress area (a cargo port access lane).

### Scenario 1

This is a typical thin surface asphalt surface with a 200mm foam bitumen stabilised basecourse and a 400mm granular subbase – this is expected to provide 10 years of life. Note that currently the embodied emissions and density of the various aggregate types (hard rock, alluvial and dredged) are set as the same and therefore can be used interchangeably for granular basecourse and subbase aggregate.

For advanced users who want to understand material assumptions have a look at the Materials tab, which contains all the lookups used to quantity mass and carbon content. The notes for foamed bitumen stabilisation states: '2.7% bitumen, 1% cement, 0.5% water, remainder aggregate. Bitumen must be heated to about 180$^{o}$C – ignore heating as assumed it will be done in situ and thus captured by onsite diesel use.'

### Scenario 2

Scenarios 2 explores another option where instead of a foamed bitumen stabilised basecourse, a structural asphaltic base course is used. This is expected to provide 20 years of life.

### Scenario 3

The final scenario uses a much thinner overall pavement depth; however, it uses a plain concrete surface as well as a lean mix basecourse. This is expected to give a design life of 50 years.

As this worked example is focused on the embodied emissions, we will skip past Maintenance Schedule & Induced Traffic Delay, Roughness Induced Pavement Vehicle Interactions, Deflection Induced Pavement

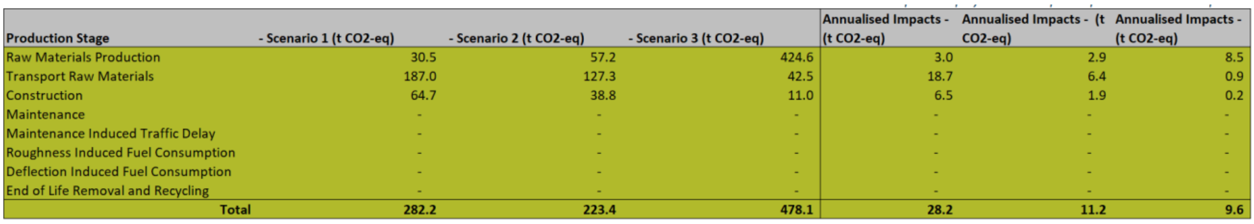
Vehicle Interactions, and Replacement and End of Life Treatment (see appendix D for a worked example including those) and move onto the Impact Analysis tab.

## C.3. Impact analysis

The Impact Analysis tab starts with an overall summary then goes into a detailed breakdown of each component (by production stage).

In this worked example we are looking at the carbon of the project as a whole (entire project), rather than per m$^2$ or by lane km, and have chosen a lifespan (time horizon of analysis) of 50 years which is the maximum life that any one scenario provides. See Layout of Analysis (rows 12–16 of the Impact Analysis tab).

Figure A-5 shows the output of the worked example (by production stage). Note that only the first 3 stages of production – raw materials production, transport raw materials and construction –are showing for each scenario. These represent the embodied carbon of an infrastructure project, or the carbon required to source and install a piece of infrastructure on the network.



| Production Stage | - Scenario 1 (t CO2-eq) | - Scenario 2 (t CO2-eq) | - Scenario 3 (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) |
|---|---|---|---|---|---|---|
| Raw Materials Production | 30.5 | 57.2 | 424.6 | 3.0 | 2.9 | 8.5 |
| Transport Raw Materials | 187.0 | 127.3 | 42.5 | 18.7 | 6.4 | 0.9 |
| Construction | 64.7 | 38.8 | 11.0 | 6.5 | 1.9 | 0.2 |
| Maintenance | - | - | - | - | - | - |
| Maintenance Induced Traffic Delay | - | - | - | - | - | - |
| Roughness Induced Fuel Consumption | - | - | - | - | - | - |
| Deflection Induced Fuel Consumption | - | - | - | - | - | - |
| End of Life Removal and Recycling | - | - | - | - | - | - |
| **Total** | **282.2** | **223.4** | **478.1** | **28.2** | **11.2** | **9.6** |

*Figure A-5: Impact analysis worked example 1*

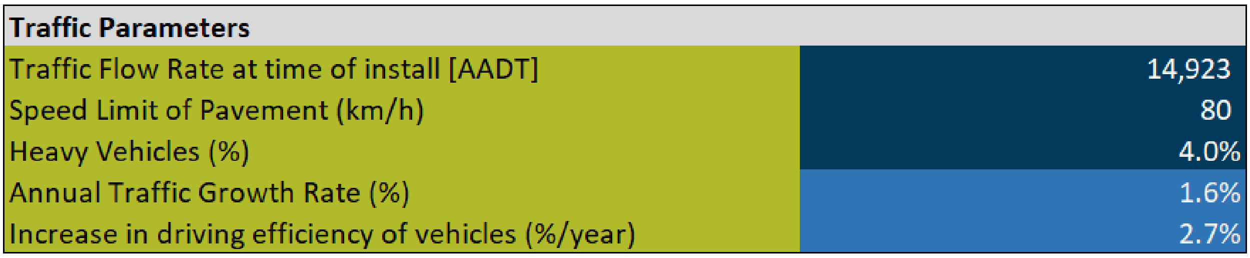
At a first glance we can see that that Scenario 3 produces the highest carbon of nearly 500t $CO_2$-e, more than double the other 2 scenarios. However, when we look at the annualised carbon emission across the entire time horizon of 50 years, scenario *3* shows the lowest emissions.

Scenario 3 has the lowest overall emissions, because the stronger pavement is only placed once in the 50-year period compared to the other 2 scenarios, where pavement is replaced multiple times. Note that this is a fictional scenario used for the 3 pavement designs and is not an endorsement for the use of the example pavement type, as economic and other considerations must also be evaluated.

