Life cycle assessment of pavements

Development of a calculator
August 2022

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Abbreviations

AADT	annual average daily traffic
AC	Dense Graded Asphaltic Concrete
ADP	abiotic depletion potential
ALCA	attributional life cycle assessment
AP	acidification potential
AusLCI	Australian Life Cycle Inventory Database
CLCA	consequential life cycle assessment
EMOGPA	Epoxy-Modified Open Graded Porous Asphalt
EN	Europäische Norm (European Standard)
EP	eutrophication potential
EPD	Environmental Product Declaration
ESA	equivalent standard axles
GWP	global warming potential
IRI	international roughness index
IS	Infrastructure Sustainability (Infrastructure Sustainability Council’s rating tool)
ISC	Infrastructure Sustainability Council
ISO	International Organization for Standardization
LCA	life cycle assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MBIE	Ministry of Business, Innovation and Employment
OGPA	Open Graded Porous Asphalt
PCR	product category rule
POCP	photochemical ozone creation potential
RAP	reclaimed asphalt pavement
RCC	recycled crushed concrete
SCM	supplementary cementitious material
SMA	Stone Mastic Asphalt

Contents

Executive summary

The uptake of recycled materials in New Zealand's pavements is currently low

Waka Kotahi NZ Transport Agency specifications allow for the inclusion of certain recycled materials and by-products (eg recycled crushed concrete) in road pavements, yet the use of these materials is relatively limited. Previous work commissioned by Waka Kotahi has shown several reasons for this, including a lack of policy incentives, risk-averse clients and contractors, cost increases relative to virgin materials and technical uncertainty over the recycled materials' long-term performance.

Waka Kotahi wishes to increase the use of recycled materials in pavements to contribute to a low-carbon circular economy

Waka Kotahi wishes to increase the use of recycled materials in pavements and the reuse of existing pavement layers. However, there can be trade-offs against other environmental indicators (such as carbon footprint), particularly when recycled or reused materials are transported over long distances. One aim of this study was to quantify the trade-offs and thereby help to avoid creating unintended negative consequences by increasing the use of recycled or reused materials.

The purpose of this project was to develop a calculator tool to compare different pavement designs, including use of recycled materials, over their full life cycle and to provide rules of thumb for environmentally conscious pavement design

The Pavement Environmental Calculator developed through this project is an Excel-based tool designed to calculate the environmental footprint of a full pavement over its full life. The tool includes all layers of the pavement but excludes supporting infrastructure (eg bridges, culverts, kerbs, catchpits).

The outputs from the Pavement Environmental Calculator are intended to sit alongside existing cost calculations in pavement design, allowing environmental attributes to be considered alongside life cycle cost and technical considerations. The Calculator allows multiple time horizons to be considered (from annualised impacts to total impacts over 100 years). It calculates the carbon footprint of the pavement (the headline indicator), along with a wide range of other environmental and human health indicators.

The Pavement Environmental Calculator is deliberately designed to take a holistic view and considers:

- production of raw materials for pavement (virgin and recycled/reclaimed)
- transport of raw materials to manufacturing plants
- manufacturing of pavement materials
- transport of pavement materials to construction site
- construction/installation of the pavement
- maintenance, repair, replacement and refurbishment of the pavement within its service life
- energy losses from pavement–vehicle interactions in vehicles travelling on the road
- deconstruction of selected pavement layers at end of life
- transport of waste to waste-processing sites
- processing of waste for cleanfill or recycling
- recovery of selected pavement layer materials such as asphalt and aggregate.

Initial rules of thumb for environmentally conscious pavement design

By comparing exemplar pavements, the following trends were seen:

- Recycled crushed concrete can be transported at least 30 km further than virgin aggregate and still have an equivalent or lower carbon footprint from ‘cradle to site’.
- Reclaimed asphalt pavement can be transported at least 500 km for recycling and still have an equivalent carbon footprint to virgin asphalt pavement from ‘cradle to site’.
- The relative impacts of raw materials are higher when pavements have shorter design lives.
- Pavement–vehicle interactions can be very significant, and they become more important as the speed and flow rate of vehicles increases.
- Reusing suitable layers of pavement is an effective method of reducing emissions.

Next steps

This project has developed an initial version of the Pavement Environmental Calculator. Waka Kotahi invites industry to use the tool in real-world projects and provide feedback on the Calculator’s usability, functionality and the availability of data for use within the tool. It is hoped that a user group will develop over time to share findings and knowledge, allowing rules of thumb for environmentally conscious pavement design to be improved and ultimately, to improve the environmental performance of New Zealand’s pavements.

Abstract

The uptake of recycled materials in New Zealand’s pavements is currently low. Waka Kotahi NZ Transport Agency wishes to increase the use of recycled materials in pavements to contribute to a circular economy. However, given that transport distances and processing requirements for some recycled materials can be significant, Waka Kotahi wants to identify materials that are circular and have a low carbon footprint.

The purpose of this project was to develop a calculator tool to compare the environmental performance of different pavement designs at the project level, considering both virgin and recycled materials. An Excel-based tool was developed through this project and named the Pavement Environmental Calculator. This tool considers the full life cycle of the pavement, including initial construction, maintenance and end of life. It applies to all layers of the pavement but excludes supporting infrastructure. The calculator tool includes a combination of primary data collected from industry through this project and secondary data from literature.

In addition to the tool itself, this report proposes some initial rules of thumb for environmentally conscious pavement design. These rules of thumb need refinement by applying the Pavement Environmental Calculator to more projects. It is hoped that a user group will develop over time to share findings and knowledge that help to improve the environmental performance of New Zealand’s pavements.

1 Introduction

1.1 Background

Waka Kotahi NZ Transport Agency specifications allow for the inclusion of certain recycled materials and by-products in road pavements, yet the use of materials such as recycled crushed concrete (RCC) and reclaimed asphalt pavement (RAP) in pavement courses is limited. The reasons for this were discussed in work that was commissioned by Waka Kotahi in 2018/19; they included a lack of policy incentives, risk-averse clients and contractors, cost increases relative to virgin materials and technical uncertainty over long-term performance (O'Donnell & Thomas, 2018; Waka Kotahi, 2019).

Waka Kotahi wishes to increase the use of recycled materials in pavements and the reuse of existing pavement layers. However, there can be trade-offs against other environmental indicators (such as carbon footprint), particularly when recycled or reused materials are transported over long distances. One aim of this study was to quantify the trade-offs and thereby help to avoid creating any unintended negative consequences resulting from increasing the use of recycled or reused materials. This would be achieved by developing a calculator tool to compare different pavement designs, including use of recycled materials, over their full life cycle and to provide rules of thumb for environmentally conscious pavement design.

1.2 Goal

The overarching goals of this study are as follows:

1. To develop a scientific understanding of the whole-of-life environmental impacts of key materials for both constructing new pavements and refurbishing existing pavements within New Zealand.
2. To use this information to support informed decision-making in pavement design and specification within Waka Kotahi.

In this project, life cycle assessment (LCA) is used to calculate the whole-of-life environmental impacts of constructing pavements, following international best practice and relevant International Organization for Standardization (ISO) and European Committee for Standardization (EN) standards: ISO 14040 and ISO 14044 for LCA, ISO 14067 for product carbon footprinting and EN 15804 for Environmental Product Declarations (EPDs) of construction products. EN 15804 is the basis of all EPDs published in New Zealand. It is used in the Infrastructure Sustainability Council's (ISC's) 'IS Materials Calculator', and it is being used by the Ministry of Business, Innovation and Employment (MBIE) in its Building for Climate Change programme. This study declares the results for both versions of the standard – EN 15804+A1 (CEN, 2013) and EN 15804+A2 (CEN, 2019) – given that there are thousands of EPDs using the older standard available worldwide.

This project includes the development of a toolkit, comprising the following:

- An Excel-based calculator for material selection in pavement design (the 'Pavement Environmental Calculator'), allowing the user to alter key parameters that affect environmental performance. The intention of this tool is to calculate a headline environmental indicator (carbon footprint) to sit alongside cost when doing options analysis in pavement design. The tool should also assess whether there are trade-offs between the headline indicator and other common environmental indicators.
- Initial rules of thumb to support selecting the right material for the project when decisions need to be made quickly (and without the use of the Calculator).
- Advice on the best use of each alternative material, based on the Calculator.
- Guidance, training and support in the use of the toolkit.

The outcomes of this project are intended for internal use within Waka Kotahi; however, given that the toolkit enables comparisons between competing material types, this project has undergone review by a panel of three independent experts (see section 1.10).

1.3 Scope

The scope of the Pavement Environmental Calculator (the Calculator) and this supporting report is a full road pavement, including all layers but excluding supporting infrastructure (bridges, culverts, kerbs, catchpits, etc). Table 1.1 shows the pavement layers and specific materials available within the Pavement Environmental Calculator. The scope of materials in this study is limited to the virgin and recycled materials currently permitted in Waka Kotahi specifications, because it is not the purpose of this project to evaluate novel materials or pavement technologies that are not yet approved.

Table 1.1 Material composition of pavement layers

Course	Type	Subtype
Wearing course	Chipseal	
	Slurry	
	Asphalt	Stone Mastic Asphalt (SMA)
		RAP
		Asphalt Concrete (AC)
		Open Graded Porous Asphalt (OGPA) (PA10)
		Epoxy-Modified Open Graded Porous Asphalt (EMOGPA) (EPA7)
	Aggregate	Aggregate from a hard-rock quarry*
		Aggregate from an alluvial quarry*
		Aggregate from dredging*
Wearing course additives		Melter slag from the Glenbrook Steel Mill†
Base course	Aggregate	Aggregate from a hard-rock quarry*
		Aggregate from an alluvial quarry*
		Aggregate from dredging*
		RCC
		Reclaimed glass
	Concrete	Concrete
		AC
	Hi-Lab	
	Modified base course	Cement modified
		Lime modified
		Bitumen modified
Upper subbase	Aggregate	Aggregate from a hard-rock quarry*
		Aggregate from an alluvial quarry*
		Aggregate from dredging*
		RCC
	Concrete	

Course	Type	Subtype
	Modified upper subbase	Cement bound
		Lime modified
	Hi-Lab	
Lower subbase	Aggregate	Aggregate from a hard-rock quarry*
		Aggregate from an alluvial quarry*
		Aggregate from dredging*
		RCC
Subgrade improvement	Aggregate	Aggregate from a hard-rock quarry*
		Aggregate from an alluvial quarry*
		Aggregate from dredging*
	Modified subgrade	Cement modified
		Lime modified
Subgrade	Bedrock	
	Clay	
	Silt	
	Sand	
	Volcanic ash	
	Pumice	

* This project collected primary data from industry. Data for quarries were collected at the site level rather than the product level and hence, the data are reported in the tool by the type of site (a hard-rock quarry, an alluvial sand and gravel quarry, or a dredging operation). Product-level data could be added over time.

† As LCA data could not be sourced for the Glenbrook Steel Mill, a proxy has been used.

1.4 Declared unit

The declared unit for this study is:

> 1 lane-km or 1 m^2 of pavement, consisting of surface course, base course and subbase course, for use in road transport.

The declared unit is thus per unit of full-depth pavement, rather than per unit of individual pavement layers. This approach aims to reduce the potential for shifting burdens between layers by viewing the pavement as a holistic unit. Thus, the Pavement Environmental Calculator can also be used to assess a whole pavement at the project level.

1.5 Life cycle assessment method

There are two broad types of process-based LCA:

- **Attributional LCA (ALCA)**, which takes a backwards-looking, accounting-based approach to LCA, attempting to divide (allocate) the impacts of activities in the real world between discrete products and services while avoiding double-counting. It is the most common type of LCA, and the type of LCA used in all EPDs.
- **Consequential LCA (CLCA)**, which takes a forward-looking approach, designed to consider what the impact of increasing the use of certain materials, energy carriers or other processes might be, given real-world constraints within the economy. For example, New Zealand has a baseload of hydropower and

geothermal power, above which demand is supplied by a combination of fossil fuels (natural gas and coal) and intermittent renewables such as wind and solar photovoltaics.

As the Pavement Environmental Calculator is intended to help its users make decisions, it allows the user to apply CLCA. As the Calculator is designed to be extendable and incorporate EPD data, it also allows the user to apply ALCA.

1.6 System boundary

The LCA is a cradle-to-grave analysis covering the following life cycle stages (see Table 1.2):

1. upstream processes (from cradle to gate), covering raw material production (A1–A3)
2. core processes (from gate to road), including transport of material to site (A4) and construction of the pavement (A5)
3. downstream processes (from road to grave), covering maintenance (B2–B5), end of life (C1–C4) and any potential credits from future use of recycled materials (D).

The processes included and excluded from the system boundary are outlined in Table 1.3. These are typical of an ALCA approach. CLCA requires system expansion by substitution to allocate impacts between coproducts. This is the same procedure used for end-of-life allocation following EN 15804, which is shown in module D in Table 1.2.

Table 1.2 System boundary for pavement LCA in line with EN 15804 modules

	Product stage	Construction process stage		Use stage				End-of-life stage				Recovery stage
	Raw material supply Transport Manufacturing	Transport	Installation	Use	Maintenance Repair Replacement Refurbishment	Operational energy use	Operational water use	Deconstruction/ demolition	Transport	Waste processing	Disposal	Future reuse, recycling or energy recovery potential
Module	A1–A3	A4	A5	B1	B2–B5	B6	B7	C1	C2	C3	C4	D
Modules declared	X[a]	X	X	ND[b]	X	ND	ND	X	X	X	X	X

[a] Included in the LCA.
[b] Not declared.

Table 1.3 System boundary inclusions and exclusions

Included	Excluded
✓ Raw material production for pavement materials ✓ Transport of raw materials to manufacturing plants ✓ Manufacturing of pavement materials ✓ Transport of pavement materials to construction site ✓ Construction/installation of pavement ✓ Maintenance, repair, resurfacing, replacement and refurbishment of pavement within its service life ✓ Energy losses in vehicles travelling on the road, from pavement–vehicle interactions ✓ Deconstruction of select pavement layers at end of life (the lower layers may not be damaged and hence they may be kept for future use) ✓ Transport of waste to processing site ✓ Processing of waste for cleanfill or recycling ✓ Recovery of select pavement layer materials (eg asphalt) and aggregate	× Road lighting × Operational water (only relevant for dust suppression on gravel roads) × Energy losses in vehicles due to horizontal pavement alignment and longitudinal grade × Environmental impacts from increases in vehicle repairs and maintenance due to pavement–vehicle interactions × Removal of vegetation during the construction of the pavements × Construction of infrastructure supplementary to the pavement (bridges, culverts, footpaths) × Production of capital goods (paving machines, trucks, crushers, offices, etc) × Operation of offices for paving and throughout the materials supply chain × Personnel transport that is not directly linked to flows of materials

1.6.1 Time coverage

The Pavement Environmental Calculator is intended to be applied in pavement design from 2021 onward. Therefore, it represents pavement technologies that were current at the time of writing, ideally drawing on primary data that were less than five years old wherever possible (as per EN 15804).

As pavements are long-lived assets, with design lives of decades and practical service lives that may essentially be indefinite, the Pavement Environmental Calculator is designed to forecast potential changes in key variables that will influence the lifetime performance of pavements (electricity mix, diesel mix, fleet make-up, etc).

1.6.2 Technology coverage

The Pavement Environmental Calculator is intended to represent technologies permitted for use in New Zealand by Waka Kotahi specifications as of 2021. Novel materials and novel pavement technologies that are not currently approved are explicitly out of scope but could be considered in a future revision.

1.6.3 Geographical coverage

This study is intended to be representative of pavements in New Zealand and therefore, materials that are available on the local market. As pavement materials are bulky, most materials are manufactured locally, but they may include imported raw materials (eg bitumen, cement, supplementary cementitious materials [SCMs]).

1.7 Allocation

1.7.1 Multi-output allocation

Multi-output allocation follows the requirements of ISO 14044, section 4.3.4.2. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step is applied and documented together with the process description in Chapter 5.

Allocation of background data (energy and materials) is taken from the ecoinvent v3.6 database (https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-6/).

1.7.2 End-of-life allocation

End-of-life allocation follows the requirements of ISO 14044, section 4.3.4.3, and EN 15804+A2, section 6.4.3.3.

Importantly for this study's focus on the use of recycled materials, the 'polluter pays' principle outlined in EN 15804+A2, section 6.3.5.1, states, 'Processes of waste processing shall be assigned to the product system that generates the waste until the end-of-waste state is reached' (CEN, 2019, p. 25). The end-of-waste state is reached if the recovered material following waste processing is 'used for specific purposes', 'a market demand exists', it meets 'lawful and specific requirements' and it 'fulfils limit values for SVHC [Substances of Very High Concern; ie the product is not classified as hazardous]' (p. 59).

The International EPD System (operating in the New Zealand market via EPD Australasia) provides further clarification of this in its General Programme Instructions:

> *The above outlined principle means that the generator of the waste shall carry the full environmental impact until the point in the product life cycle in which all the end-of-waste criteria are fulfilled. Waste may have a negative economic market value, and then the end-of-waste stage is typically reached after (part of) the waste processing and further refinement, at the point at which the waste no longer has a negative market value.* (EPD International, 2021, p. 67)

For recycled materials where the recycler is operating a waste treatment service, such as for RCC, all environmental impacts up to the point of a saleable product are allocated to the previous product system and the environmental impact of using the RCC is close to zero.

1.8 Cut-off criteria

The cut-off criteria defined for this study are as follows:

- Flows that collectively contribute less than 1% of the final mass of the pavement may be excluded.
- Within material production, flows that collectively contribute less than 1% of the total mass or total energy can also be excluded, provided they are not expected to be environmentally relevant.