# Appendix D: Worked example 2 – maintenance approaches

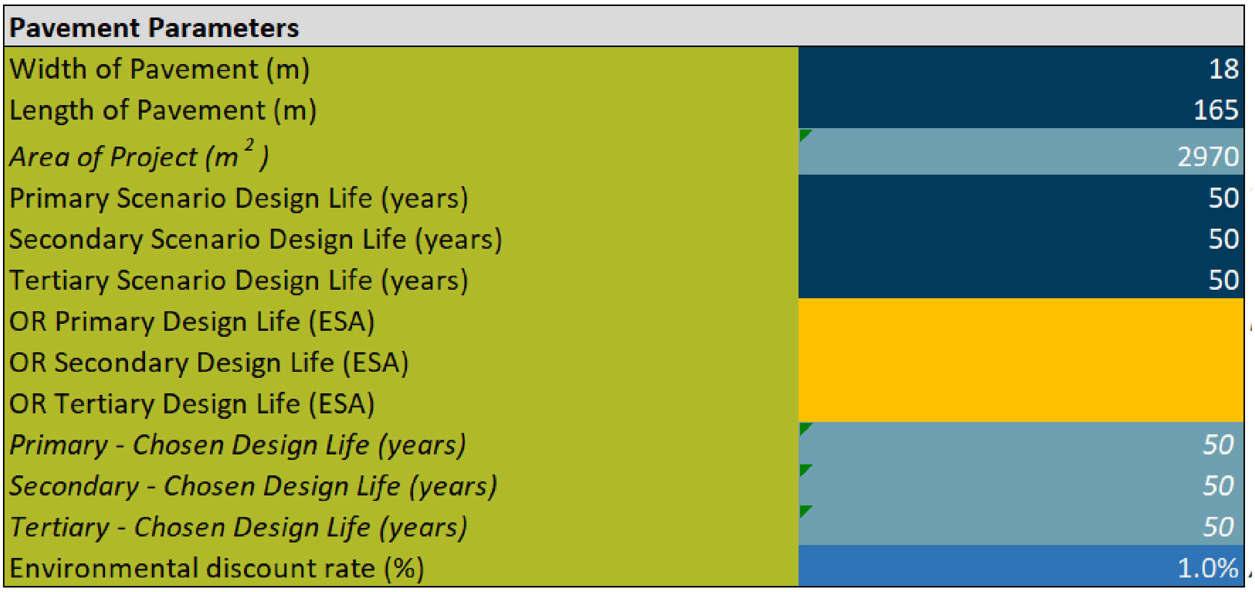
## D.1. Set up parameters

For our second worked example we will be focusing on the other modules of LCAP outside embodied carbon. This is why in the following figure the same pavement has been presented in triplicate. We have also added the traffic and pavement parameters used in this worked example.



| **Traffic Parameters** | |
|---|---|
| Traffic Flow Rate at time of install [AADT] | 14,923 |
| Speed Limit of Pavement (km/h) | 80 |
| Heavy Vehicles (%) | 4.0% |
| Annual Traffic Growth Rate (%) | 1.6% |
| Increase in driving efficiency of vehicles (%/year) | 2.7% |

*Figure A-6: Traffic parameters for worked example 2*



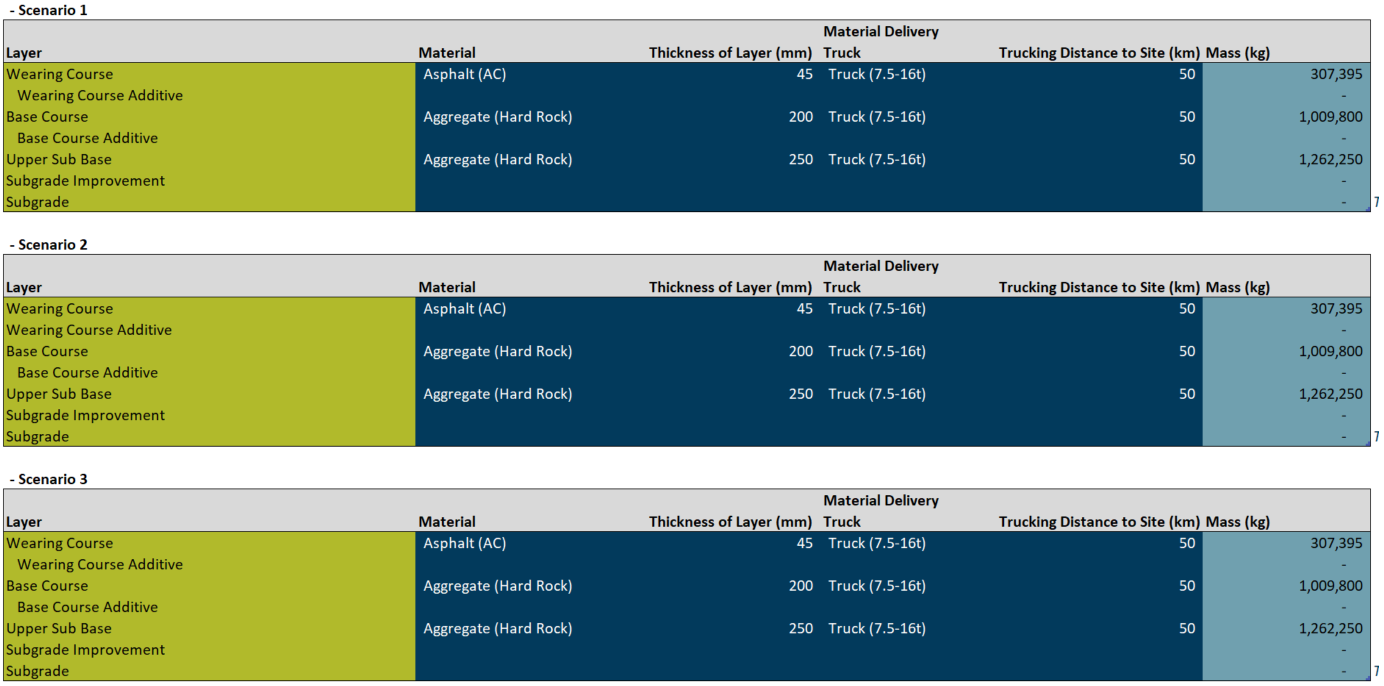
| **Pavement Parameters** | |
|---|---|
| Width of Pavement (m) | 18 |
| Length of Pavement (m) | 165 |
| *Area of Project ($m^2$)* | 2970 |
| Primary Scenario Design Life (years) | 50 |
| Secondary Scenario Design Life (years) | 50 |
| Tertiary Scenario Design Life (years) | 50 |
| OR Primary Design Life (ESA) | |
| OR Secondary Design Life (ESA) | |
| OR Tertiary Design Life (ESA) | |
| *Primary - Chosen Design Life (years)* | *50* |
| *Secondary - Chosen Design Life (years)* | *50* |
| *Tertiary - Chosen Design Life (years)* | *50* |
| Environmental discount rate (%) | 1.0% |

*Figure A-7: Pavement parameters for worked example 2*

| **Manufacturing Emissions** | **- Scenario 1** | **- Scenario 2** | **- Scenario 3** |
|---|---|---|---|
| Diesel Combusted During Production (litres/$m^2$) | 1.69 | 1.69 | 1.69 |

*Figure A-8: Manufacturing emission assumptions for worked example 2*

# D.2. Scenario builder



- Scenario 1

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | Asphalt (AC) | 45 | Truck (7.5-16t) | 50 | 307,395 |
| Wearing Course Additive | | | | | - |
| Base Course | Aggregate (Hard Rock) | 200 | Truck (7.5-16t) | 50 | 1,009,800 |
| Base Course Additive | | | | | - |
| Upper Sub Base | Aggregate (Hard Rock) | 250 | Truck (7.5-16t) | 50 | 1,262,250 |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

- Scenario 2

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | Asphalt (AC) | 45 | Truck (7.5-16t) | 50 | 307,395 |
| Wearing Course Additive | | | | | - |
| Base Course | Aggregate (Hard Rock) | 200 | Truck (7.5-16t) | 50 | 1,009,800 |
| Base Course Additive | | | | | - |
| Upper Sub Base | Aggregate (Hard Rock) | 250 | Truck (7.5-16t) | 50 | 1,262,250 |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

- Scenario 3

| Layer | Material | Thickness of Layer (mm) | Material Delivery Truck | Trucking Distance to Site (km) | Mass (kg) |
|---|---|---|---|---|---|
| Wearing Course | Asphalt (AC) | 45 | Truck (7.5-16t) | 50 | 307,395 |
| Wearing Course Additive | | | | | - |
| Base Course | Aggregate (Hard Rock) | 200 | Truck (7.5-16t) | 50 | 1,009,800 |
| Base Course Additive | | | | | - |
| Upper Sub Base | Aggregate (Hard Rock) | 250 | Truck (7.5-16t) | 50 | 1,262,250 |
| Subgrade Improvement | | | | | - |
| Subgrade | | | | | - |

*Figure A-9: Scenario builder worked example 2*

The example depicts a typical thin surface asphalt concrete pavement. Let us assume this is for a road with the traffic properties described in the figure above and is reaching its end of life and so will require some form of intervention to either extend its life or a full replacement. Usually at this stage pavement engineers will undertake a project feasibility report (PFR) to look through the available options and work out the most cost-effective solution through an NPV (net present value) analysis.

For the worked example, let us assume that at the point of intervention the IRI of the pavement is 5, which is considered poor and suggests serious defects. In addition, let us assume that any pavement rehabilitation will result in a reduced IRI of either 4 or 3. This will effectively calculate the vehicle emissions associated with those 3 roughness measures using the traffic properties specified across the project lifetime.

For now, the default deflection parameters will be kept as the default since this module is still under review (revised module to be released with LCAP3). The next step is to identify the different options to compare life extension vs replacement. This is done in the Maintenance & Traffic Delay tab.

# D.3. Building maintenance schedules

We will be modelling a different maintenance option for each scenario.

### Scenario 1: Existing maintenance strategy

Year 1: This will begin with a full area asphalt resurface (mill and fill) followed by a 17% dig out replacing like-for-like pavement to fix the existing pavement failures.

The strategy for year 1 will be applied every 7 years, where it is expected that the pavement will return to a similar condition. It is expected that the mill and fill will take 4 hours to implement and will cause an average delay of 5 minutes per vehicle, and the dig out will cause a similar delay over 8 hours of implementation.

**Scenario 2: Rehabilitation**

Year 1: This will begin with a rehab (dig out) replacing the current pavement with a similar pavement, but with a 125mm basecourse of structural AC. It is assumed that the dig out will be completed in 16 hours and cause a delay of 10 minutes per vehicle.

After 15 years a resurface of the asphaltic concrete will occur followed by another at year 30.

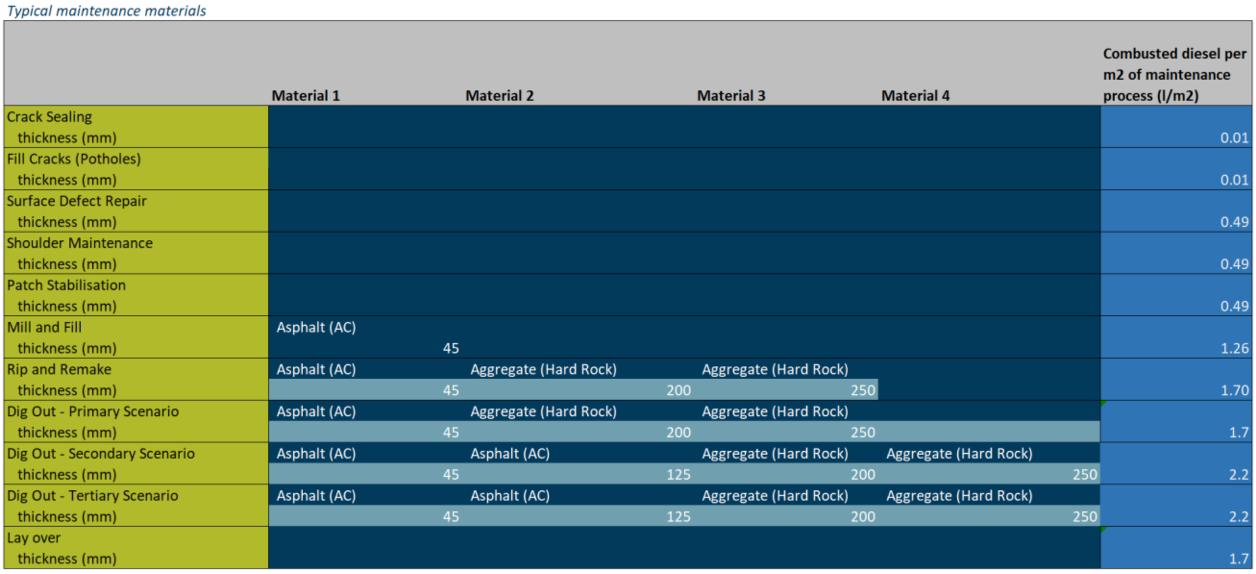
**Scenario 3: Deferred rehabilitation and holding maintenance**

Year 1: This begins with an initial asphalt mill and fill resurface followed by a like-for-like pavement dig out for 16% of the area to treat current failures.

This will be followed by 4 years of resurface and like-for-like dig outs for 2.5% of the area as patch repair.

At 5 years there is a rehab (dig out), replacing the current pavement with a similar pavement but with a 125mm basecourse of structural AC. It is assumed that the dig out will be completed in 16 hours and cause a delay of 10 minutes per vehicle. At this point similar assumptions as scenario 2 take place.

To model the above scenarios the following treatments, need to be created in the Maintenance & Traffic Delay tab.