Wherever possible, all available energy and material flows are included for the processes within the system boundary (see section 1.6). In cases where no matching life cycle inventories are available to represent a flow, proxy data are applied based on conservative assumptions regarding environmental impacts. The choice of proxy data is documented in Chapter 5. One exception is Glenbrook melter slag, where no suitable proxy could be identified and crushed aggregate is used as a crude proxy.

Production of capital goods, operation of offices and transport of personnel are outside of the system boundary of this study and therefore not considered for the cut-off criteria.

1.9 Selection of life cycle impact assessment methodology and impact categories

The primary indicator for this study is global warming potential (GWP). Additionally, results for the following sets of indicators are included, as they are considered to be of high relevance to the goals of the project:

- EN 15804+A1 impact categories (CEN, 2013)
- EN 15804+A2 impact categories (CEN, 2019)

- human health and nuisance indicators.

1.9.1 Environmental indicators (EN 15804+A1 and EN 15804+A2)

1.9.1.1 Environmental impact indicators

EN 15804+A1 requires the environmental impact indicators shown in Table 1.4. EN 15804+A2 requires the environmental impact indicators shown in Table 1.5. These indicators are calculated using Life Cycle Impact Assessment (LCIA). They quantify the potential impacts of emissions on the natural environment in a relative sense, but do not account for actual impacts in any specific ecosystem. Put another way, they represent pressure on the natural environment, but do not try to predict if this pressure will lead to any specific harm or change.

Table 1.4 EN 15804+A1 environmental impact indicators

Indicator	Abbrev.	Unit
GWP100, following IPCC AR4	GWP	kg CO_2 eq.
Depletion potential of the stratospheric ozone layer	ODP	kg CFC 11 eq.
Acidification potential of soil and water	AP	kg SO_2 eq.
Eutrophication potential	EP	kg $(PO_4)^{3-}$ eq.
Formation potential of tropospheric ozone	POCP	kg C_2H_4 eq.
Abiotic depletion potential of elements	APDe	kg Sb eq.
Abiotic depletion potential of fossil fuels	ADPf	MJ

Table 1.5 EN 15804+A2 environmental impact indicators

Indicator	Abbrev.	Unit
Climate change – total (GWP100, following IPCC AR5)	GWP-total	kg CO_2-eq.
Climate change – fossil (GWP100, following IPCC AR5)	GWP-fossil	kg CO_2-eq.
Climate change – biogenic (GWP100, following IPCC AR5)	GWP-biogenic	kg CO_2-eq.
Climate change – land use and land use change (GWP100, following IPCC AR5)	GWP-luluc	kg CO_2-eq.
Ozone depletion	ODP	kg CFC11-eq.
Acidification	AP	Mole of H+ eq.
Eutrophication – aquatic freshwater	EP-freshwater	kg P eq.
Eutrophication – aquatic marine	EP-marine	kg N eq.
Eutrophication – terrestrial	EP-terrestrial	Mole of N eq.
Photochemical ozone formation	POCP	kg NMVOC[a] eq.
Depletion of abiotic resources – minerals and metals	ADP-m&m	kg Sb eq.
Depletion of abiotic resources – fossil fuels	ADP-fossil	MJ
Water (user) deprivation potential	WDP	m^3 world equiv.

[a] Non-methane volatile organic compound.

The impact categories listed above represent impact *potentials*; that is, they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory captures only that fraction of the total environmental load that corresponds to the functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts or give information about the endpoints of impact categories, the exceeding of thresholds, safety margins, or risks.

1.9.1.2 Inventory indicators

The following environmental parameters are based on the Life Cycle Inventory (LCI). They describe the use of renewable and non-renewable material resources, renewable and non-renewable primary energy, and water, as shown in Table 1.6.

Table 1.6 Resource use indicators

Indicator	Abbrev.	Unit
Renewable primary energy as energy carrier	PERE	MJ, net calorific value
Renewable primary energy resources as material utilisation	PERM	MJ, net calorific value
Total use of renewable primary energy resources	PERT	MJ, net calorific value
Non-renewable primary energy as energy carrier	PENRE	MJ, net calorific value
Non-renewable primary energy as material utilisation	PENRM	MJ, net calorific value
Total use of non-renewable primary energy resources	PENRT	MJ, net calorific value
Use of secondary material	SM	kg
Use of renewable secondary fuels	RSF	MJ, net calorific value
Use of non-renewable secondary fuels	NRSF	MJ, net calorific value
Use of net fresh water	FW	m^3

EN 15804 also requires the declaration of waste materials and output flows, such as components for reuse and recycling, as shown in Table 1.7.

Table 1.7 Waste material and output flow indicators

Indicator	Abbrev.	Unit
Hazardous waste disposed	HWD	kg
Non-hazardous waste disposed	NHWD	kg
Radioactive waste disposed	RWD	kg
Components for reuse	CRU	kg
Materials for recycling	MFR	kg
Materials for energy recovery	MER	kg
Exported electrical energy	EEE	MJ
Exported thermal energy	EET	MJ

1.9.2 Human health and nuisance indicators

This study includes the following indicators relating to human health:

- photochemical ozone creation potential (EN 15804+A1) (kg C_2H_4 equivalent)
- photochemical ozone formation potential (EN 15804+A2)
- human toxicity (cancer effects and non-cancer effects) (USEtox) (EN 15804+A2).

Waka Kotahi has commissioned two projects to monetise the burden on the healthcare system from particulate matter, nitrogen dioxide emissions and noise. Therefore, the following flows – as calculated from the LCI – are also included within the tool:

- particulate matter ($PM_{2.5}$ and PM_{10}, declared separately)
- nitrogen dioxide emissions
- noise.

The intention is that a future version of the Pavement Environmental Calculator could incorporate these values in dollar terms. As these projects were not completed at the time this study was undertaken, the Pavement Environmental Calculator incorporates the raw data for these indicators but does not yet include the full monetisation.

1.10 Critical review

The Pavement Environmental Calculator and this report have undergone a panel review following ISO 14044, section 6.3, to ensure the methodology followed is sound and the study is fit for publication. Given that the purpose of this study is not to make specific comparisons but rather, to design a tool that allows comparisons to be made, not all provisions of ISO 14044 apply to this study.

The reviewers were:

- Rob Rouwette (Chair)
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- Clare Dring
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The Critical Review Statement can be found in Appendix A. The Critical Review Commentary, containing the comments and recommendations by the independent experts as well as the practitioners’ responses, can be found in Appendix C.

2 Literature review

This project includes both ALCA and CLCA. The goals of the literature review were to guide the development of a practical methodology for carrying both LCAs and to define the data needs.

2.1 Attributional life cycle assessment

ALCA is the most common type of LCA. It is used in the vast majority of LCA projects for industry, and it is the LCA technique used for all EPDs worldwide. ALCA applies a backwards-looking, accounting approach – essentially aiming to divide up the impacts of human society and assign them to discrete products and services. ALCA assumes that producing one additional unit of a product will have the same impact as the product that was produced before. It is an approach that relies on averages and linear scaling.

Within the context of an assessment of pavement technologies for Waka Kotahi, there are defined processes and standards to conduct this type of LCA. The attributional part of this project complies with EN 15804 and the data requirements for ALCA follow EN 15804.

2.2 Consequential life cycle assessment

2.2.1 Background

In contrast with a static benchmarking ALCA, CLCA considers the impacts of making changes to processes and assists directly with supporting decision-making. Although ALCA is commonly used to structure the environmental efforts of practitioners and organisations, it has limitations that CLCA tries to address (Consequential-LCA, 2020).

One limitation is that the attributional model isolates the product system in a bubble, using strict cut-off rules and coproduct allocation. By viewing the product as being separate from the real world, any potential changes are viewed the same way, and indirect downstream impacts from those changes are not considered (Earles & Halog, 2011). For example, as the demand for a product changes because of a process change to the product system, this has knock-on effects throughout the wider economy. For a large organisation, or an organisation with significant market power, these changes can have significant impacts on the supply and demand of a given product (Weidema, 2003). CLCA uses system expansion and marginal data to capture these changes in a forward-looking manner. In essence, it merges LCA and economic modelling (Earles & Halog, 2011).

2.2.2 Data requirements

Before classifying the data requirements, the constrained technologies or suppliers must first be identified. For this, the approach for identification of these technologies from Ekvall and Weidema (2004) can be applied.

Weidema et al. (1999) originally described these as ‘marginal technologies’ but this term has since been changed to ‘affected/constrained technology’, as there was potential for confusion. Ekvall (2020) expanded on the five-step process to clarify that it is not a methodology to identify all the real marginal effects but rather, a structured process to make assumptions about marginal effects for modelling. Each simplification made does reduce overall accuracy, but these simplifications are needed, given the constraints on data.

The five steps to identify constrained technologies/suppliers are as follows:

1. Time aspects: Are the effects of a change in process short term or long term? These concepts are sometimes described as ‘operating margins’ and ‘built margins’, which aids in communication, but the

metaphor does mask some marginal effects. Note that the ecoinvent database defaults to long-term effects in its consequential modelling (Wernet et al., 2016).

2. Breadth of impacts: Are the impacts just for specific processes or do they have an impact on the whole market? If a decision affects only one process, it is marginal. If the entire market is affected, the affected marginal processes within that market need to be identified. Put another way: Is the process in the foreground or background model? Foreground implies site-specific data and this will be the constrained technology. A background process will be at the market level.
3. What is the market trend? If the whole market is affected (see step 2), do the trends imply that demand is going to increase further, or will the decrease in overall demand be counteracted by a demand increase resulting from the change? If the market segment is decreasing faster than the replacement rate of the existing production, the market will eventually phase out. This can imply replacement with international supply or a technological or material shift.
4. How flexible is the technology? If production capacity is fixed or cannot respond fast enough to the induced demand from the modelled change, it will not be affected by the change, and different markets or processes will need to make up the demand.
5. What technology will be affected? If technologies cease to run, they are assumed to be the oldest or the most expensive variants to operate. If an expansion in capacity is required, the assumption is that they are the most modern technology and/or cheaper to operate. These can affect elements such as grid mixes, for example.

The application of the above steps to this Waka Kotahi study led to the following conclusions:

- Construction materials for building pavements are heavy and bulky, and they are generally sourced locally. Therefore, it is unlikely that materials other than bitumen will be imported for pavement construction. For virgin bitumen production, international markets were considered due to the near-term change from domestic production to importation (Pullar-Strecker, 2020).
- Similarly, market trends showed a steady decline in local diesel production and an increase in imports (MBIE, 2020). This factor was included within this study, considering the different capacity constraints and environmental intensity factors of our international trading partners.

3 Methodology

LCA quantifies potential environmental impacts and resource use by first building an inventory of input and output data (known as a Life Cycle Inventory, or LCI) and then by carrying out impact assessment (known as a Life Cycle Impact Assessment, or LCIA). The LCA process is standardised under ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), and hence there is suitable guidance on methodology for a conventional LCA study. Additionally, product category rules (PCRs) specific to roads exist for creating EPDs for highways, streets and roads (PCR 2013:20 v2.11), as well as for asphalt mixtures (2018:04 v1.03).

The LCA standards and PCR for developing EPDs are generally applied via the most common approach for conducting LCA – ALCA. This study used both the ALCA and CLCA approaches.

The high-level process implemented for carrying out both LCAs is described below:

- Step 1A: Data collection for ALCA and CLCA parameters
- Step 1B: Build calculator with non-regionalised data
- Step 2: Modelling ALCA
- Step 3: Modelling CLCA
- Step 4: Results analysis
- Step 5: Sensitivity analysis
- Step 6: Reporting
- Step 7: Update Excel calculator with specific data
- Step 8: Peer review
- Step 9: Toolkit/Implementation (rules of thumb).

3.1 Step 1A: Data collection – attributional life cycle assessment

The LCI for pavement materials has been developed using a combination of primary data from New Zealand manufacturers collected specifically for this project, specifications from Waka Kotahi (eg for the bitumen content in asphalt mix designs) and secondary data from the ecoinvent v3.6 database (Wernet et al., 2016), the Australian Life Cycle Inventory (AusLCI) database (Australian Life Cycle Assessment Society, 2011) and GaBi Databases 2021 (Sphera, 2021).

The high-level data requirements for this project are laid out in Table 3.1, with the detailed data requirements in Table 3.2. Table 3.1 presents the *intended* source of data (prior to the commencement of data collection) in the middle, with the *actual* source of data at the right. In cases where primary data could not be sourced from industry, secondary data from databases/literature adapted to New Zealand conditions (eg New Zealand electricity) were used instead, to ensure the Pavement Environmental Calculator is sufficiently complete and fit for purpose. The specific data collected for this project can be found in Chapter 5.

The geographical reference for the data was New Zealand, wherever possible, using current technologies available within New Zealand. Data for the 2019 calendar year has been used for this study where available, as this reflected the situation prior to Covid-19 and thus, production was unaffected by factors such as lockdowns.

Table 3.1 High-level data requirements and expected sources of data, prior to the data collection commencing

Data required	Intended source of data	Actual source of data
Aggregate production		
Aggregate production: crushed rock	Primary data from industry	Primary data from industry
Aggregate production: alluvial sand and gravel	Primary data from industry	Primary data from industry
RCC	Primary data from industry	Primary data from industry
Melter slag	Primary data from New Zealand Steel	Secondary data (estimate)
Recycled glass	Primary data from industry	Primary data (estimated from RCC)
RAP	Primary data from industry	Primary data from industry
Lime filler	Secondary data from LCI databases	Secondary data from LCI databases
Binder production		
Bitumen	Secondary data from LCI databases	Secondary data from LCI databases
Epoxy (for epoxy-modified asphalt)	Secondary data from LCI databases and EPDs	Secondary data from LCI databases and EPDs
Other inputs (eg Sasobit wax, fibre)	Secondary data from LCI databases and EPDs	Secondary data from LCI databases and EPDs
Asphalt production		
Asphalt manufacture	Primary data from industry	Primary data from industry
Construction		
Additional materials: cement, lime, geotextile barriers, bitumen emulsion for chipsealing	Secondary data from LCI databases and EPDs	Secondary data from LCI databases and EPDs
Construction of pavement	Primary data from industry (high-level national averages only)	Combination of primary and secondary data
Use stage		
Maintenance, repair, replacement and refurbishment	Based on Waka Kotahi specifications and replacement of the materials above	Based on Waka Kotahi specifications and replacement of the materials above
End of life		
RAP milling	Primary data from industry	Primary data from industry
Excavation of granular courses	Primary data from industry and/or secondary data from LCI databases (high-level averages only)	Combination of primary and secondary data

Table 3.2 Detailed data requirements and actual sources of data used

Data required	Actual source of data
Aggregate production	
Aggregate (crushed rock) production from New Zealand quarries: • Input of explosives for quarries • Fuel use for mobile plant (excavators, front-end loaders, mobile crushers, pumps) • Energy use (electricity or diesel) for crushing and screening rock • Output wastes associated with aggregate production (eg wastewater) • Economic data (wholesale price of aggregate) • Transport distance to asphalt plant • Water use • Energy use for drying (if dried)	Site-level diesel and electricity data from a selection of quarries operated by Fulton Hogan and Winstone Aggregates
Aggregate (alluvial sand and gravel): • Energy use for screening (and crushing, if applicable) • Water use • Energy for pumping • On-site transport (diesel)	Site-level diesel and electricity data from a selection of quarries operated by Fulton Hogan and Winstone Aggregates
Recycled concrete: • Energy use (diesel and electricity) for transport, loading, unloading, crushing, screening • Economic data (wholesale price of RCC)	Site-level diesel consumption from Green Vision Recycling (Downer), Atlas Concrete and Ward Demolition (all sites use diesel plant only – electricity is used only for offices)
Melter slag: • Energy for crushing and screening • Energy use (diesel) for transport • Economic data (wholesale price of slag)	Proxy data based on aggregate from hard-rock quarries because data could not be sourced from New Zealand Steel (no suitable proxy for this material because of New Zealand Steel's unique process for making steel from iron sand rather than iron ore)
Recycled glass: • Crushing and screening • Water use and washing • Transport • Economic data (wholesale price of recycled glass)	Secondary data from ecoinvent v3.6
RAP production: • Energy (diesel, electricity) for crushing and screening the material to required grades • Transport of the material to asphalt production plant • Economic data (wholesale price of RAP) • Average bitumen content of grades in RAP	Based on data for RCC because some recyclers use the same plant for both RCC and RAP
Lime filler	Secondary data from ecoinvent v3.6
Binder production	
Bitumen: • Bitumen production for use in New Zealand (types: straight run or polymer modified) • Bitumen transport distance to asphalt plant • Economic data (wholesale price of bitumen)	Secondary data from ecoinvent v3.6

Data required	Actual source of data
Epoxy-modified asphalt: • Epoxy manufacture inputs • Epoxy transport distance to asphalt production plant • Economic data (wholesale price of epoxy)	Secondary data from ecoinvent v3.6
Any other inputs (eg Sasobit wax, fibre)	Secondary data from ecoinvent v3.6
Asphalt production	
Asphalt manufacture at plant involving: • Mix designs (Bill of Materials) • Fuel use (diesel) for loading raw materials and transport on site • Energy use (natural gas, LPG, diesel, electricity) for asphalt production • Waste from asphalt production • Transport of asphalt to construction site • Economic data (wholesale price of asphalt)	Site-level thermal energy and electricity data from the three major plant operators (Fulton Hogan, Downer and Higgins Contractors)
Construction	
Additional materials: • Cement • Lime • Geotextile barriers • Bitumen emulsion for chipsealing • Concrete steel reinforcing	EPDs and secondary data from ecoinvent v3.6

3.2 Step 1A: Data collection – consequential life cycle assessment

Most data sources used here were the same as for the ALCA. As discussed in the previous section, it is unlikely that material other than glass (via imported glass containers that are later crushed), bitumen and diesel will be imported for pavement construction. Furthermore, other materials were deemed to be constrained or unlikely to change due to a lack of alternatives.