*Typical maintenance materials*

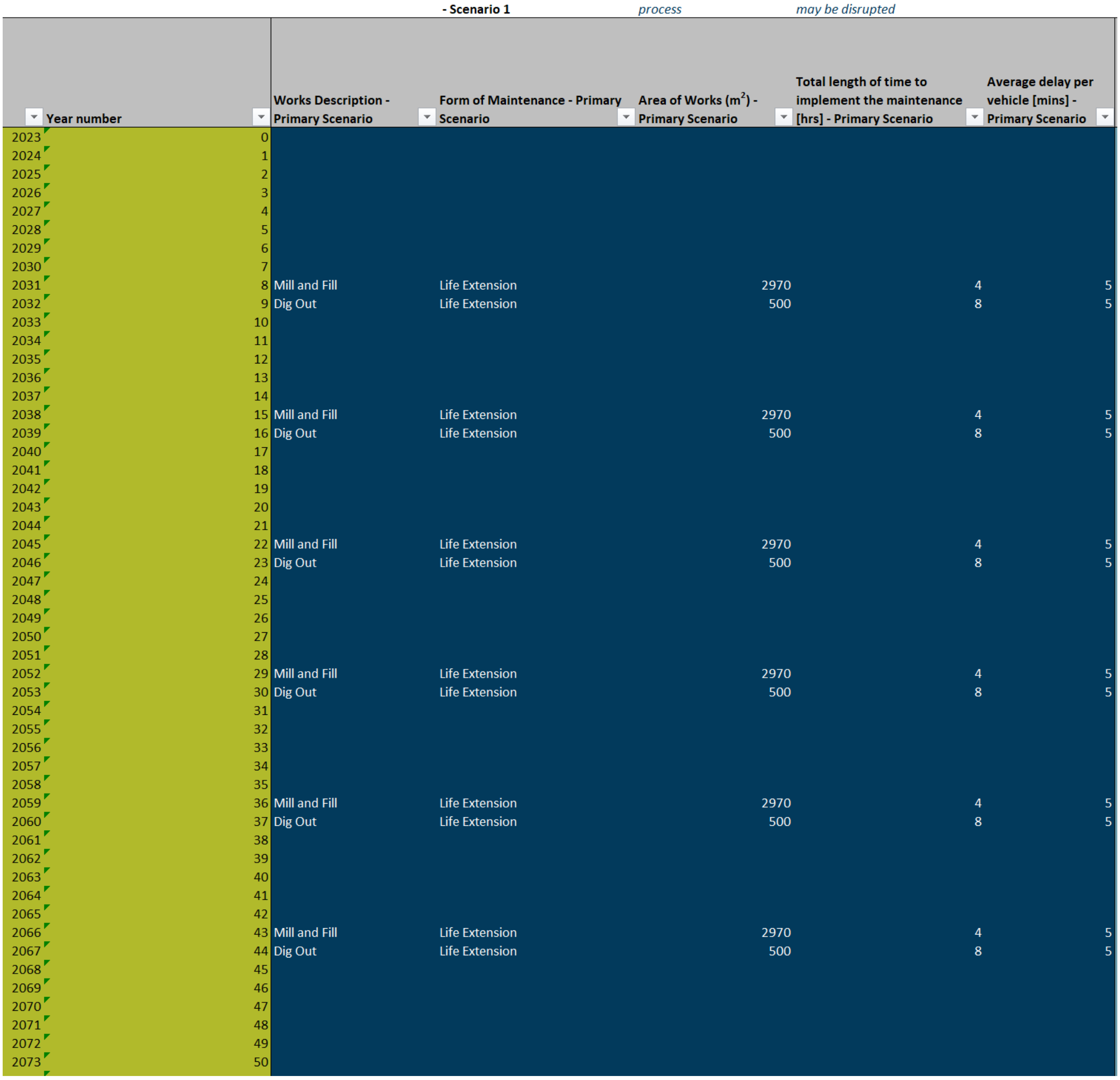
| | Material 1 | Material 2 | Material 3 | Material 4 | Combusted diesel per m2 of maintenance process (l/m2) |
|---|---|---|---|---|---|
| Crack Sealing | | | | | |
| thickness (mm) | | | | | 0.01 |
| Fill Cracks (Potholes) | | | | | |
| thickness (mm) | | | | | 0.01 |
| Surface Defect Repair | | | | | |
| thickness (mm) | | | | | 0.49 |
| Shoulder Maintenance | | | | | |
| thickness (mm) | | | | | 0.49 |
| Patch Stabilisation | | | | | |
| thickness (mm) | | | | | 0.49 |
| Mill and Fill | Asphalt (AC) | | | | |
| thickness (mm) | 45 | | | | 1.26 |
| Rip and Remake | Asphalt (AC) | Aggregate (Hard Rock) | Aggregate (Hard Rock) | | |
| thickness (mm) | 45 | 200 | 250 | | 1.70 |
| Dig Out - Primary Scenario | Asphalt (AC) | Aggregate (Hard Rock) | Aggregate (Hard Rock) | | |
| thickness (mm) | 45 | 200 | 250 | | 1.7 |
| Dig Out - Secondary Scenario | Asphalt (AC) | Asphalt (AC) | Aggregate (Hard Rock) | Aggregate (Hard Rock) | |
| thickness (mm) | 45 | 125 | 200 | 250 | 2.2 |
| Dig Out - Tertiary Scenario | Asphalt (AC) | Asphalt (AC) | Aggregate (Hard Rock) | Aggregate (Hard Rock) | |
| thickness (mm) | 45 | 125 | 200 | 250 | 2.2 |
| Lay over | | | | | |
| thickness (mm) | | | | | 1.7 |

*Figure A-10: Maintenance treatments*

The form shown is similar to the scenario builder form but is used to build maintenance treatments, with the layers laid out horizontally in materials 1-4. Worked example 2 is represented through:

- **Mill and fill:** This represents the resurface item of the top wearing course of 45mm. Diesel and distance values are left as default.
- **Rip and remake:** This has been used to show a like-for-like rehab or dig out that is required in scenario 3. This is so the scenario 3 dig out treatment can be used to show a structural AC replacement.
- **Dig out primary scenario:** A like-for-like pavement rehab or dig out that is used in scenario 1.
- **Dig out secondary/tertiary scenario:** A replacement of the current pavement with one that has a 125mm structural AC basecourse. Diesel consumption per m$^2$ is set higher as there is more paving required and a deeper pavement is used.

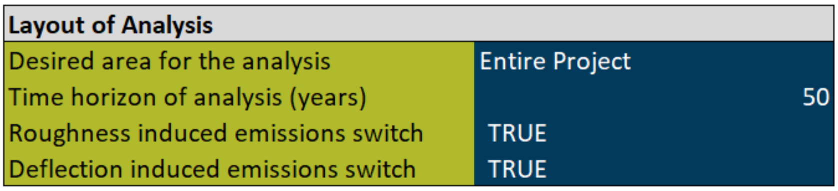
## Schedule builder scenarios 1–3



| | | | - Scenario 1 | process | may be disrupted | |
|---|---|---|---|---|---|---|
| | Year number | Works Description - Primary Scenario | Form of Maintenance - Primary Scenario | Area of Works ($m^2$) - Primary Scenario | Total length of time to implement the maintenance [hrs] - Primary Scenario | Average delay per vehicle [mins] - Primary Scenario |
| 2023 | 0 | | | | | |
| 2024 | 1 | | | | | |
| 2025 | 2 | | | | | |
| 2026 | 3 | | | | | |
| 2027 | 4 | | | | | |
| 2028 | 5 | | | | | |
| 2029 | 6 | | | | | |
| 2030 | 7 | | | | | |
| 2031 | 8 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2032 | 9 | Dig Out | Life Extension | 500 | 8 | 5 |
| 2033 | 10 | | | | | |
| 2034 | 11 | | | | | |
| 2035 | 12 | | | | | |
| 2036 | 13 | | | | | |
| 2037 | 14 | | | | | |
| 2038 | 15 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2039 | 16 | Dig Out | Life Extension | 500 | 8 | 5 |
| 2040 | 17 | | | | | |
| 2041 | 18 | | | | | |
| 2042 | 19 | | | | | |
| 2043 | 20 | | | | | |
| 2044 | 21 | | | | | |
| 2045 | 22 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2046 | 23 | Dig Out | Life Extension | 500 | 8 | 5 |
| 2047 | 24 | | | | | |
| 2048 | 25 | | | | | |
| 2049 | 26 | | | | | |
| 2050 | 27 | | | | | |
| 2051 | 28 | | | | | |
| 2052 | 29 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2053 | 30 | Dig Out | Life Extension | 500 | 8 | 5 |
| 2054 | 31 | | | | | |
| 2055 | 32 | | | | | |
| 2056 | 33 | | | | | |
| 2057 | 34 | | | | | |
| 2058 | 35 | | | | | |
| 2059 | 36 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2060 | 37 | Dig Out | Life Extension | 500 | 8 | 5 |
| 2061 | 38 | | | | | |
| 2062 | 39 | | | | | |
| 2063 | 40 | | | | | |
| 2064 | 41 | | | | | |
| 2065 | 42 | | | | | |
| 2066 | 43 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2067 | 44 | Dig Out | Life Extension | 500 | 8 | 5 |
| 2068 | 45 | | | | | |
| 2069 | 46 | | | | | |
| 2070 | 47 | | | | | |
| 2071 | 48 | | | | | |
| 2072 | 49 | | | | | |
| 2073 | 50 | | | | | |