Melter slag from New Zealand Steel is a somewhat unique case, as its production is constrained and there are multiple end users for the slag. Avertana is one end user, refining and processing the slag into valuable minerals such as titanium dioxide. Their products have considerably lower embodied CO_2 than virgin minerals and therefore, the exhaustion of this material by the construction industry may have knock-on impacts. However, this has been excluded from this analysis because Waka Kotahi has few viable alternatives to this material, there is a lack of available quantitative data, and the material is produced in a low volume compared with other materials.

Electrification/decarbonisation of aggregate transport was out of scope in the short term but it could become significant overall in the medium to long term.

3.3 Step 1B: Build calculator with non-regionalised data

An Excel-based calculator for road pavement assessment – the Pavement Environmental Calculator – was developed in parallel to the data collection, to allow feedback from Waka Kotahi early in the project. The initial versions of this calculator used generic data from international LCI databases and EPDs. The Calculator was later updated (in step 7) to include New Zealand-specific data.

3.4 Steps 2 and 3: Modelling ALCA and CLCA

This study used OpenLCA together with the ecoinvent v3.6 and AusLCI databases. OpenLCA provides the capacity to conduct both ALCA and CLCA. As OpenLCA does not allow dynamic toggling between the ALCA and CLCA modelling approaches, two separate models were built for each material: one for ALCA and another for CLCA.

3.5 Step 4: Impact assessment and results analysis

The indicators from section 1.9 are calculated and reported within the Pavement Environmental Calculator.

3.6 Step 5: Sensitivity and scenario analysis

Sensitivity and scenario analysis were initially part of this project. However, the scope was subsequently changed to allow sensitivity analysis at the project level within the Pavement Environmental Calculator (by varying the input parameters). This step has been left here as a placeholder only.

3.7 Step 6: Reporting

This document has been produced to support the Pavement Environmental Calculator.

3.8 Step 7: Update Excel calculator with specific data

The preliminary Pavement Environmental Calculator developed as part of step 1B was updated to use specific data collected for the study (primary data).

3.9 Step 8: Peer review

The study has undergone a three-person panel review to ensure the comparisons and methodology followed were sound and thus the study is fit for publication and/or use outside of Waka Kotahi.

3.10 Step 9: Toolkit/Implementation (rules of thumb)

The toolkit will include the following to aid its application by Waka Kotahi:

- an executive summary written in plain English, with key findings in a text and slide format
- the Pavement Environmental Calculator, allowing impacts incurred through different scenarios to be evaluated (eg varying levels of recycled/virgin materials, transport distances, etc)
- a short guide with guiding principles and ‘rules of thumb’ based on the research to support decision-making
- an infographic explaining this research and key findings
- short accompanying webinar recordings and presentations that Waka Kotahi can make available, either internally or on its website
- high-level explanation of the methodology
- guidance for using the Pavement Environmental Calculator
- guidance for interpreting LCA data and identifying credible data
- guidance on reading EPDs that have been produced by material manufacturers outside of this project and including the EPD results within the Pavement Environmental Calculator.

4 Pavement Environmental Calculator

This section outlines the process of intended use of the Pavement Environmental Calculator, its structure and its assumptions. The Pavement Environmental Calculator allows three different pavement designs to be compared side by side. There are four tabs with which the user interacts to complete a comparison of pavements, along with six other tabs containing data (but not requiring interaction). The four tabs that a user interacts with are:

- User Guide – a summary of the Calculator and details for the process of completing a comparison
- Data Entry – where the different properties and characteristics of the pavements are detailed
- Traffic Delay – an additional data entry tab that models the impacts of maintenance on traffic
- Impact Analysis – a summary and breakdown of the results for the pavements.

The Calculator allows the results to be presented in a multitude of different ways – the user can select their preferred LCA approach, either CLCA (default) or ALCA, along with a timeline for the results. The tool can consider multiple time horizons ranging from 10 to 100 years, in iterations as detailed below. In addition, given that few roads are decommissioned and converted to another land use at the end of their useable life, the tool annualises all impacts across the design life. The intention of the annualised timeline is to show the effects of extending a pavement's useable life through initial design and maintenance.

The time horizons are:

- 10 years
- 15 years
- 20 years
- 25 years (the Waka Kotahi default design life)
- 30 years
- 40 years
- 50 years
- 60 years
- 80 years
- 100 years.

To enhance a user's ability to interpret the results of the Calculator, the results are broken down into the following main sources of impacts:

1. raw materials for initial construction (these can also be viewed at the specific material level)
2. transport of raw materials (these can also be viewed at the specific material level)
3. initial construction process
4. pavement maintenance (these can also be viewed by each type of maintenance)
5. vehicle–pavement interactions (includes both surface roughness and pavement deflection)
6. pavement end of life.

4.1 Overview pavement parameters

The first inputs required of the user detail each of the different pavement project details, expected vehicle parameters and pavement life expectancies. The project details include a description for each pavement scenario, the location of the project, the LCA methodology used to assess the results and the applicable version of EN 15804.

The speed limit, annual average daily traffic (AADT) flow, annual growth rate and annual increase in the efficiency of vehicles are input within the traffic parameters section. The included vehicle properties are used within the traffic delay, surface roughness and pavement deflection sections to quantify the impacts of varying amounts of additional fuel consumption in each respective situation.

Lastly, the high-level pavement parameters are detailed, including the physical area of the pavement, the design life of the pavement and a variable to define the environmental discount rate. The design life of the pavements can be entered as either years of use or equivalent standard axles (ESA). In a situation where the design life is to be entered in ESA, but this is not known for a pavement, the AADT can be converted to ESA by multiplying it by 1.62 (the national average for 2019; A. Leslie, pers. comm., 2021). The AADT is a readily available form of data that can be converted to the expected ESA using the pavement by accounting for the proportion of heavy vehicles within the national fleet. The timespan of use is also calculated when designing to a set quantity of ESA, to allow time-dependent variables, such as New Zealand's electrical grid, to be appropriately implemented.

The environmental discount rate is a generic adjustment factor aimed at capturing the expected increase in resource and energy efficiency for different processes. The environmental discount rate is only used in processes that do not already have future projections.

4.2 Raw materials for initial construction

The initial stages of the 'Raw Materials' section within the Calculator includes a series of default values, which can be hidden or shown as desired. The purpose of each data series is outlined in sections 4.2.1 to 4.2.3 below. While there are already default values within each data series that can be used as is, each of the sections may be altered to increase the adaptability of the Calculator.

4.2.1 Data entry prompts

Current and future adaptations of the Calculator can be made to ensure its ongoing suitability as potential changes in pavement design or policy occur. To aid with ensuring that valid results are produced in the instances of change, there are several data entry prompts that can be triggered should a user enter information outside of a defined range. The defined ranges are currently listed for layer thicknesses, recycled content, material production energy inputs and diesel consumption during both pavement manufacture and maintenance.

4.2.2 Wearing course customisation

Average design mixes for each of the different wearing courses were provided by Waka Kotahi. By default, these average mixes are used throughout the Calculator. However, should a user wish to alter the composition of a wearing course, they can do so at the beginning of the 'Raw Materials' section of the 'Data Entry' tab. As most of the impacts from a wearing course are due to the inclusion of bitumen, this ability to customise helps to ensure the results are valid when compositions differ from the industry average. The default values from Waka Kotahi can be found in section 5.8.

4.2.3 Energy inputs for materials

The final adjustable dataset covers the respective energy intensities required to produce both the different aggregates and the recycled materials included within the Calculator. The default values are a mix of primary data collected from New Zealand suppliers and values extracted for respective production processes from ecoinvent v3.6. Should a specific supplier with known production energy intensities be selected, these default values can be adjusted to suit.

4.2.4 Pavement design

The first compulsory section within the raw materials section of the Calculator requires details of the physical design of each investigated pavement, particularly the appropriate material and thickness for each layer. Additives within a given layer can be included by detailing the respective thickness that would produce the desired composition rate. For example, if 5% of a 250 mm aggregate base course is to be substituted with RCC, then the thicknesses would be 237.5 mm of aggregate and 12.5 mm of RCC.

The environmental impacts from the raw materials used in construction and any other stage of pavement construction are listed per kilogram in the ‘Materials’ tab of the Calculator. For each raw material, the impacts are determined based on New Zealand industry data for key energy and materials inputs, as detailed in Chapter 5. Impacts due to material consumption throughout the projects are determined by calculating the total mass of each of the raw materials and then multiplying them by their respective unit impacts.

Additionally, the impact of transporting each of the raw materials to site via trucks is accounted for, using trucking emission factors from OpenLCA. The user is required to select the size of the truck used and the distance between the source of the raw material and the construction site.

4.2.5 Construction process

The impacts of constructing the pavement from the respective raw materials is assumed to be entirely due to the combustion of diesel in machinery. The values for the approximate diesel consumption per square metre of constructed pavement are provided within the Calculator in the form of a table (see Table 4.1). The values for the diesel consumption are taken from section 5.3.4 of the *Greenhouse Gas Assessment Workbook for Road Projects* (Transport Authorities Greenhouse Group, 2013). The values listed in Table 4.1 are for some common examples of pavements. These values were cross-checked against primary data from industry (provided as diesel consumption per square metre of total paving of all types) and were found to be representative of New Zealand conditions in 2019/2020. Where necessary, the user may be required to interpolate/extrapolate the values of diesel consumption to suit the expected level of construction intensity. Evaluating the appropriate level of diesel consumption for pavements outside of the listed designs will require a suitable level of professional expertise. If calculating diesel use, it is important to include all diesel combusted to lay and compact all pavement layers and the transport of *machines* to/from the site. The transport of *materials* to/from the site is captured elsewhere within the Calculator and should not be entered here.

Table 4.1 Default diesel consumption factors for pavement construction

Pavement	Diesel (l/m^2)
Full-depth asphalt	1.69
Deep-strength asphalt	2.15
Warm mix asphalt	1.58
Chipseal	1.82
Plain concrete	1.44
Reinforced concrete	1.44

4.3 Pavement maintenance

Pavement maintenance and maintenance-induced traffic delays are calculated in the next tab of the Calculator: ‘Maintenance & Traffic Delay’. This information has been isolated from the remainder of the data entry sections due to the scale of data entry that is required.

The following nine forms of maintenance have been included within the Calculator:

- Crack Sealing
- Fill Cracks (Potholes)
- Surface Defect Repair
- Shoulder Maintenance
- Patch Stabilisation
- Mill and Fill
- Rip and Remake
- Dig Outs
- Lay Over.

Life extension consists of the first five forms of maintenance; replacement maintenance consists of the last four forms.

Impacts are determined using a combination of the methods used during both the ‘raw materials’ and ‘initial construction’ phases. As a given maintenance process is not expected to vary significantly across different installations, or even according to the base pavement, the default materials and layer thicknesses for each maintenance process can be defined once, for all scenarios. One exception is for a dig out, where no default inputs are required; instead, the re-laid pavement is assumed to be of the same design as the initial pavement. The transport distance and vehicle type used for the maintenance materials are also included within the default maintenance process table.

A separate table is then used to determine the impacts of the required maintenance materials (as well as the induced traffic delay – see section 4.4) by entering the area of works alongside the respective year of operations. Maintenance processes can be expected to increase in frequency and intensity towards the end of a pavement’s useful working life.

The impacts due to the maintenance materials are then calculated by multiplying the materials with the respective impacts per kilogram.

The impacts from conducting the maintenance are accounted for with variable diesel consumption per square metre value, in the same way as in the ‘initial construction’ phase. The values for the diesel consumption depend on the type of pavement and the maintenance processes that are occurring (see Table 4.2).

Table 4.2 Default diesel consumption factors for pavement maintenance

Pavement	Diesel (l/m^2)
Crack Sealing	0.1
Fill Cracks (Potholes)	0.1
Surface Defect Repair	0.49
Shoulder Maintenance	0.49
Patch Stabilisation	1.82
Mill and Fill	2.2
Rip and Remake	2.2
Dig Outs	*Equal to the original laying method*
Lay Over	*Equal to the original laying method*

4.4 Induced traffic delay

The environmental impacts of pavement maintenance and replacement are not limited to the consumed materials and installation process. Any pavement maintenance will typically induce traffic delays and increase the idling time of vehicles during a given commute. These additional idling times lead to increased fuel and electricity consumption for each affected vehicle.

Continuing within the ‘Maintenance & Traffic Delay’ tab, the Traffic Delay section has a single table that contains the expected AADT flow for each year across the life of the pavements. The projected maintenance, replacement and eventual end-of-life schedule is then entered for each pavement design. The projected schedules are expected to be taken from the Waka Kotahi *NPV Template* (Waka Kotahi, 2018) and efforts have been made to ensure these data can be accepted in the Calculator in their original form. The values taken from the *NPV Template* to use within the Calculator include:

- description of work
- form of maintenance (life extension or replacement – this is not in the *NPV Template*)
- number of temporary traffic management events occurring that year
- length of time of temporary traffic management event
- expected average delay per vehicle.

Information detailing the national fleet composition from 2021 to 2055 has been taken from the Ministry of Transport’s *Vehicle Fleet Emissions Model* (Ministry of Transport, 2021). The national fleet has been broken down into eight subgroups according to size and fuel: light diesel, light petrol, light electric, light hydrogen, heavy diesel, heavy petrol, heavy electric and heavy biofuel. Light hydrogen vehicles have been grouped with light electric vehicles due to the small percentage of the fleet they comprise and the fact that they will ultimately be powered by electricity (though they will have additional electricity losses through electrolysis of water to produce green hydrogen). After 2055, the fleet is assumed to reach a steady state. The projected fleet composition is shown in Figure 4.1.

Figure 4.1 New Zealand transport fleet projection

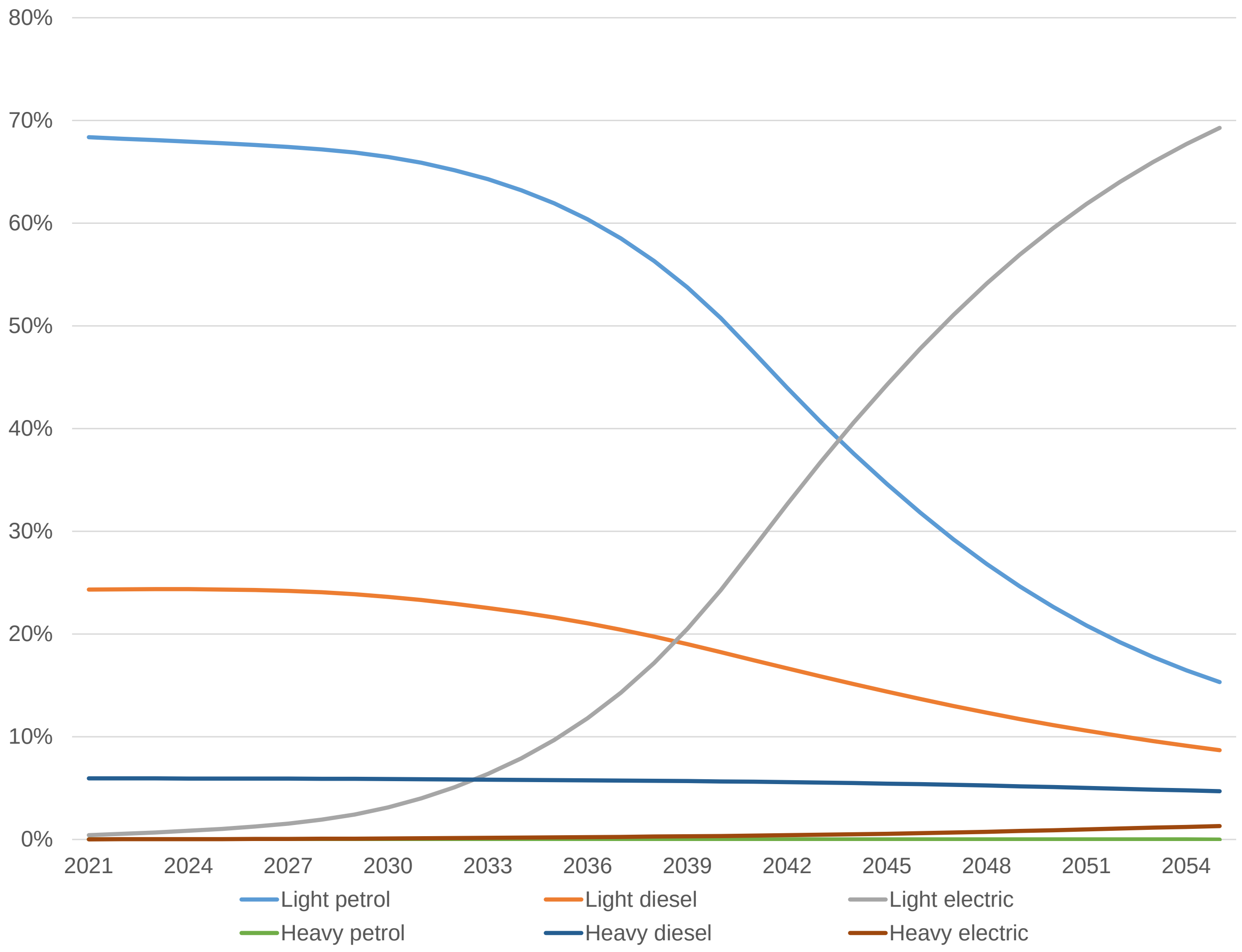


Table 4.3 details the assumed idling fuel or energy consumption rate of the different vehicle classes within the national fleet. The consumption of fuel/energy is due to both the idling of combustion engines and the operation of air-conditioning systems (most pavement maintenance occurs during the summer). The respective fleet composition, idling fuel consumption rates and total period of additional traffic delay are used to determine the total additional fuel used and the corresponding environmental impacts of traffic-induced delays.