*Figure A-11: Maintenance schedule for scenario 1, worked example 2*

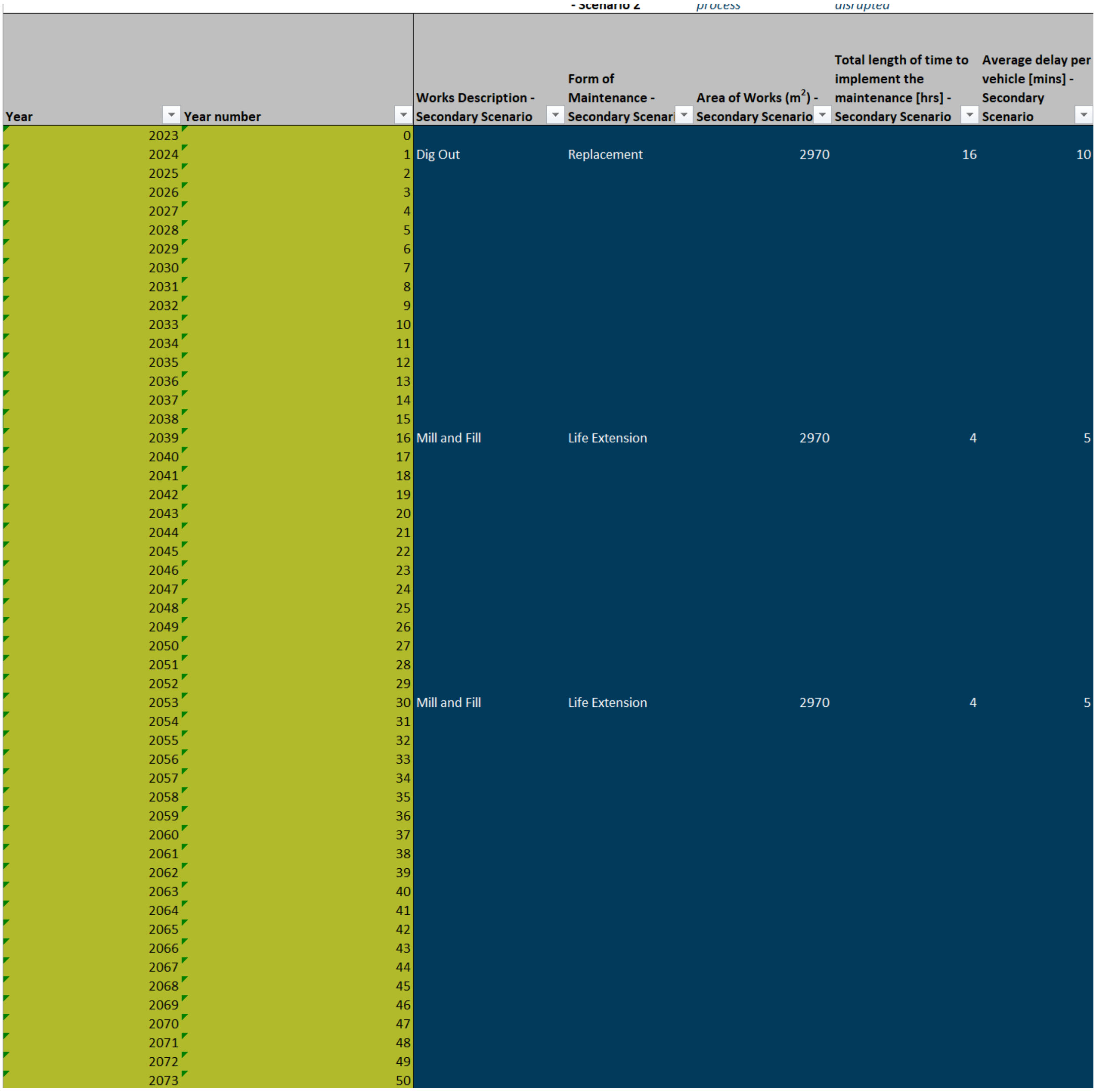
Figure A-11 shows how scenario 1 will be inputted in the Maintenance Schedule form. To change the timeline of the analysis, users need to use the time horizon field in the Impact Analysis tab (row 14), See Figure A-12.



| Layout of Analysis | |
|---|---|
| Desired area for the analysis | Entire Project |
| Time horizon of analysis (years) | 50 |
| Roughness induced emissions switch | TRUE |
| Deflection induced emissions switch | TRUE |

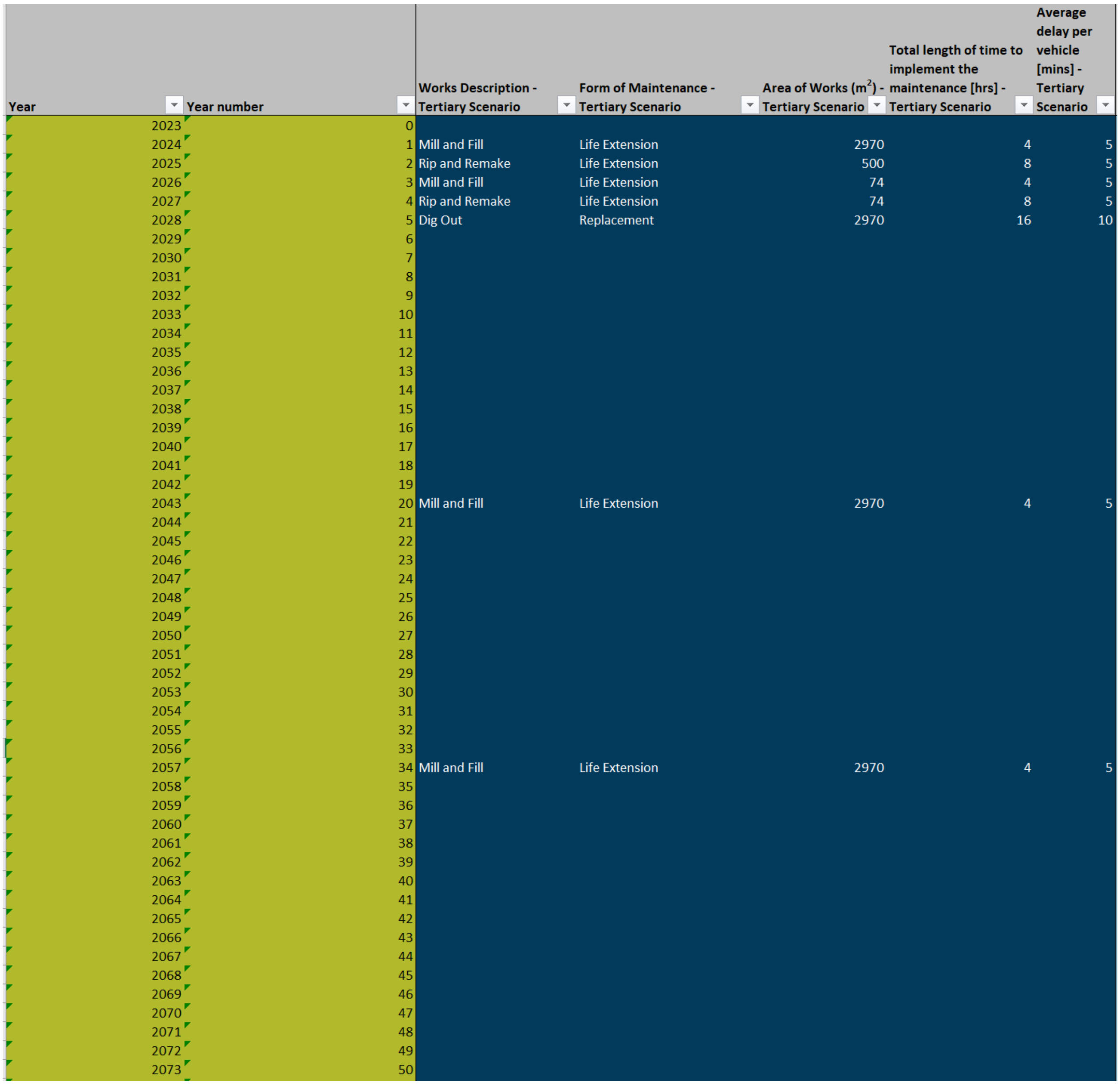
*Figure A-12: Analysis layout inputs*

Note that users can specify the area of the treatment in order to represent a full resurface or partial resurface due to patch repair. This is also the form where users specify the length of time it takes to implement the treatment and the delay it can cause on public traffic. The following figures show the inputs required to model scenario 2 and 3 respectively.



| Year | Year number | Works Description - Secondary Scenario | Form of Maintenance - Secondary Scenari | Area of Works ($m^2$) - Secondary Scenario | Total length of time to implement the maintenance [hrs] - Secondary Scenario | Average delay per vehicle [mins] - Secondary Scenario |
|---|---|---|---|---|---|---|
| 2023 | 0 | | | | | |
| 2024 | 1 | Dig Out | Replacement | 2970 | 16 | 10 |
| 2025 | 2 | | | | | |
| 2026 | 3 | | | | | |
| 2027 | 4 | | | | | |
| 2028 | 5 | | | | | |
| 2029 | 6 | | | | | |
| 2030 | 7 | | | | | |
| 2031 | 8 | | | | | |
| 2032 | 9 | | | | | |
| 2033 | 10 | | | | | |
| 2034 | 11 | | | | | |
| 2035 | 12 | | | | | |
| 2036 | 13 | | | | | |
| 2037 | 14 | | | | | |
| 2038 | 15 | | | | | |
| 2039 | 16 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2040 | 17 | | | | | |
| 2041 | 18 | | | | | |
| 2042 | 19 | | | | | |
| 2043 | 20 | | | | | |
| 2044 | 21 | | | | | |
| 2045 | 22 | | | | | |
| 2046 | 23 | | | | | |
| 2047 | 24 | | | | | |
| 2048 | 25 | | | | | |
| 2049 | 26 | | | | | |
| 2050 | 27 | | | | | |
| 2051 | 28 | | | | | |
| 2052 | 29 | | | | | |
| 2053 | 30 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2054 | 31 | | | | | |
| 2055 | 32 | | | | | |
| 2056 | 33 | | | | | |
| 2057 | 34 | | | | | |
| 2058 | 35 | | | | | |
| 2059 | 36 | | | | | |
| 2060 | 37 | | | | | |
| 2061 | 38 | | | | | |
| 2062 | 39 | | | | | |
| 2063 | 40 | | | | | |
| 2064 | 41 | | | | | |
| 2065 | 42 | | | | | |
| 2066 | 43 | | | | | |
| 2067 | 44 | | | | | |
| 2068 | 45 | | | | | |
| 2069 | 46 | | | | | |
| 2070 | 47 | | | | | |
| 2071 | 48 | | | | | |
| 2072 | 49 | | | | | |
| 2073 | 50 | | | | | |