Table 4.3 Idling vehicle energy/fuel consumption rates

Vehicle	Idling energy/fuel consumption rate[a]
Light petrol	0.64 l/hour
Light diesel	0.89 l/hour
Light electric/hydrogen	6.40 MJ/hour
Heavy diesel	2.24 l/hour
Heavy electric	6.40 MJ/hour
Heavy biofuel	2.24 l/hour

[a] Energy/fuel consumption rates are measured at the vehicle.

4.5 Vehicle–pavement interactions

The approach taken in this study is that while pavements are not responsible for the environmental impacts of the vehicles travelling over them, they are responsible for the extra fuel consumption in vehicles due to pavement–vehicle interactions, as well as all fuel consumption in vehicles due to delays caused by maintenance activities. Using this logic, the perfect pavement is one that contributes to zero additional vehicle fuel consumption.

There are two main sources of pavement–vehicle interactions: pavement deflection and surface roughness. Each is described in further detail below. Other road parameters, such as horizontal road alignment (curvature in degrees per kilometre) and longitudinal grades (rise or fall in metres per kilometre) also have an impact on fuel consumption; however, these have not been considered here, as they are constrained by the site where the pavement is built.

Neither pavement deflection nor surface roughness can be completely designed out of a pavement. By including the impacts arising from both interactions, the relative importance of minimising their effects can be determined. Several major assumptions around the current and future state of New Zealand's vehicle fleet were made to be able to apply the models that were intended for individual vehicle interactions to the vehicles that were expected to utilise a given pavement. These parameters and their sources are noted below.

4.5.1 Pavement deflection

As a vehicle travels over a pavement, it produces a marginal amount of vertical deflection of the pavement surface due to the load applied by the vehicle. The deflection of the pavement results in additional fuel being consumed to overcome the induced incline, as well as resistance due to the deformation of the viscous paving materials. While some pavement deformation is inevitable, the Calculator aims to help identify the environmental impacts of both the materials used to construct the pavement and the additional vehicle fuel use caused by pavement deflection. This will help the user determine an optimum middle ground between paving material use and additional vehicle fuel use for a specific pavement type.

To quantify the impacts of pavement deflection, a model was constructed using information from *Flügge's Conjecture: Dissipation- versus Deflection-Induced Pavement–Vehicle Interactions* (Louhghalam et al., 2014). This paper outlined the required variables that could be used in a simplified model to determine the rate of additional fuel consumption that would occur for a given pavement due to deflection. The parameters are detailed in Table 4.4.

Table 4.4 Pavement deflection input variables (following Louhghalam et al., 2014)

Parameter	Symbol	Unit
Top layer modulus of elasticity	E	Pa
Top layer thickness	h	M
Subgrade stiffness	k	Pa/m
Vehicle axle load	P	N
Vehicle speed	c	m/s
Beam width	b	M
Surface density	ρ	kg/m^3
Relaxation time	τ	S

Using the above parameters, the values for the variables shown in Table 4.5 can be determined – these are used later in the calculation.

Table 4.5 Pavement deflection input variables

Parameter	Symbol	Formula
Winkler length	ls	(((E*h^3)/12)/k)0.25
Surface mass density	m	ρ*h
Critical speed	ccr	ls*(k/m)0.5
Damping ratio	ζ	т(k/m)0.5 or П2
П1	П1	c/ccr
П2	П2	(т*ccr)/ls

The following equations are then used to determine the additional fuel consumption, δE:

$$\delta E = \frac{D}{c} = \frac{P^2}{{l_s}^2 b} \times \frac{c_{cr}}{c} \times F\left(\Pi_1 = \frac{c}{c_{cr}}; \Pi_2 = \zeta = \tau\left(\frac{k}{m}\right)^{1/2}\right) \qquad \text{(Equation 4.1)}$$

where the Pi function, $F(\Pi)$, is calculated from the following series sum using the coefficients in Table 4.6:

$$\log_{10} F\left(\Pi_1 = \frac{c}{c_{cr}}; \Pi_2 = \zeta\right) = \sum_{i=0}^{i=5} \sum_{j=0}^{j=3} p_{ij} {\Pi_1}^i \times \log_{10}(\Pi_2)^j \qquad \text{(Equation 4.2)}$$

Table 4.6 Pavement deflection Pi coefficients

i	0	1	2	3	4	5
j						
0	−1.918	4.487	−19.54	59.58	−92.51	56.23
1	−0.4123	−1.802	4.014	−4.628	1.375	–
2	−0.06942	0.2153	−0.8618	0.7344	–	–
3	−0.009575	0.0203	0.04669	–	–	–

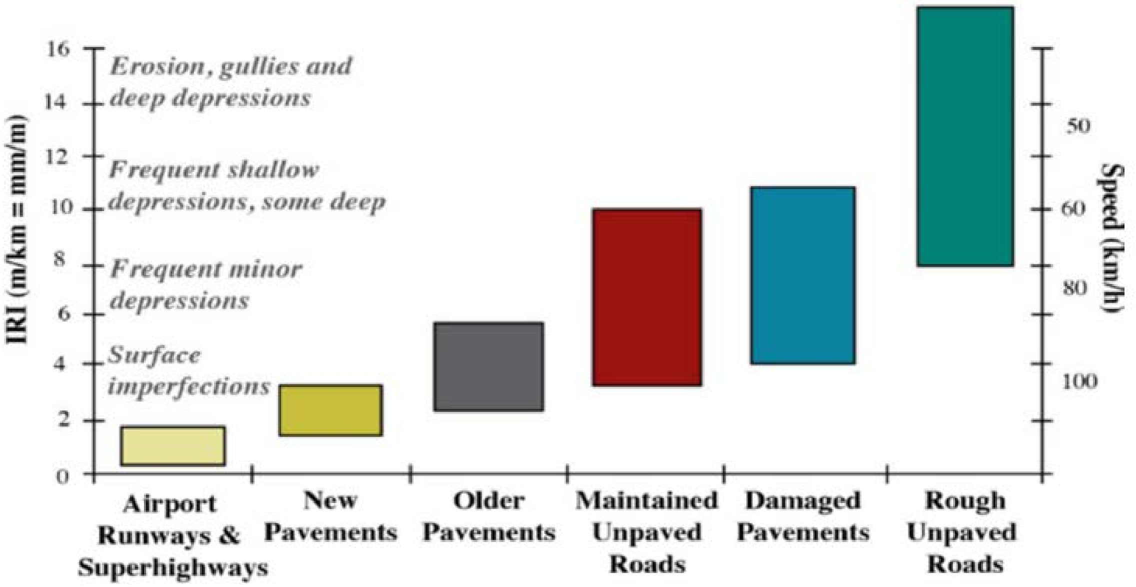
4.5.2 Surface roughness

Pavement roughness is the measure of surface irregularities with wavelengths above 50 mm. When a vehicle travels over a pavement, surface irregularities cause energy to be dissipated by the suspension system. To compensate for the energy absorbed by the suspension system, additional fuel must be combusted. As with the impacts of pavement deflection, all pavements have some surface roughness and will therefore create some additional fuel consumption. The level of additional fuel consumption is dependent on many of the vehicle's mechanical properties. The only pavement parameter that impacts on the fuel consumption is the international roughness index (IRI) of the pavement, which can be measured. To determine the level of additional fuel consumption, the losses due to a pavement surface of IRI = 1.0 (the lowest real-world value for a vehicle pavement) have been removed from the comparison in the Calculator.

The additional energy required to overcome the roughness of a pavement was calculated using the principles outlined in *Roughness-Induced Pavement–Vehicle Interactions: Key Parameters and Impact on Vehicle Fuel Consumption* (Louhghalam et al., 2015). The utilised methodology follows a theoretical approach, unlike other reports that take an empirical approach. The empirical approaches seen in other reports fail to capture the current variability in, and future changes to, the national fleet and so were not considered appropriate for this study.

The IRI is a well-documented metric for measuring user comfort during transit. Thus, the value of the IRI for a given pavement is a familiar variable for a pavement engineer. The relationship between qualitative pavement conditions and the IRI can also be approximated from data, as illustrated in Figure 4.2.

Figure 4.2 Relationship between pavement roughness and condition (reprinted from Greene et al., 2013)



4.6 Pavement end of life and re-laying

In terms of the end of a pavement's useable working life, the Calculator provides two options: leaving the pavement in-ground or removing it. Leaving a pavement in-ground is used in cases where the next pavement will be laid directly over the original. Where removal occurs, environmental impacts arise from the following two processes:

- diesel combustion in the machinery used on site to remove the pavement
- diesel combustion from the trucks used to transport the removed material.

As pavements typically wear from the top layer down, it is common practice to leave some of the lower layers of pavement in-ground. Where layers are left in-ground at the end of their working life, raw materials are not required for the subsequent pavement. To account for the benefits of reusing some of the pavement layers, it is possible in the Calculator to select only the specific layers that are to be removed. As the time horizon for a comparison may extend across multiple pavement replacements, the layers that are intended for removal can be varied across time.

The rate of diesel combustion in removing pavement material is 1.0l/m^3, which is based on diesel consumption for earthworks listed by the Transport Authorities Greenhouse Group (2013). Transportation emissions from trucking are based on the same emission factors as those detailed in section 4.2.

5 Life cycle inventory

5.1 Input materials and energy

5.1.1 Data sources

Most of the materials and processes included within the Calculator are some combination of the following five materials or energy flows: bitumen, diesel, aggregate, cement and electricity. Where possible, primary data were gathered from industry and compared against data sourced from the literature. The sources of primary data were detailed earlier in section 3.1.

thinkstep-anz wishes to acknowledge the following companies who provided data for this project:

- Atlas Concrete
- Downer
- Fulton Hogan
- Green Vision Recycling
- Higgins Contractors
- Hiway Stabilizers
- Stevenson
- Ward Demolition
- Winstone Aggregates.

All primary data were collected over a 12-month period. The reference year for the data ranged from 2016 through to 2020, depending on the company and site, with data from the 2018 to 2019 period (pre-Covid-19) given preference where suitable data were available. Data were collected at the site level in all cases, excluding the use of energy and water by the site offices. Production of capital goods was excluded.

Table 5.1 details the datasets from the LCA databases used at the start of this project. Some continued to be used in the final version of the Calculator (bitumen, diesel and electricity), while others were replaced with primary data from industry (crushed aggregate, alluvial sand and gravel). The flows of energy and materials included within the datasets are described in sections 5.2 to 5.7.

Table 5.1 Key datasets from the literature, used to validate collected primary data where required

Material/process	Location	Dataset	Literature data provider	Reference year	Proxy?[a]
Bitumen	ROW[b]	Pitch production, petroleum refinery operation	ecoinvent v3.6	2014	No*
Diesel	ROW	Diesel production, petroleum refinery operation	ecoinvent v3.6	2014	No*
Crushed aggregate	ROW	Gravel production, crushed	ecoinvent v3.6	2001	No*
Alluvial sand	ROW	Sand quarry operation, extraction from river bed	ecoinvent v3.6	1997	No*
Electricity	NZ	New Zealand Electricity	Bullen, 2020	2020	No

[a] The proxy column indicates whether a dataset accurately represents the desired material or process. It considers two dimensions: the technology/process used and the geographical location:
No = the dataset is not a proxy and correctly reflects technology and geography.
No* = a geographical proxy for the correct process where the region of manufacture is expected to have little influence on its environmental profile.
Yes* = a geographical proxy for the correct process where the region of manufacture is expected to materially influence its environmental profile.
Yes = the chosen dataset is a proxy because it does not consider the correct process or the correct geography.

[b] ROW = Rest of World.

5.1.2 Bitumen

Refining New Zealand ceased production of bitumen within New Zealand in 2021 (Gandhi, 2020). This means that now, all bitumen must be imported. Singapore is one of our major sources of bitumen (Waka Kotahi, 2019). However, no data were available for Singapore within the ecoinvent database. Therefore, a global dataset based on the international market was used. Bitumen data from ecoinvent was used for both ALCA and CLCA. Transport by sea from Singapore to Wellington was included. No adjustments were made for marginal supply in the New Zealand market, given that all bitumen is now imported.

5.1.3 Epoxy-modified bitumen

Epoxy-modified bitumen has the potential to extend the life of wearing courses for open graded surfaces. Over time, its epoxy resin cures and hardens to create a hard binder. For the purposes of the Calculator, the composition of epoxy-modified bitumen was taken from a research paper produced by Opus for Waka Kotahi (Herrington, 2010). The epoxy resin is provided as a two-part mixture: part A is used at 14.6% by weight and consists of epichlorohydrin and bisphenol-A; part B is included at a rate of 85.4% by weight and consists of a fatty acid curing agent and bitumen with a penetration grade of approximately 70. As the ratio of materials within each part was not known, a 1:1 ratio was assumed. The datasets for the materials within the epoxy-modified bitumen are shown in Table 5.2.

Table 5.2 Component datasets for epoxy-modified bitumen

Material/Process	Location	Dataset	Data provider	Reference year	Proxy?[a]
Bitumen with penetration grade of 70	ROW[b]	Pitch production, petroleum refinery operation	ecoinvent v3.6	2014	Yes*
Fatty acid curing agent	ROW	Phenolic resin production	ecoinvent v3.6	2019	Yes
Epichlorohydrin	ROW	Epichlorohydrin production from allyl chloride	ecoinvent v3.6	2019	No
Bisphenol-A	ROW	Bisphenol-A epoxy-based vinyl ester resin production	ecoinvent v3.6	2019	No

[a] The proxy column indicates whether a dataset accurately represents the desired material or process. It considers two dimensions: the technology/process used and the geographical location:
No = the dataset is not a proxy and correctly reflects technology and geography.
No* = a geographical proxy for the correct process where the region of manufacture is expected to have little influence on its environmental profile.
Yes* = a geographical proxy for the correct process where the region of manufacture is expected to materially influence its environmental profile.
Yes = the chosen dataset is a proxy because it does not consider the correct process or the correct geography.

[b] ROW = Rest of World.

5.1.4 Diesel

The dataset for diesel was taken from ecoinvent. There was no dataset within ecoinvent representing the New Zealand market, so a ‘rest-of-world’ dataset was used, based on the average technology and refining processes found in Europe. As the crude oil refining technology found in Europe is similar to that in New Zealand, the rest-of-world dataset was considered suitable.

5.1.5 Cement

Cement included within pavement components is modelled as ordinary Portland cement with no cement replacement, which is common practice within the New Zealand cement and concrete industry, given the lack of locally available SCMs. Fly ash from coal-fired power stations and Ground Granulated Blast Furnace Slag are the two most common SCMs. New Zealand’s only coal-fired power station is Huntly, which burns a mixture of natural gas and coal, creating an intermittent supply of fly ash. New Zealand's only primary steelmaker is New Zealand Steel at Glenbrook, Auckland. Their steelmaking process is from iron sand rather than iron ore and uses melters, rather than a blast furnace, in iron making (hence the production of melter slag, which is not suitable as a cement replacement). As a result, there is very limited availability of locally produced SCMs in the New Zealand market, meaning SCMs must be imported and New Zealand concrete makers must compete on the global market, which often makes SCMs financially unattractive.

The Calculator includes EPD data for Golden Bay Cement (2019) and Holcim (2019), the two largest cement suppliers in the New Zealand market. This cement data is also used as the basis for concrete within the Calculator. The user can select which cement is used to produce the concrete.

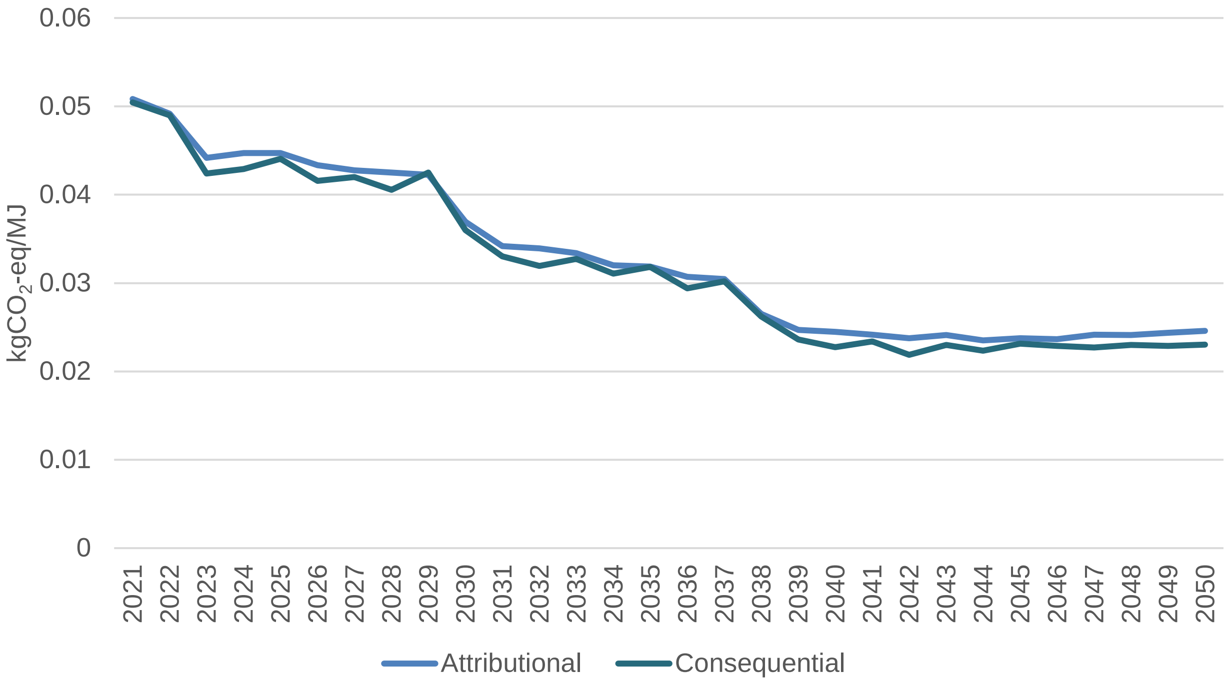
5.1.6 Electricity

As the Calculator aims to quantify the impacts of pavements across multiple decades, the changes to New Zealand's electricity grid mix need to be accounted for. Projected electricity emissions across the multiple impact categories were provided by the New Zealand Life Cycle Management Centre and BRANZ, based on the 'Environmental' scenario from MBIE's Electricity Demand and Generation Scenarios 2019, detailing the projected electricity demand and generation (Bullen, 2020).