*Figure A-13: Maintenance schedule for scenario 2, worked example 2*

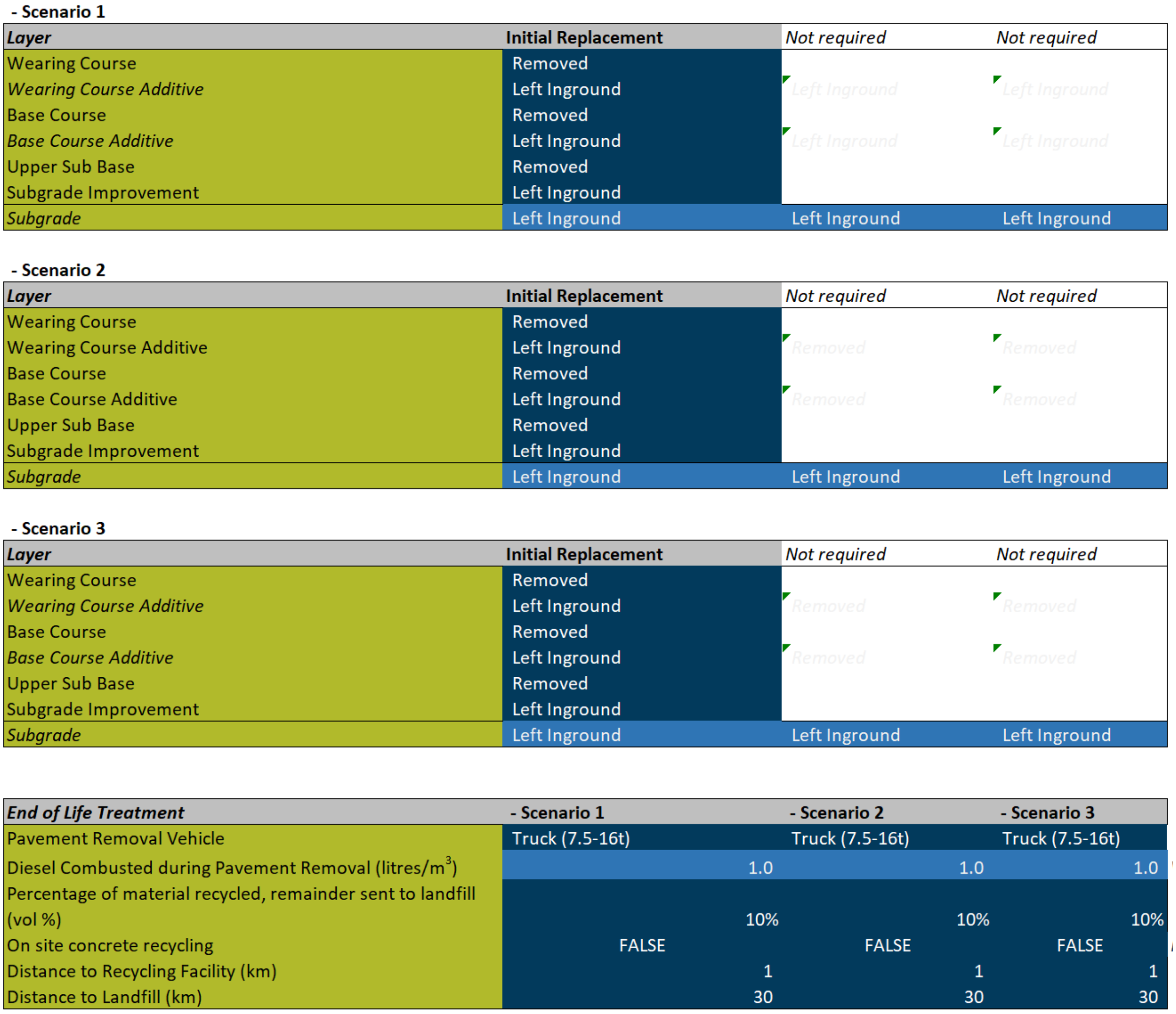


| Year | Year number | Works Description - Tertiary Scenario | Form of Maintenance - Tertiary Scenario | Area of Works (m$^2$) - Tertiary Scenario | Total length of time to implement the maintenance [hrs] - Tertiary Scenario | Average delay per vehicle [mins] - Tertiary Scenario |
|---|---|---|---|---|---|---|
| 2023 | 0 | | | | | |
| 2024 | 1 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2025 | 2 | Rip and Remake | Life Extension | 500 | 8 | 5 |
| 2026 | 3 | Mill and Fill | Life Extension | 74 | 4 | 5 |
| 2027 | 4 | Rip and Remake | Life Extension | 74 | 8 | 5 |
| 2028 | 5 | Dig Out | Replacement | 2970 | 16 | 10 |
| 2029 | 6 | | | | | |
| 2030 | 7 | | | | | |
| 2031 | 8 | | | | | |
| 2032 | 9 | | | | | |
| 2033 | 10 | | | | | |
| 2034 | 11 | | | | | |
| 2035 | 12 | | | | | |
| 2036 | 13 | | | | | |
| 2037 | 14 | | | | | |
| 2038 | 15 | | | | | |
| 2039 | 16 | | | | | |
| 2040 | 17 | | | | | |
| 2041 | 18 | | | | | |
| 2042 | 19 | | | | | |
| 2043 | 20 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2044 | 21 | | | | | |
| 2045 | 22 | | | | | |
| 2046 | 23 | | | | | |
| 2047 | 24 | | | | | |
| 2048 | 25 | | | | | |
| 2049 | 26 | | | | | |
| 2050 | 27 | | | | | |
| 2051 | 28 | | | | | |
| 2052 | 29 | | | | | |
| 2053 | 30 | | | | | |
| 2054 | 31 | | | | | |
| 2055 | 32 | | | | | |
| 2056 | 33 | | | | | |
| 2057 | 34 | Mill and Fill | Life Extension | 2970 | 4 | 5 |
| 2058 | 35 | | | | | |
| 2059 | 36 | | | | | |
| 2060 | 37 | | | | | |
| 2061 | 38 | | | | | |
| 2062 | 39 | | | | | |
| 2063 | 40 | | | | | |
| 2064 | 41 | | | | | |
| 2065 | 42 | | | | | |
| 2066 | 43 | | | | | |
| 2067 | 44 | | | | | |
| 2068 | 45 | | | | | |
| 2069 | 46 | | | | | |
| 2070 | 47 | | | | | |
| 2071 | 48 | | | | | |
| 2072 | 49 | | | | | |
| 2073 | 50 | | | | | |

*Figure A-14: Maintenance schedule for scenario 3, worked example 2*

## D.4. End of life

The final module to consider is the end-of-life option for the scenarios – that is, what happens after the 50 years. This is completed in the Data Entry tab (rows 150–194), in the form shown in Figure A-15.



**- Scenario 1**

| *Layer* | **Initial Replacement** | *Not required* | *Not required* |
|---|---|---|---|
| Wearing Course | Removed | | |
| *Wearing Course Additive* | Left Inground | *Left Inground* | *Left Inground* |
| Base Course | Removed | | |
| *Base Course Additive* | Left Inground | *Left Inground* | *Left Inground* |
| Upper Sub Base | Removed | | |
| Subgrade Improvement | Left Inground | | |
| *Subgrade* | Left Inground | Left Inground | Left Inground |

**- Scenario 2**

| *Layer* | **Initial Replacement** | *Not required* | *Not required* |
|---|---|---|---|
| Wearing Course | Removed | | |
| Wearing Course Additive | Left Inground | *Removed* | *Removed* |
| Base Course | Removed | | |
| Base Course Additive | Left Inground | *Removed* | *Removed* |
| Upper Sub Base | Removed | | |
| Subgrade Improvement | Left Inground | | |
| *Subgrade* | Left Inground | Left Inground | Left Inground |

**- Scenario 3**

| *Layer* | **Initial Replacement** | *Not required* | *Not required* |
|---|---|---|---|
| Wearing Course | Removed | | |
| *Wearing Course Additive* | Left Inground | *Removed* | *Removed* |
| Base Course | Removed | | |
| *Base Course Additive* | Left Inground | *Removed* | *Removed* |
| Upper Sub Base | Removed | | |
| Subgrade Improvement | Left Inground | | |
| *Subgrade* | Left Inground | Left Inground | Left Inground |

| ***End of Life Treatment*** | **- Scenario 1** | **- Scenario 2** | **- Scenario 3** |
|---|---|---|---|
| Pavement Removal Vehicle | Truck (7.5-16t) | Truck (7.5-16t) | Truck (7.5-16t) |
| Diesel Combusted during Pavement Removal (litres/m$^3$) | 1.0 | 1.0 | 1.0 |
| Percentage of material recycled, remainder sent to landfill (vol %) | 10% | 10% | 10% |
| On site concrete recycling | FALSE | FALSE | FALSE |
| Distance to Recycling Facility (km) | 1 | 1 | 1 |
| Distance to Landfill (km) | 30 | 30 | 30 |

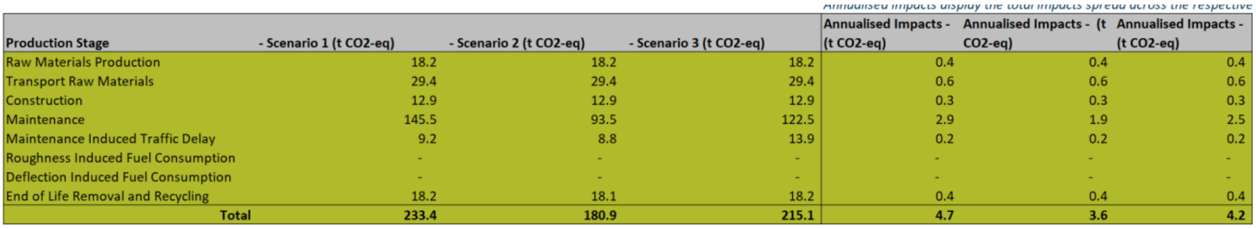
*Figure A-15: End of Life Treatment.*

For worked example 2 we have used the inputs shown in the figure above, which specifies a removal to waste at 50 years.

We have also specified the distance to landfill recycling facilities as well as the expected percentage of materials that should be recycled. Currently recycling only accounts for the fuel consumed in transporting the proportion of recycled material to the recycling facility, as opposed to carbon savings gained by utilising recycled material in the initial product.

In future versions of this tool the ability to specify a quantity of recycled material will appear in the Raw Materials sections as an option during scenario building.

## D.5. Impact analysis



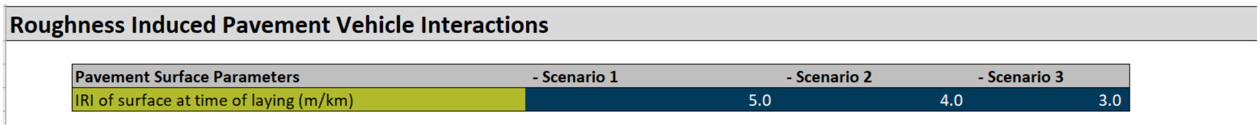
| Production Stage | - Scenario 1 (t CO2-eq) | - Scenario 2 (t CO2-eq) | - Scenario 3 (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) |
|---|---|---|---|---|---|---|
| Raw Materials Production | 18.2 | 18.2 | 18.2 | 0.4 | 0.4 | 0.4 |
| Transport Raw Materials | 29.4 | 29.4 | 29.4 | 0.6 | 0.6 | 0.6 |
| Construction | 12.9 | 12.9 | 12.9 | 0.3 | 0.3 | 0.3 |
| Maintenance | 145.5 | 93.5 | 122.5 | 2.9 | 1.9 | 2.5 |
| Maintenance Induced Traffic Delay | 9.2 | 8.8 | 13.9 | 0.2 | 0.2 | 0.2 |
| Roughness Induced Fuel Consumption | - | - | - | - | - | - |
| Deflection Induced Fuel Consumption | - | - | - | - | - | - |
| End of Life Removal and Recycling | 18.2 | 18.1 | 18.2 | 0.4 | 0.4 | 0.4 |
| **Total** | **233.4** | **180.9** | **215.1** | **4.7** | **3.6** | **4.2** |

*Figure A-16: Results worked example 2.*

In the analysis for worked example 2 (See Figure A-16) the impacts for roughness and deflection have been disabled using the switches in Figure A-12.

Typically, in a project feasibility report an NPV analysis focused on cost would show that scenario 1 is most ideal as it uses the least amount of rehabilitation (which is very expensive in the current market). However, conducting a parallel carbon analysis shows that scenario 1 also outputs the most carbon and that scenario 2, which involves a rehab and minimises materials use and traffic disruption, results in a 22% saving in carbon emissions across 50 years. This should also be considered towards the benefits in a cost–benefit analysis.

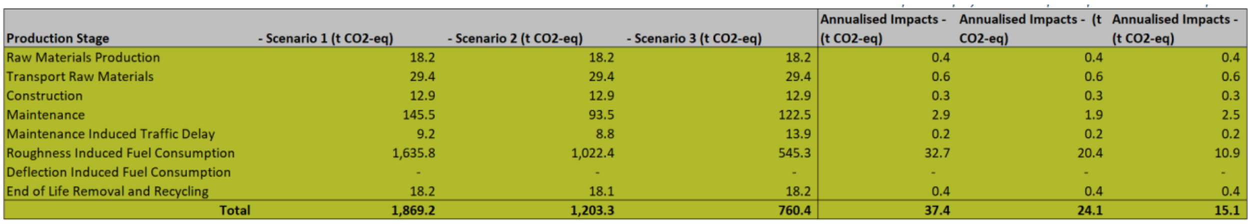
## D.6. Roughness impact



**Roughness Induced Pavement Vehicle Interactions**

| Pavement Surface Parameters | - Scenario 1 | - Scenario 2 | - Scenario 3 |
|---|---|---|---|
| IRI of surface at time of laying (m/km) | 5.0 | 4.0 | 3.0 |

*Figure A-17: Worked example 2 roughness impact.*



| Production Stage | - Scenario 1 (t CO2-eq) | - Scenario 2 (t CO2-eq) | - Scenario 3 (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) | Annualised Impacts - (t CO2-eq) |
|---|---|---|---|---|---|---|
| Raw Materials Production | 18.2 | 18.2 | 18.2 | 0.4 | 0.4 | 0.4 |
| Transport Raw Materials | 29.4 | 29.4 | 29.4 | 0.6 | 0.6 | 0.6 |
| Construction | 12.9 | 12.9 | 12.9 | 0.3 | 0.3 | 0.3 |
| Maintenance | 145.5 | 93.5 | 122.5 | 2.9 | 1.9 | 2.5 |
| Maintenance Induced Traffic Delay | 9.2 | 8.8 | 13.9 | 0.2 | 0.2 | 0.2 |
| Roughness Induced Fuel Consumption | 1,635.8 | 1,022.4 | 545.3 | 32.7 | 20.4 | 10.9 |
| Deflection Induced Fuel Consumption | - | - | - | - | - | - |
| End of Life Removal and Recycling | 18.2 | 18.1 | 18.2 | 0.4 | 0.4 | 0.4 |
| **Total** | **1,869.2** | **1,203.3** | **760.4** | **37.4** | **24.1** | **15.1** |

*Figure A-18: Worked example 2 roughness impact*

In Figure A-18 the switch for roughness induced impacts is turned on for worked example 2 using the inputs in Figure A-17. This explores the effect on vehicle emissions of reducing pavement roughness from IRI of 5 – 4 – 3. Note that this has nothing to do with the maintenance schedules we have developed in example 2.

The total lifecycle emissions from scenario 1 is 1869t $CO_2$-e, of which roughness inducted impacts (1635t $CO_2$-e) make up nearly 88%. Between scenarios 1 and 2, a change in IRI from 5 to 4 has led to a carbon saving of 613t $CO_2$-e (1635-1022). The roughness induced fuel consumption is significantly greater compared to the other production stages, showing the importance of considering user emissions.