Impact factors were provided in two different ways: attributional and consequential. As explained earlier in this study, the attributional and consequential methods utilise two different methods in accounting for the impacts of electricity generation, transmission and distribution infrastructure.

A plot of the forecasted global warming emission factors can be seen in Figure 5.1, while the datasheets with the projected consequential and attributional environmental impacts from 2021 to 2050 can be found in Appendix B. Beyond 2050, the electricity grid mix has been assumed to remain constant, which is considered a valid assumption given that Figure 5.1 shows the grid emissions appearing to stabilise around this time.

Figure 5.1 **New Zealand's forecasted electricity grid mixes GWP**



5.2 Aggregates: Manufactured sand and gravel

Manufactured sand and manufactured gravel (‘crushed rock’ or ‘crushed stone’) come from hard-rock quarries, which are particularly common in the North Island. Explosives are used at a rock face or pit to break down the rock to a manageable size. Then it is loaded by an excavator or front loader into haul trucks and taken to stationary crushers and screens, where it is processed to the desired size. In some quarries, mobile crushers/screens are used in place of, or in addition to, fixed crushers/screens. Some products can be processed in a single pass; others might require additional crushing/screening stages. Many products are supplied unwashed, but certain products are washed and then left to drain in the open air (thermal drying of aggregate is uncommon in New Zealand quarries). Following processing, the crushed stone and manufactured sand are loaded by front loaders into road-going trucks for distribution to customers.

Fixed crushers can be either electric or diesel. All other mobile plant is typically diesel, with some quarries using a share of biodiesel.

There can be significant differences in energy use within the quarry, for the following reasons:

- **Quarry layout and topology:** Some quarries are quite flat and have their crushing plant near to the face. Others might have deep pits with longer haul roads that trucks must travel up and down.
- **Product mix:** The mix of products that the quarry produces has an impact on the quarry’s environmental performance, with some quarries using primary crushing/screening for most of their production and other quarries using secondary and tertiary crushing/screening stages for a larger share of their products.
- **Geology:** The hardness of the rock affects the energy required to crush it.

Given the differences between sites and the difficulty of getting data at the product level from most producers, this study collected data at the site level only. This means that the impacts for all crushed aggregates were assumed to be the same, regardless of their grade. Only data for energy use and production tonnages were collected. The use of explosives was omitted, as this was assumed to fall below the cut-off criteria defined for this study.

A weighted average of energy data (see Table 5.3) was drawn from a sample of 10 quarries from Fulton Hogan, Stevenson and Winstone Aggregates. Data were sourced from the period between 2016 and 2020, with a focus on the years 2018 to 2019. As there are minimal technological differences among hard-rock quarries, the included datasets were considered sufficiently representative for all national hard-rock quarries. However, despite the minimal differences in technology, there were still significant differences in energy use among sites, with a coefficient of variation of 40% for diesel use and 90% for electricity use.

Table 5.3 LCI for crushed aggregate from a hard-rock quarry (intensity per tonne of production)

Flow	Input/ Output	Amount (reference)	Amount (as collected)	Unit	Difference
Rock	Input	1,040	1,040	kg	n/a
Diesel	Input	0.533	1.13	L	+0.597
Electricity	Input	9.06	2.06	kWh	−7.00
Water withdrawal	Input	12.2	12.2	kg	n/a
Rainwater	Input	1,112	1,112	kg	n/a
Aggregate	Output	1,000	1,000	kg	n/a
Crusher dust and oversized rock	Output	40	40	kg	n/a
Particulates < 2.5 um	Output	4.00E-07	4.00E-07	kg	n/a
Particulates > 10 um	Output	5.60E-06	5.60E-06	kg	n/a
Particulates > 2.5 um and < 10 um	Output	2.00E-06	2.00E-06	kg	n/a
Water to river/groundwater	Output	818	818	kg	n/a
Water vapour	Output	307	307	kg	n/a

5.3 Aggregates: Alluvial sand and gravel

Aggregates produced in the South Island of New Zealand are typically extracted from either land- or water-based alluvial deposits. In rivers and seabeds, dredging with either buckets or suction pipes extracts the material while allowing the water to drain back out. Additional screening and washing processes typically occur on land to separate the aggregate by size and remove contaminants such as chlorine.

A land-based alluvial aggregate quarry may be either wet or dry, depending on the local topography; both are typically open-pit excavations. In a wet quarry, the deposit will be worked from above, usually by a long-arm excavator or sometimes by suction pipe, to dredge up the aggregate for processing. In a dry quarry, the face may be worked by a front-end loader or an excavator. Before further processing, the aggregate may need to be cleaned (depending on the source), typically through a trommel, which may be powered by diesel or electricity depending on the quarry set-up. The washing water is usually treated with flocculant and put through a settlement process, then reused. The aggregate is then screened to sort it into its natural sizes. This is generally a wet process, to help wash the sand off the larger aggregate. Again, the water is usually captured, treated and reused.

Where a smaller aggregate size is desired, the larger-sized aggregates pass through a crushing process and further screening to sort them into specific sizes. Typically, fewer crushing steps are required for alluvial sources than for hard-rock sources, as the incoming aggregate is already smaller.

A weighted average of energy data (see Table 5.4) was drawn from a sample of 13 quarries from Fulton Hogan, Stevenson and Winstone Aggregates. All quarries were land-based and therefore they are not representative of dredging operations. Data were sourced from the period between 2016 and 2020, with a focus on the years 2018 to 2019. As there are minimal technological differences among alluvial quarries, the included datasets were considered sufficiently representative for all national alluvial sand and gravel quarries. However, despite the minimal differences in technology, there were still significant differences in energy use among sites, with a coefficient of variation of 84% for diesel use and 71% for electricity use. Table 5.4 only includes rainwater used in quarry operations – for simplicity, rainwater that falls on the site was assumed to be free draining (and not lost as evaporation).

Table 5.4 LCI for aggregate from an alluvial sand and gravel quarry (intensity per tonne of production)

Flow	Input/ Output	Amount (reference)	Amount (as collected)	Unit	Difference
Gravel, in ground	Input	1,040	1,040	kg	n/a
Diesel	Input	0.475	0.71	L	+0.233
Electricity	Input	2.72	2.36	kWh	−0.360
Water withdrawal	Input	10.1	10.1	kg	n/a
Rainwater	Input	1,380	1,380	kg	n/a
Aggregate	Output	1,000	1,000	kg	n/a
Spoil, returned to ground	Output	40	40	kg	n/a
Water to river/groundwater	Output	1,390	1,390	kg	n/a
Water vapour (additional)	Output	0	0	kg	n/a

5.4 Aggregates: Recycled crushed concrete

Concrete crushers can be either diesel or electric powered. However, as RCC is often produced on site from scrap concrete, the plant is typically mobile. Mobile crushers are predominantly diesel powered to allow for ease of set-up and fuelling.

As no suitable secondary dataset could be identified from the literature, the primary data were collected by using Auckland as a case study. In 2021, Auckland had at least four significant producers of RCC: Atlas Concrete in the north (Albany), Ward Demolition and Green Vision Recycling in the south (both in Onehunga) and Western Aggregates & Soil in the west (Glendene). Many smaller operations also existed.

For this project, data were collected from Atlas Concrete, Ward Demolition and Green Vision Recycling. All data were for the period 2020 to 2021. The key findings were as follows:

- All sites had a production capacity of between 50,000 and 80,000 tonnes per year.
- All sites charged for scrap concrete received at their yard. One site accepted certain types of concrete at no charge, but the disposer had to either pay for its delivery or pay a fee for its disposal. Therefore, the end-of-waste state (as per section 1.7.2) was not reached until after the concrete had been crushed and therefore, the environmental burden of concrete recycling was assigned to the previous product's life cycle and *not* to the life cycle that would use the RCC. Put another way, from the perspective of the user, the RCC was burden-free up to the producer's outbound gate.
- All sites used diesel plant exclusively (crushers, excavators, loaders). Most processing was done in a single pass, using a single crusher/screen with a return for oversize. Electricity was only used for the site offices.
- Diesel consumption was 0.52 L per tonne of recycled material produced (weighted average).
- The amount of waste produced from each site was effectively zero. All sites rejected incoming loads if they did not meet their screening criteria. As the recycled products sold were typically all-passing, there was no undersized waste to dispose of.
- The amount of reinforcing steel in the concrete varied significantly per site. Green Vision Recycling only accepted unreinforced concrete at the time this study was conducted. Atlas Concrete took concrete with minimal reinforcing, leading to an average steel content of 0.6% mass/mass. Ward Demolition was the only site to accept heavily reinforced concrete. In their case, the steel content varied between 2% and 5% mass/mass (with an average of approximately 3% mass/mass), depending on the scrap concrete being processed in a given period.

5.5 Aggregates: Reclaimed glass

As no specific data could be sourced for reclaimed glass, it was based on RCC in section 5.4.

5.6 Aggregates: Glenbrook melter slag

New Zealand Steel were invited to provide data for melter slag from their Glenbrook steelworks but they decided not to provide data at this time. New Zealand Steel's operation is unique in the world in that it produces iron and steel from iron sand (using multi-hearth furnaces and melters), rather than from iron ore (using a blast furnace). Therefore, we were not able to identify a suitable proxy for Glenbrook melter slag. Crushed aggregate is currently used as a proxy within the Calculator. A standard steelmaking slag could be considered a better proxy from an environmental impact perspective; however, this is unlikely to be the material used if melter slag is unavailable.

5.7 Asphalt plant

Asphalt is produced by binding together an aggregate mix with bitumen. The type and grade of aggregate, along with the type of bitumen, varies depending on the asphalt being produced. Five types of asphalt were included within the Calculator:

- SMA

- dense graded asphaltic concrete (AC)
- OGPA
- EMOGPA
- RAP.

Asphalt may be produced in a plant heated by either natural gas or liquid fuels. Natural gas plants are common in the urban parts of the North Island, where there is ready access to natural gas. Liquid fuel plants are used in the South Island and smaller towns in the North Island that do not have access to a natural gas pipeline. Liquid fuel plants may be run on diesel, biodiesel, waste oil and used oil, or any combination of these fuels. In addition, asphalt plants may operate as either hot mix or warm mix. In the 2020 to 2021 period, nearly all asphalt plants in New Zealand produced hot mix asphalt exclusively.

Data were collected from 29 fixed asphalt plants around New Zealand operated by Fulton Hogan, Downer, and Higgins Contractors: 10 powered by natural gas and 19 powered by liquid fuels. Natural gas plants tended to be larger (averaging 74,000 tonnes per annum), while liquid fuel plants tended to be smaller (averaging 23,000 tonnes per annum), though this was primarily due to location rather than technology. The data collected covered all energy used by the plant (heating fuel, burner fuel, mobile plant, plant electricity), but excluded energy used by site offices.

Only plants operating at near 100% hot mix asphalt were included within the averages. The energy intensity of warm mix asphalt was calculated by scaling down the thermal energy input (natural gas or liquid fuel) by a factor of 15%, based on Calabi-Floody et al. (2020), which found fuel reductions of 10% and 15% (corresponding to a temperature reduction of 20°C) and cited an earlier study by Anderson et al. (2008) that showed fuel reductions averaging 22% across 13 projects (from a 27°C temperature reduction).

Plant-level inputs and outputs (excluding materials) are shown below for hot mix asphalt using natural gas (see Table 5.5), warm mix asphalt using natural gas (see Table 5.6), hot mix asphalt using liquid fuels (see Table 5.7) and warm mix asphalt using liquid fuels (see Table 5.8). Asphalt mix designs are described in the next section.

Table 5.5 LCI for hot mix asphalt (natural gas), excluding raw materials (per tonne of production)

Flow	Direction	Amount	Unit
Raw materials	Input	1,000	kg
Natural gas	Input	272	MJ
Diesel	Input	0.19	litres
Electricity	Input	8.88	kWh
Asphalt	Output	1,000	kg

Table 5.6 LCI for warm mix asphalt (natural gas), excluding raw materials (per tonne of production)

Flow	Direction	Amount	Unit
Raw materials	Input	1,000	kg
Natural gas	Input	232	MJ
Diesel	Input	0.19	litres
Electricity	Input	8.88	kWh
Asphalt	Output	1,000	kg

Table 5.7 LCI for hot mix asphalt (liquid fuels), excluding raw materials (per tonne of production)

Flow	Direction	Amount	Unit
Raw materials	Input	1,000	kg
Diesel equivalent	Input	8.21	litres
Electricity	Input	13.8	kWh
Asphalt	Output	1,000	kg

Table 5.8 LCI for warm mix asphalt (liquid fuels), excluding raw materials (per tonne of production)

Flow	Direction	Amount	Unit
Raw materials	Input	1,000	kg
Diesel equivalent	Input	7.01	litres
Electricity	Input	13.8	kWh
Asphalt	Output	1,000	kg

5.8 Wearing course mixtures

The mixture for wearing courses can vary dramatically depending on factors such as location, the specific contractor and intended pavement function. To aid in creating a user-friendly interface, default values for pavement wearing course mixes are already included within the tool. Default compositions for wearing courses were based on the average of the Waka Kotahi-approved design mixtures and are detailed in Table 5.9. To increase the flexibility of the tool, the default wearing course mixtures can be varied if desired.

Table 5.9 Waka Kotahi default wearing course mixtures

Pavement type	Wearing course	Aggregate, hard rock & alluvial (mass %)	Aggregate, dredged (mass %)	Bitumen (mass %)	Cement (mass %)	Epoxy-modified bitumen (mass %)
Unbound base (chipseal)	Chipseal	88.0%	0.0%	12.0%	0.0%	0.0%
Unbound base (AC)	AC	95.0%	0.0%	5.0%	0.0%	0.0%
Hi-Lab (SMA)	SMA	53.5%	40.0%	6.5%	0.0%	0.0%
Structural asphalt (OGPA)	OGPA	94.0%	0.0%	6.0%	0.0%	0.0%
Modified base (EMOGPA)	EMOGPA	94.0%	0.0%	4.5%	0.0%	1.5%

5.9 Pavement construction

In the Calculator, the environmental impacts of constructing a pavement from raw materials are accounted for in two processes: transportation and laying. All materials that require transportation are assumed to be delivered to site by truck. To quantify the impacts of transportation, every raw material has a specified size of truck and transportation distance associated with them. Three different-sized trucks are available for selection (see Table 5.10). Euro 4 engines (available from 2006 in Europe) were selected as being most representative of average New Zealand trucks in 2021, based on the average age of vehicles on the road. The sulfur content of the fuel was defined as 10 ppm, to match New Zealand legislation. The share of biofuels in the fuel mix was set to 0% by default.

Table 5.10 Transportation datasets

Flow	Location	Dataset	Data provider	Utilisation factor	Reference year
Truck (7.5–16 t)	Global	Truck, Euro 4, 7.5 t-12 t gross weight/5 t payload capacity	GaBi Databases 2021	50%	2020
Truck (16–32 t)	Global	Truck (16-32 t)	GaBi Databases 2021	50%	2020
Truck (32 t+)	Global	Truck, Euro 4, more than 32 t gross weight/24.7 t payload capacity	GaBi Databases 2021	50%	2020

The environmental impacts of laying a pavement were assumed to be solely due to the combustion of diesel within the machinery used. As not enough primary data could be collected to determine the rates of diesel combustion for different types of pavements, values from the literature were used, as outlined earlier in section 4.2.5.

5.10 Background data

Data for the remaining upstream and downstream processes were obtained from the ecoinvent v3.6 database within OpenLCA and the GaBi Databases 2021 within the GaBi Professional LCA software. Details for the additional datasets are shown in Table 5.11.

Table 5.11 Material and energy consumption unit process datasets

Material/Process	Location	Dataset	Database	Reference year	Proxy?[a]
Diesel combustion (construction)	Global	Excavator, 100 kW, construction	GaBi Databases 2021	2020	Yes
Diesel combustion (road vehicles)	Global	Car diesel, Euro 4, engine size more than 2 l	GaBi Databases 2021	2020	Yes
Petrol combustion (road vehicles)	Global	Car petrol, Euro 4, engine size more than 2 l	GaBi Databases 2021	2020	Yes
Bitumen emulsion	Europe	Bitumen adhesive compound production, cold	ecoinvent v3.6	1994	No*
Pumice	Germany	Pumice quarry operation	ecoinvent v3.6	2000	No*
Lime	Switzerland	Quicklime production, in pieces, loose	ecoinvent v3.6	2019	No*
Polyurethane	ROW[b]	Polyurethane production, rigid foam	ecoinvent v3.6	1997	Yes

[a] The proxy column indicates whether a dataset accurately represents the desired material or process. It considers two dimensions: the technology/process used and the geographical location:
No = the dataset is not a proxy and correctly reflects technology and geography.
No* = a geographical proxy for the correct process where the region of manufacture is expected to have little influence on its environmental profile.
Yes* = a geographical proxy for the correct process where the region of manufacture is expected to materially influence its environmental profile.
Yes = the chosen dataset is a proxy because it does not consider the correct process or the correct geography.

[b] ROW = Rest of World.

6 Life cycle impact assessment

6.1 Example pavements

This section presents data inputs and results for several example pavements, to demonstrate how to use the Calculator and provide some sample results. However, it is important to note that these pavements are not functionally equivalent and therefore, they cannot be directly compared to one another.

Data for three example pavements are provided in Table 6.1 and Table 6.2, based on information provided by Beca (G. Smith, pers. comm., 2021). While over 100 different environmental indicators are included within the Calculator, the results below are solely for the headline environmental indicator of carbon footprint (GWP).

Table 6.1 Example pavement designs

Type		Wearing course	Base course	Upper base course	Subgrade improvement	Subgrade
Unbound base (chipseal)	Material	Chipseal	Aggregate (M/4 AP40)	Aggregate AP65	Lime-modified subgrade	Cohesive soil
	Thickness (mm)	10	150	250	250	∞
Unbound base (AC)	Material	Asphalt (AC)	Aggregate M/4 AP40	Aggregate AP65	Lime-modified subgrade	Cohesive soil
	Thickness (mm)	55	150	350	250	∞
Hi-Lab (SMA)	Material	Asphalt (SMA)	Hi-Lab 40	Hi-Lab 65	Sand subgrade improvement	Cohesive soil
	Thickness (mm)	50	180	230	860	∞

Table 6.2 Additional pavement parameters

Scenario	Pavement	Expected life of pavement surface (years)	Expected traffic (AADT)	Average speed of vehicles (km/h)
Low volume, low speed	Unbound base (chipseal)	25	5,000	50
	Unbound base (AC)	25		
	Hi-Lab (SMA)	35		

Additional parameters used in the investigation were as follows, consistent across all pavements:

- pavement area: 2-lane kilometre (7 m x 1 km)
- annual traffic volume growth rate: 1.6%
- annual increase in driving efficiency: 2.7% (Ministerial Forum on Vehicle Emissions, 2016)
- environmental discount of impacts to account for annual technology efficiency improvements: 1.0%.

The environmental impacts for the three scenarios are presented here using both a 25-year life (see Figure 6.1) – chosen because this is the default design life used by Waka Kotahi – and annualised across the design life (see Figure 6.2). The annualised results convey the potential residual environmental benefits of a pavement lasting beyond the required 25-year design life. Both charts show the results using ALCA to align with EN 15804. Importantly, there was very little difference in the results if CLCA was applied instead, providing evidence that ALCA is likely to be suitable for future-oriented decision-making in the New Zealand context. This is an advantage, given that EPD data for specific materials always uses ALCA.

Figure 6.1 and Figure 6.2 illustrate the following:

- Pavement–vehicle interactions can be very significant. In some cases, they may contribute more than half of the carbon footprint of the pavement over its life cycle.
- The impacts of both the raw materials used and the physical construction of the pavement are significant contributors to carbon footprint. The impact of transporting materials to site is typically a lesser contributor to the total carbon footprint.
- For the Hi-Lab (SMA) pavement, increased raw materials impacts (largely due to the addition of cement in the Hi-Lab layers) can be partly offset by a combination of reduced vehicle fuel consumption (caused by pavement–vehicle interactions and maintenance traffic delay) and a longer pavement life. The extent to which these improvements do offset the initial carbon footprint embodied in the materials depends on traffic levels and pavement performance.
- These charts show that the impacts of maintaining the pavement are much smaller than the impacts of building the initial pavement. However, the extent to which this is true depends on how effective the maintenance schedule is at prolonging the life of the pavement’s layers. The benefits of maintenance quickly tend towards zero as a greater share of the total length of the original pavement needs to be dug out and re-laid.

Figure 6.1 **Pavement environmental impacts, 25-year time horizon (not a direct comparison)**

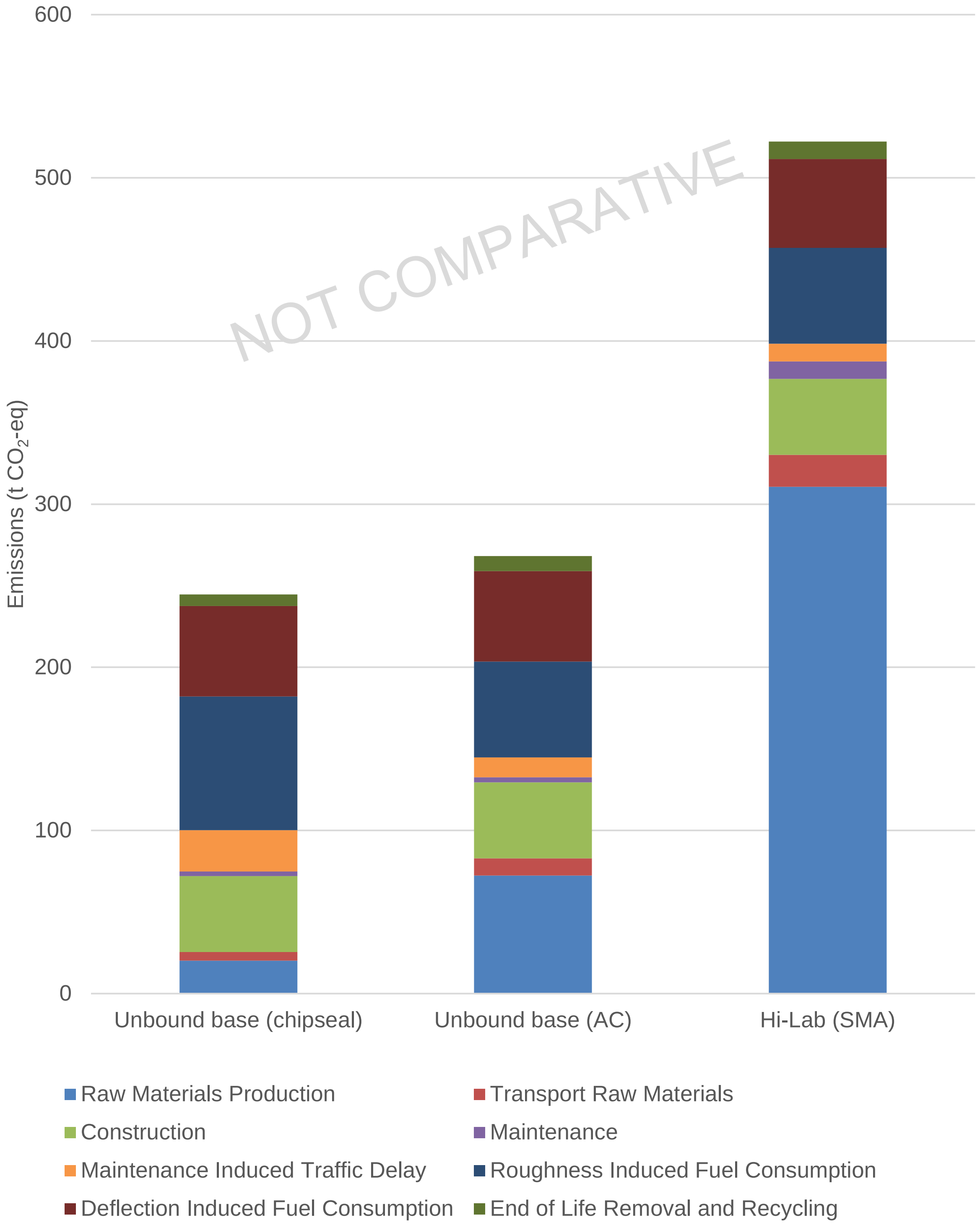
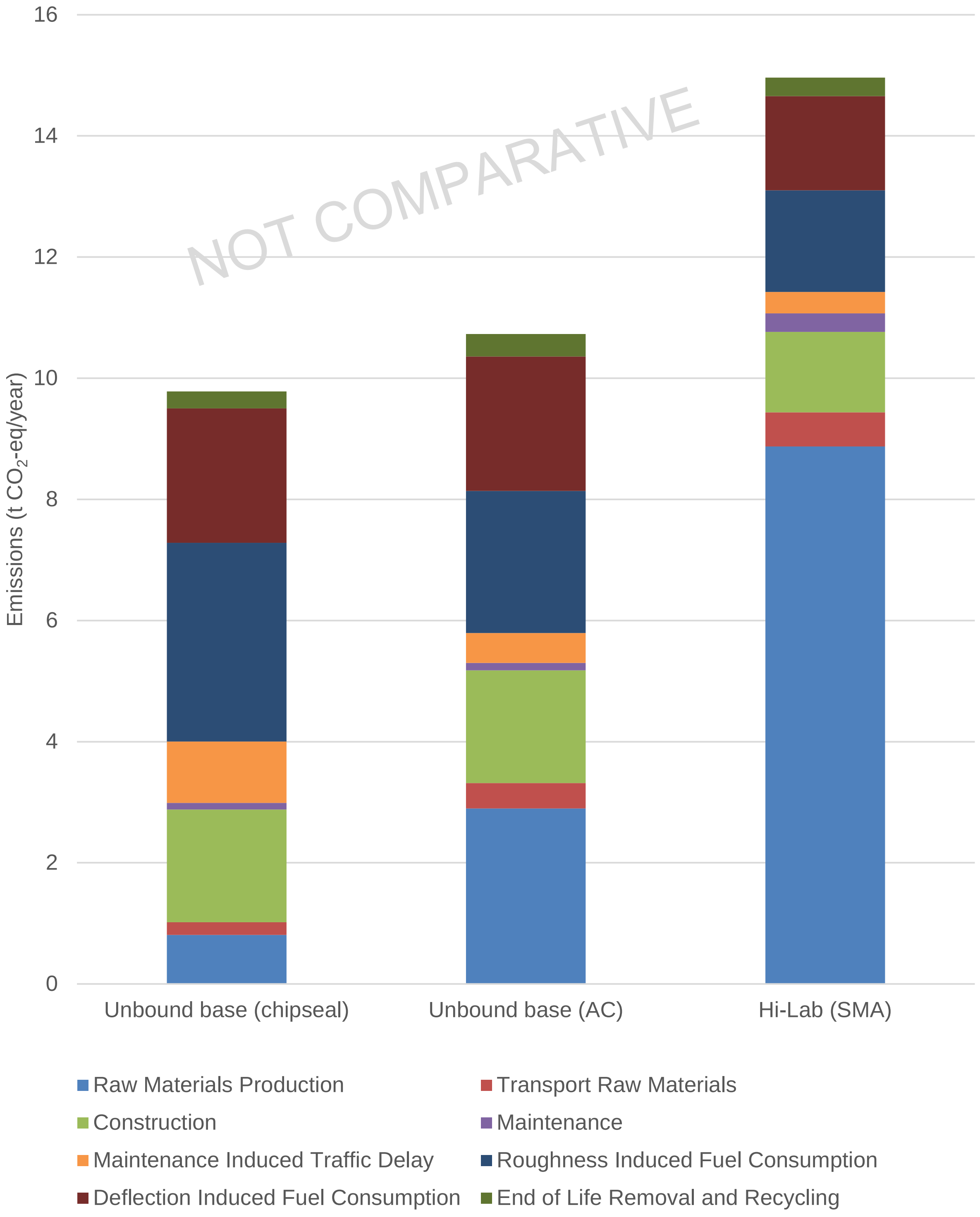


Figure 6.2 Pavement environmental impacts, annualised across the design life (not a direct comparison)



6.2 Rules of thumb for recycled material

Table 6.3 below provides initial rules of thumb for the use of recycled materials. These can be summarised as follows:

- The source of RCC can be up to 49 km further from the paving site than a hard-rock quarry and up to 33 km further away than an alluvial sand and gravel quarry and still have a carbon footprint that is the same as, or lower than, virgin aggregate. Beyond this additional distance, virgin aggregate should be used.
- The source of reclaimed glass can be up to 28 km further away than an alluvial sand and gravel quarry and still have a carbon footprint that is the same as, or lower than, virgin sand. Beyond this additional distance, virgin sand should be used.
- The source of RAP can be over 500 km further away than the source of virgin asphalt and still have a carbon footprint that is the same as, or lower than, virgin asphalt pavement. This means that recycling of RAP will be the low-carbon, circular-economy solution in virtually all practical cases.

The comparisons above assume that the recycled material has the equivalent technical performance as the virgin material it replaces and an equivalent (or longer) functional life.

Table 6.3 Rules of thumb for recycled material

Recycled material	Comparative virgin material	Recycled material GWP (kg CO_2e/t)	Virgin material GWP (kg CO_2e/t)	Transport emissions per kgkm	Additional one-way distance (km)
RCC	Hard-rock aggregate	0	0.00386	7.93E-05	48.7
RCC	Alluvial aggregate	0	0.00262	7.93E-05	33.0
Reclaimed glass	Alluvial aggregate	0	0.00262	9.41E-05	27.9
RAP	AC	0.00161	0.05582	9.41E-05	576

7 Conclusions, limitations and recommendations

7.1 Conclusions

A calculator tool for comparing the environmental performance of pavements has successfully been developed. This tool – the Pavement Environmental Calculator – assesses the environmental footprint of a full pavement over its full life cycle. It uses the pavement's life cycle carbon footprint as a headline indicator, intended to be considered in decision-making alongside the pavement's life cycle cost. It also considers a wide range of other environmental indicators to help the user understand whether there are any trade-offs between carbon footprint and other areas of environmental concern.

Through comparing the example pavements, the following trends were observed:

- Pavement–vehicle interactions can be very significant; they can make up over half of the pavement's life cycle carbon footprint in certain circumstances. These interactions become more important as the speed and flow rate of vehicles increases.
- The relative impacts of raw materials are higher when pavements have shorter design lives.
- The environmental impacts from materials increase significantly as the use of binders (bitumen and cement) increases. This is important for surface courses, Hi-Lab pavements and cement-stabilised subgrade. The use of SCMs to partially replace cement is likely to be an important strategy to decarbonise the carbon footprint embodied in paving materials.
- Reusing layers of the pavement is an effective method of reducing emissions.

As an initial rule of thumb, for recycled materials to have a lower carbon footprint than equivalent virgin materials (provided they meet the same technical performance and lifetime criteria):

- RCC may be up to 50 km further from the job site than virgin aggregate from a hard-rock quarry
- RCC and reclaimed glass may be up to 30 km further from the job site than virgin aggregate from an alluvial sand and gravel quarry
- RAP may be up to 500 km further from the job site than virgin asphalt pavement.

There were no significant differences in the results observed for ALCA and CLCA. As a result, the default LCA method within the tool has been set to ALCA, as this allows for EPD data to be used. Waka Kotahi may wish to remove the CLCA option and data in future versions of the Calculator, to make it easier to maintain.

7.2 Limitations

Several assumptions were made in this study, as described in earlier sections. Where possible, a conservative approach was applied, including proxies rather than cutting off elements for which there was uncertainty. The minor flows that were excluded from the study using cut-off criteria were assumed to have negligible impact on the outcome of the study.

As a result of these assumptions, the following limitations should be noted:

- Pavement–vehicle interactions depend heavily on the nature of the fleet driving over it. While an attempt was made to model the composition of the future fleet, it is difficult to do this accurately.
- Pavement–vehicle interactions are highly complex. We attempted to include these in the Calculator as best as possible within the timeline and budget available for this project. However, they could be further revised and refined over time.
- We consider the human health and nuisance impacts costed within the Calculator to be speculative, as the Calculator does not account for the proximity of the pavement to people.

- While the Calculator accounts for the environmental impacts of ‘average’ materials, the impact of materials can vary significantly between suppliers and sites. (Custom materials are available in the Calculator to help to address this limitation.)
- Material sent to landfill was assumed to be inert. With no landfill emissions, the environmental impacts of sending any degradable materials to landfill were not captured.

7.3 Recommendations

This project has developed an initial version of the Pavement Environmental Calculator. The authors recommend that Waka Kotahi invites industry to use the tool in real-world projects and to provide feedback on its usability, functionality and the availability of data to use within the Calculator. It is hoped that a user group will develop over time to share findings and knowledge, allowing rules of thumb for environmentally conscious pavement design to be improved and, ultimately, to improve the environmental performance of New Zealand’s pavements.

Specific recommendations are as follows:

- Request feedback from the paving industry on the use of the Calculator.
- Compile a library of analyses run within the Calculator to allow the rules of thumb to be expanded to include other questions relevant to paving, beyond the use of recycled materials.
- Use the Pavement Environmental Calculator to conduct analyses of alternative types of pavements, including those that are currently uncommon in New Zealand (eg pavements with a concrete base layer). Use the Calculator to run different scenarios for these pavements, to understand the trade-offs between up-front materials impacts and longer-term payback from reduced pavement–vehicle interactions, maintenance-induced traffic delays and reduced maintenance activities.
- Further work on pavement–vehicle interactions would be beneficial, as environmental impacts due to additional fuel use and wear in vehicles travelling over the pavement can be both high impact and highly uncertain. The initial version of the Calculator includes pavement–vehicle interactions that increase fuel consumption in vehicles travelling over the pavement. It excludes environmental impacts due to increased repairs and maintenance of vehicles, though these could be considered in a future version. Surface roughness currently does not account for deterioration over time, as this is complicated by parts of the pavement deteriorating at different rates and maintenance reducing roughness for some segments of the pavement.
- Further work on the costing of the human health impact is required. The current approach does not account for the spatial distribution of emissions (eg urban versus rural) and therefore, any potential hazards to human health are likely significantly overestimated.
- Invite the ISC to use the new LCA datasets for New Zealand construction materials developed within this project (eg for aggregates from hard-rock quarries) within its ISC IS v2 Materials Calculator for use in future ISC-rated projects.

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Appendix A: Critical review statement

CRITICAL REVIEW OF LCA TOOL FOR ROADS

FINAL REVIEW STATEMENT

WAKA KOTAHI (NZTA)
28 JUNE 2021
S2017

Waka Kotahi (NZTA) – Review LCA tool for roads

Project Details

Project Title
Waka Kotahi (NZTA) – Critical review of LCA tool for roads

Client Details
Waka Kotahi – NZ Transport Agency

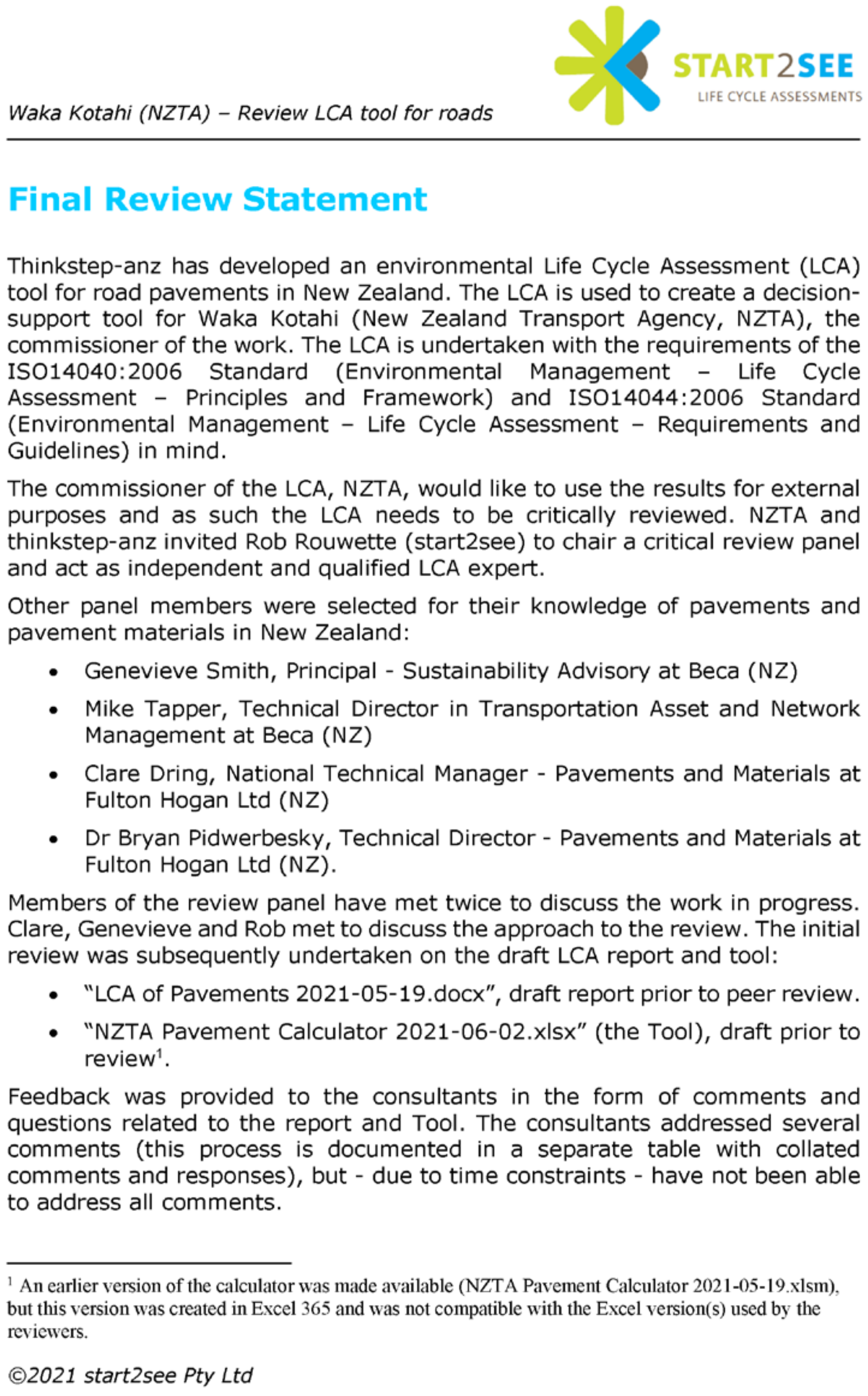
Client Contact	start2see Project Manager
Jeff Vickers (thinkstep-anz)	**Rob Rouwette**

Report version	Author(s)	Date
Final Review Statement	**Rob Rouwette (start2see)** **Clare Dring, Bryan Pidwerbesky (Fulton Hogan)** **Genevieve Smith, Mike Tapper (Beca)**	**28 June 2021**

Disclaimer

If you would like to discuss any of the topics or have any questions please feel free to contact start2see (Rob Rouwette) on mobile +61 403 834 470.

Melbourne, Australia
ABN: 43 143 127 315



Waka Kotahi (NZTA) – Review LCA tool for roads

START2SEE
LIFE CYCLE ASSESSMENTS

Final Review Statement

Thinkstep-anz has developed an environmental Life Cycle Assessment (LCA) tool for road pavements in New Zealand. The LCA is used to create a decision-support tool for Waka Kotahi (New Zealand Transport Agency, NZTA), the commissioner of the work. The LCA is undertaken with the requirements of the ISO14040:2006 Standard (Environmental Management – Life Cycle Assessment – Principles and Framework) and ISO14044:2006 Standard (Environmental Management – Life Cycle Assessment – Requirements and Guidelines) in mind.

The commissioner of the LCA, NZTA, would like to use the results for external purposes and as such the LCA needs to be critically reviewed. NZTA and thinkstep-anz invited Rob Rouwette (start2see) to chair a critical review panel and act as independent and qualified LCA expert.

Other panel members were selected for their knowledge of pavements and pavement materials in New Zealand:

- Genevieve Smith, Principal - Sustainability Advisory at Beca (NZ)
- Mike Tapper, Technical Director in Transportation Asset and Network Management at Beca (NZ)
- Clare Dring, National Technical Manager - Pavements and Materials at Fulton Hogan Ltd (NZ)
- Dr Bryan Pidwerbesky, Technical Director - Pavements and Materials at Fulton Hogan Ltd (NZ).

Members of the review panel have met twice to discuss the work in progress. Clare, Genevieve and Rob met to discuss the approach to the review. The initial review was subsequently undertaken on the draft LCA report and tool:

- "LCA of Pavements 2021-05-19.docx", draft report prior to peer review.
- "NZTA Pavement Calculator 2021-06-02.xlsx" (the Tool), draft prior to review[1].

Feedback was provided to the consultants in the form of comments and questions related to the report and Tool. The consultants addressed several comments (this process is documented in a separate table with collated comments and responses), but - due to time constraints - have not been able to address all comments.

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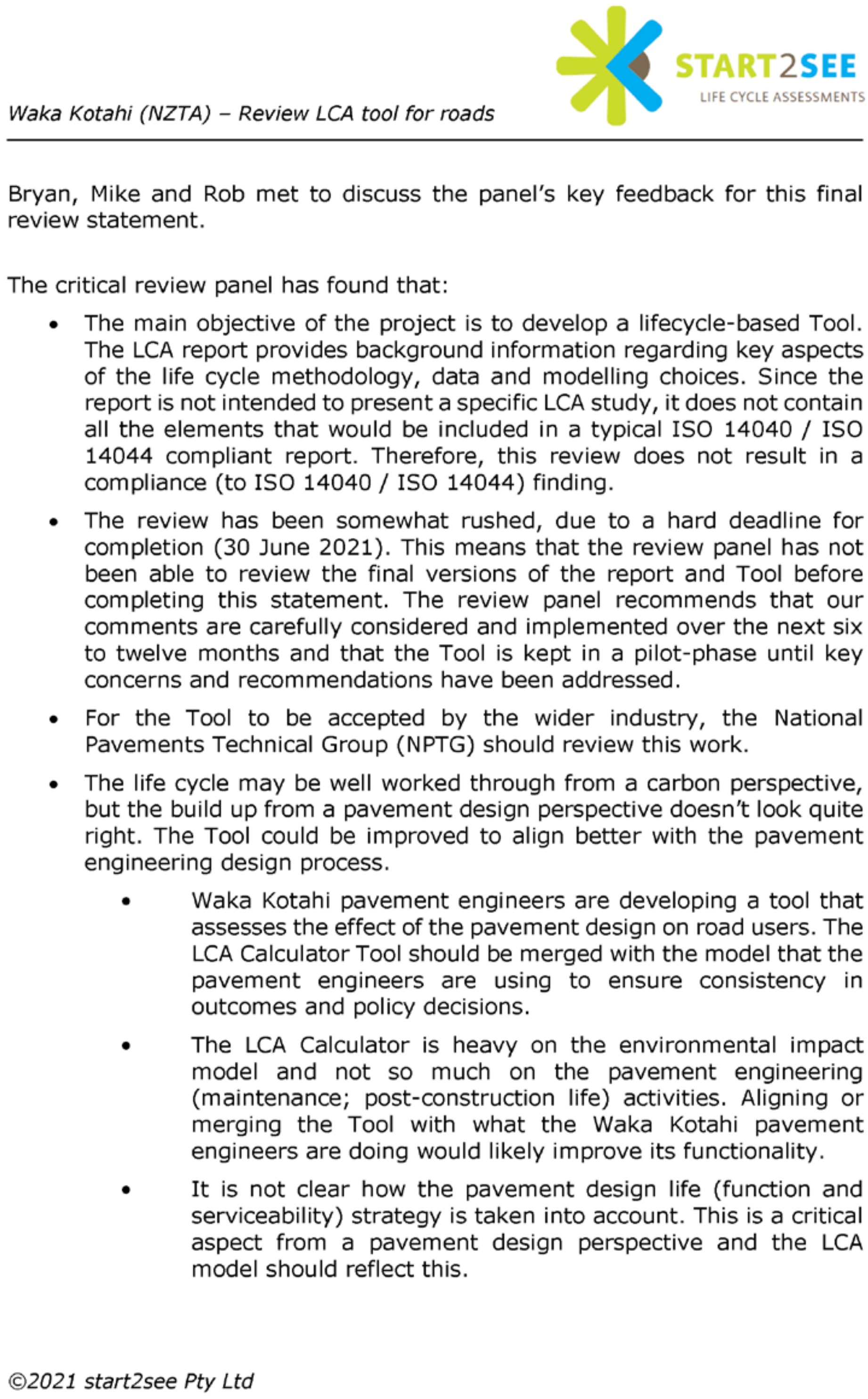
[1] An earlier version of the calculator was made available (NZTA Pavement Calculator 2021-05-19.xlsm), but this version was created in Excel 365 and was not compatible with the Excel version(s) used by the reviewers.



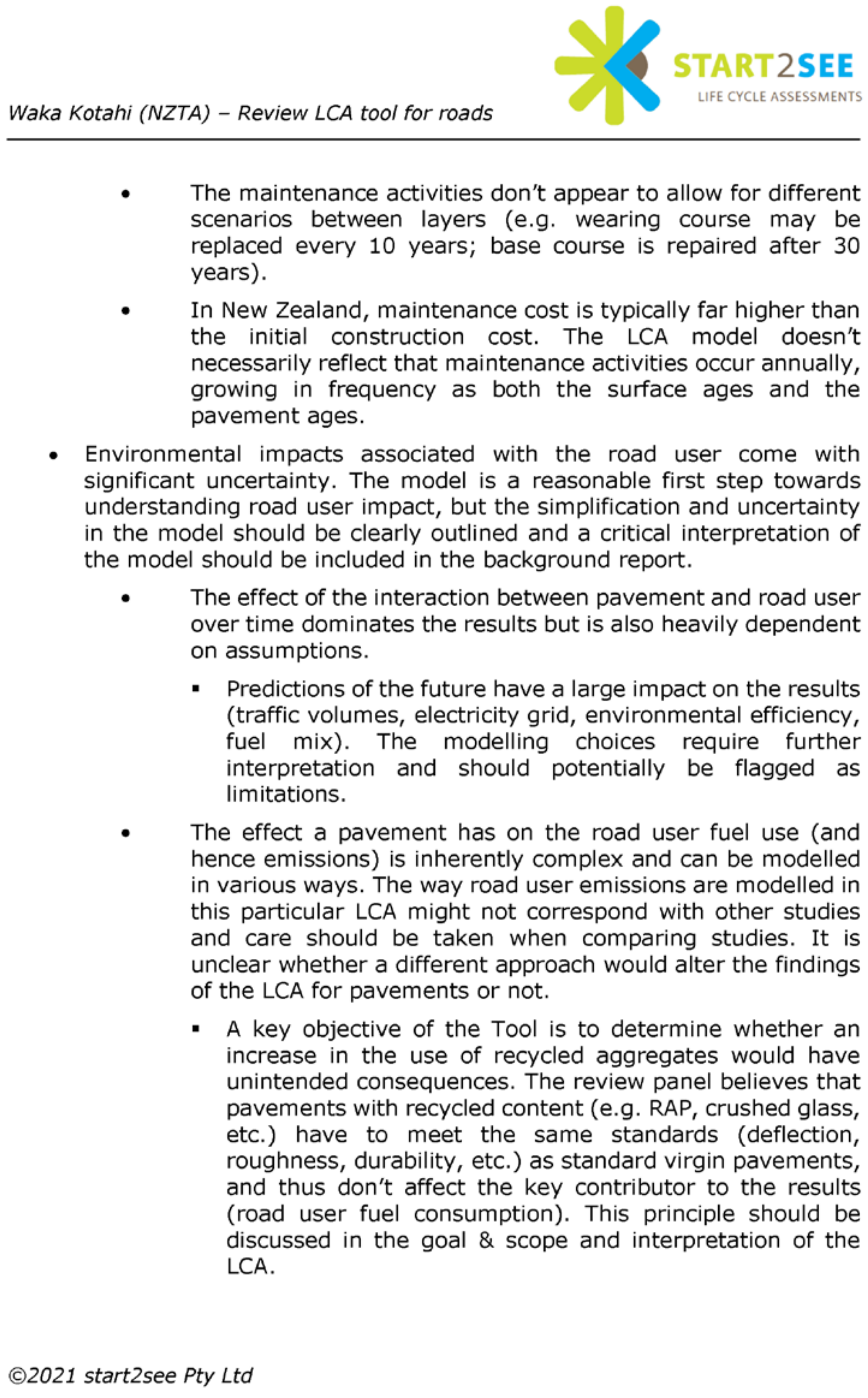
Waka Kotahi (NZTA) – Review LCA tool for roads

START2SEE
LIFE CYCLE ASSESSMENTS

Bryan, Mike and Rob met to discuss the panel's key feedback for this final review statement.

The critical review panel has found that:

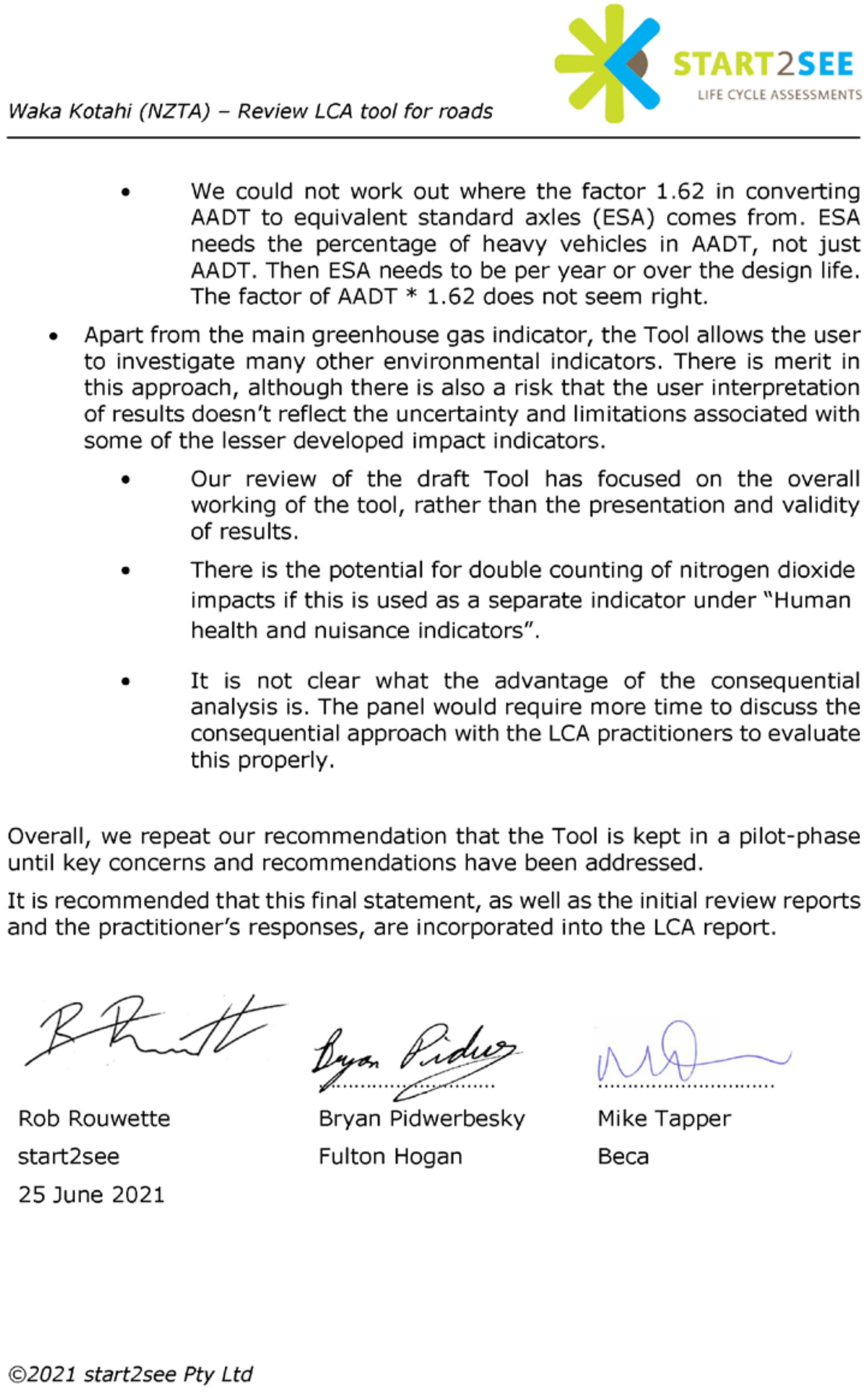
- The main objective of the project is to develop a lifecycle-based Tool. The LCA report provides background information regarding key aspects of the life cycle methodology, data and modelling choices. Since the report is not intended to present a specific LCA study, it does not contain all the elements that would be included in a typical ISO 14040 / ISO 14044 compliant report. Therefore, this review does not result in a compliance (to ISO 14040 / ISO 14044) finding.
- The review has been somewhat rushed, due to a hard deadline for completion (30 June 2021). This means that the review panel has not been able to review the final versions of the report and Tool before completing this statement. The review panel recommends that our comments are carefully considered and implemented over the next six to twelve months and that the Tool is kept in a pilot-phase until key concerns and recommendations have been addressed.
- For the Tool to be accepted by the wider industry, the National Pavements Technical Group (NPTG) should review this work.
- The life cycle may be well worked through from a carbon perspective, but the build up from a pavement design perspective doesn't look quite right. The Tool could be improved to align better with the pavement engineering design process.
    - Waka Kotahi pavement engineers are developing a tool that assesses the effect of the pavement design on road users. The LCA Calculator Tool should be merged with the model that the pavement engineers are using to ensure consistency in outcomes and policy decisions.
    - The LCA Calculator is heavy on the environmental impact model and not so much on the pavement engineering (maintenance; post-construction life) activities. Aligning or merging the Tool with what the Waka Kotahi pavement engineers are doing would likely improve its functionality.
    - It is not clear how the pavement design life (function and serviceability) strategy is taken into account. This is a critical aspect from a pavement design perspective and the LCA model should reflect this.



Waka Kotahi (NZTA) – Review LCA tool for roads

START2SEE
LIFE CYCLE ASSESSMENTS

    - The maintenance activities don't appear to allow for different scenarios between layers (e.g. wearing course may be replaced every 10 years; base course is repaired after 30 years).
    - In New Zealand, maintenance cost is typically far higher than the initial construction cost. The LCA model doesn't necessarily reflect that maintenance activities occur annually, growing in frequency as both the surface ages and the pavement ages.
- Environmental impacts associated with the road user come with significant uncertainty. The model is a reasonable first step towards understanding road user impact, but the simplification and uncertainty in the model should be clearly outlined and a critical interpretation of the model should be included in the background report.
    - The effect of the interaction between pavement and road user over time dominates the results but is also heavily dependent on assumptions.
        - Predictions of the future have a large impact on the results (traffic volumes, electricity grid, environmental efficiency, fuel mix). The modelling choices require further interpretation and should potentially be flagged as limitations.
    - The effect a pavement has on the road user fuel use (and hence emissions) is inherently complex and can be modelled in various ways. The way road user emissions are modelled in this particular LCA might not correspond with other studies and care should be taken when comparing studies. It is unclear whether a different approach would alter the findings of the LCA for pavements or not.
        - A key objective of the Tool is to determine whether an increase in the use of recycled aggregates would have unintended consequences. The review panel believes that pavements with recycled content (e.g. RAP, crushed glass, etc.) have to meet the same standards (deflection, roughness, durability, etc.) as standard virgin pavements, and thus don't affect the key contributor to the results (road user fuel consumption). This principle should be discussed in the goal & scope and interpretation of the LCA.



Waka Kotahi (NZTA) – Review LCA tool for roads

START2SEE
LIFE CYCLE ASSESSMENTS

  - We could not work out where the factor 1.62 in converting AADT to equivalent standard axles (ESA) comes from. ESA needs the percentage of heavy vehicles in AADT, not just AADT. Then ESA needs to be per year or over the design life. The factor of AADT * 1.62 does not seem right.
- Apart from the main greenhouse gas indicator, the Tool allows the user to investigate many other environmental indicators. There is merit in this approach, although there is also a risk that the user interpretation of results doesn't reflect the uncertainty and limitations associated with some of the lesser developed impact indicators.
  - Our review of the draft Tool has focused on the overall working of the tool, rather than the presentation and validity of results.
  - There is the potential for double counting of nitrogen dioxide impacts if this is used as a separate indicator under "Human health and nuisance indicators".
  - It is not clear what the advantage of the consequential analysis is. The panel would require more time to discuss the consequential approach with the LCA practitioners to evaluate this properly.

Overall, we repeat our recommendation that the Tool is kept in a pilot-phase until key concerns and recommendations have been addressed.

It is recommended that this final statement, as well as the initial review reports and the practitioner's responses, are incorporated into the LCA report.

Rob Rouwette	Bryan Pidwerbesky	Mike Tapper
start2see	Fulton Hogan	Beca
25 June 2021		

Appendix B: Electricity emissions

Table B.1 Consequential electricity emissions projections (2020–2050)

Indicator	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
GWP	kg CO_2 eq./kWh	0.176706	0.181601	0.176369	0.152679	0.154406	0.158689	0.14962	0.15116	0.146037	0.15307	0.129524	0.118827	0.114917	0.117887	0.111796
ODP	kg R11 eq./kWh	1.03E-09	1.28E-09	1.32E-09	7.99E-10	7.90E-10	1.08E-09	7.68E-10	9.92E-10	7.58E-10	1.31E-09	9.58E-10	9.46E-10	6.33E-10	1.01E-09	9.03E-10
AP	kg SO_2 eq./kWh	0.001671	0.001541	0.001715	0.001924	0.001918	0.001933	0.00185	0.001877	0.001824	0.001894	0.001698	0.001588	0.001721	0.001758	0.001771
EP	kg Phosphate eq./kWh	0.000404	0.000393	0.000386	0.000368	0.000366	0.000392	0.000358	0.000378	0.000352	0.000406	0.000317	0.000226	0.000218	0.000245	0.00024
POCP	kg C_2H_4 eq./kWh	5.01E-05	5.21E-05	5.11E-05	4.36E-05	4.37E-05	4.71E-05	4.25E-05	4.48E-05	4.16E-05	4.82E-05	3.89E-05	3.39E-05	3.09E-05	3.45E-05	3.27E-05
ADPE	kg Sb eq./kWh	6.41E-07	5.48E-07	5.42E-07	5.12E-07	5.05E-07	7.11E-07	4.92E-07	6.51E-07	4.85E-07	8.90E-07	6.84E-07	4.91E-07	4.72E-07	6.76E-07	6.71E-07
ADPF	MJ/kWh	2.261942	2.376805	2.229328	1.796466	1.823946	1.888429	1.770991	1.785548	1.720654	1.814678	1.460353	1.270338	1.163	1.200222	1.102471
PENRT	MJ/kWh	2.270642	2.386043	2.238748	1.803337	1.829537	1.898499	1.776153	1.794789	1.725515	1.829261	1.470057	1.277227	1.168983	1.209109	1.112066
PERT	MJ/kWh	2.777166	2.842208	2.755425	2.712655	2.698573	2.696639	2.760252	2.766141	2.784978	2.791309	2.903198	2.91784	2.830902	2.83064	2.862837
PED	MJ/kWh	5.043571	5.226285	4.975933	4.503329	4.526857	4.612409	4.525923	4.563294	4.496777	4.622338	4.382582	4.208889	3.996057	4.05351	3.971514

Indicator	Unit	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
GWP	kg CO_2 eq./kWh	0.114584	0.105792	0.108714	0.094438	0.084992	0.081857	0.084178	0.078766	0.082778	0.080403	0.083264	0.082447	0.081685	0.082736	0.082349	0.082888
ODP	kg R11 eq./kWh	1.15E-09	8.80E-10	1.11E-09	1.09E-09	9.86E-10	8.50E-10	1.12E-09	8.56E-10	1.11E-09	1.07E-09	1.24E-09	1.20E-09	1.07E-09	1.16E-09	1.09E-09	1.09E-09
AP	kg SO_2 eq./kWh	0.001798	0.001626	0.001638	0.001673	0.001579	0.001534	0.001543	0.001504	0.001527	0.001557	0.001573	0.001583	0.001559	0.001564	0.001557	0.001551
EP	kg Phosphate eq./kWh	0.000258	0.000229	0.000244	0.000238	0.000225	0.000207	0.00023	0.000198	0.000203	0.000211	0.000223	0.000209	0.000199	0.000207	0.000198	0.000197
POCP	kg C_2H_4 eq./kWh	3.54E-05	3.11E-05	3.35E-05	3.07E-05	2.83E-05	2.61E-05	2.88E-05	2.49E-05	2.70E-05	2.65E-05	2.82E-05	2.75E-05	2.56E-05	2.66E-05	2.57E-05	2.56E-05
ADPE	kg Sb eq./kWh	7.91E-07	6.38E-07	7.15E-07	7.52E-07	7.08E-07	5.94E-07	7.72E-07	5.64E-07	5.94E-07	6.83E-07	7.84E-07	6.53E-07	6.32E-07	6.94E-07	6.37E-07	6.32E-07
ADPF	MJ/kWh	1.138213	1.062459	1.096928	0.860972	0.762979	0.726826	0.763373	0.687552	0.739624	0.69602	0.736536	0.714795	0.711688	0.727332	0.722137	0.731993
PENRT	MJ/kWh	1.150829	1.0724	1.109975	0.873374	0.774501	0.73684	0.778321	0.698305	0.752455	0.709901	0.753495	0.730646	0.725039	0.742237	0.737444	0.746872
PERT	MJ/kWh	2.856147	2.973165	2.990659	3.052031	3.153634	3.157497	3.185617	3.187294	3.176815	3.180184	3.172855	3.159296	3.128294	3.139502	3.128794	3.122271
PED	MJ/kWh	4.02149	4.051083	4.107556	3.926167	3.931791	3.897793	3.971331	3.890558	3.932782	3.890457	3.932084	3.884816	3.85823	3.881918	3.869979	3.875148

Table B.2 Attributional electricity emissions projections (2020–2050)

Indicator	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
GWP	kg CO_2 eq./kWh	0.18	0.183	0.177	0.159	0.161	0.161	0.156	0.154	0.153	0.152113884	0.132974399	0.123039835	0.122119737	0.120249542	0.115279386
ODP	kg R11 eq./kWh	1.62E-09	1.64E-09	1.61E-09	1.56E-09	1.57E-09	1.57E-09	1.57E-09	1.56E-09	1.56E-09	1.56E-09	1.52E-09	1.47E-09	1.44E-09	1.44E-09	1.43E-09
AP	kg SO_2 eq./kWh	0.00164	0.00151	0.00168	0.00192	0.00192	0.00189	0.00185	0.00185	0.00183	0.00182	0.001669139	0.001585701	0.001733628	0.001726311	0.001746478
EP	kg Phosphate eq./kWh	0.000379	0.000381	0.000372	0.000363	0.000363	0.000361	0.000358	0.000355	0.000353	0.000350219	0.000294883	0.000229181	0.000224031	0.000222326	0.000219627
POCP	kg C_2H_4 eq./kWh	4.94E-05	5.01E-05	4.85E-05	4.53E-05	4.55E-05	4.54E-05	4.47E-05	4.43E-05	4.39E-05	4.36E-05	3.82E-05	3.41E-05	3.34E-05	3.31E-05	3.22E-05
ADPE	kg Sb eq./kWh	4.14E-07	4.30E-07	4.23E-07	4.27E-07	4.30E-07	4.32E-07	4.44E-07	4.45E-07	4.50E-07	4.48E-07	4.75E-07	4.88E-07	4.67E-07	4.69E-07	4.75E-07
ADPF	MJ/kWh	2.28	2.37	2.21	1.85	1.88	1.89	1.83	1.8	1.78	1.775141742	1.479165364	1.301284051	1.232336792	1.205723119	1.122354981
PENRT	MJ/kWh	2.29	2.38	2.22	1.86	1.89	1.9	1.84	1.81	1.79	1.78	1.49	1.31	1.24	1.21	1.13
PERT	MJ/kWh	2.75	2.82	2.73	2.69	2.68	2.69	2.74	2.75	2.77	2.77	2.9	2.91	2.81	2.82	2.84
PED	MJ/kWh	5.04	5.2	4.95	4.55	4.57	4.59	4.58	4.56	4.56	4.56	4.38	4.22	4.05	4.03	3.97

Indicator	Unit	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
GWP	kg CO_2 eq./kWh	0.114672845	0.110548718	0.10960983	0.095468136	0.08886242	0.088114774	0.086915115	0.085525536	0.086829587	0.08464386	0.085508883	0.085186523	0.086955887	0.086876584	0.087698439	0.088459995
ODP	kg R11 eq./kWh	1.44E-09	1.46E-09	1.47E-09	1.47E-09	1.47E-09	1.48E-09	1.49E-09	1.50E-09	1.51E-09	1.51E-09	1.52E-09	1.53E-09	1.55E-09	1.57E-09	1.58E-09	1.60E-09
AP	kg SO_2 eq./kWh	0.001740947	0.00161877	0.001600275	0.001642819	0.001566058	0.001549039	0.00152409	0.001528807	0.001535798	0.0015593	0.001556301	0.001573955	0.001577224	0.001571057	0.001575827	0.001571733
EP	kg Phosphate eq./kWh	0.000219258	0.000221443	0.000221509	0.000216804	0.000214853	0.000214672	0.000213727	0.000212345	0.000212191	0.000210432	0.000210352	0.000209628	0.00020995	0.00020956	0.000209542	0.000209575
POCP	kg C_2H_4 eq./kWh	3.21E-05	3.19E-05	3.18E-05	2.96E-05	2.86E-05	2.86E-05	2.84E-05	2.81E-05	2.83E-05	2.78E-05	2.80E-05	2.79E-05	2.81E-05	2.81E-05	2.83E-05	2.84E-05
ADPE	kg Sb eq./kWh	4.85E-07	5.22E-07	5.34E-07	5.49E-07	5.67E-07	5.78E-07	5.85E-07	5.90E-07	5.95E-07	5.99E-07	6.05E-07	6.11E-07	6.17E-07	6.24E-07	6.30E-07	6.36E-07
ADPF	MJ/kWh	1.115517039	1.098641621	1.091560451	0.860878201	0.787054429	0.782135908	0.772281733	0.748981781	0.766390685	0.72428644	0.738506737	0.727257973	0.753350165	0.75414595	0.765069649	0.778142909
PENRT	MJ/kWh	1.12	1.11	1.1	0.871	0.798	0.793	0.783	0.76	0.778	0.736	0.751	0.74	0.766	0.767	0.778	0.792
PERT	MJ/kWh	2.84	2.95	2.97	3.04	3.13	3.15	3.17	3.17	3.15	3.15	3.14	3.13	3.11	3.12	3.1	3.1
PED	MJ/kWh	3.97	4.06	4.07	3.91	3.93	3.94	3.95	3.93	3.93	3.89	3.89	3.87	3.88	3.88	3.88	3.89

Appendix C: Critical review commentary

The table below outlines feedback received on 4 June 2021, which was made on a previous version of this report. As a result, section, figure, and table numbers may now be different from those in this version of the report.

Table C.1 Feedback received

Page	Section	Comment	By	Response from thinkstep-anz
3	Abbreviations	“A list of all abbreviations and acronyms used in the report are outlined below” – need to add to the table TERM AC. MEANING Dense Graded Asphaltic Concrete – can be DG or AC type mixes in NZ TERM PCCP. MEANING Portland Cement Concrete Pavement.	Beca	AC added, PCCP is not currently referenced anywhere else.
6	Exec Summary	“Waka Kotahi NZTA wishes to increase the use of recycled materials in pavements to contribute to a low-carbon circular economy” – agree with this statement, but the majority of the LCA work is focused on pavements with a high or 100% virgin aggregate component.	BP	The LCA calculator allows for both virgin and recycled materials to be considered. It is therefore up to the user what they wish to select. The examples in this report are limited by the data that we had available.
7	1.2 Goal	“To develop a scientific understanding of the whole-of-life environmental impacts of key materials for asphalt pavements in New Zealand” – why just asphalt pavements? CD agreed: should be changed to roading pavements.	Beca & CD	Amended.
7	1.2 Goal	“An excel-based calculator for material selection in pavement design” – Is it just greenfield sites or does it include improvements in existing pavements such as capital improvements and end of life pavement renewals. The spreadsheet tool and options seem to imply a greenfield approach.	Beca	The tool does currently lean towards being best set up for greenfield sites but can be used to determine impacts of improvements. The only difference is the work which takes place to remove existing pavements.
8	Table 1.1	Basecourse Add concrete Remove melter slag from basecourse option, currently unsustainable as a non-surfacing aggregate	CD	Melter slag removed, concrete added as a basecourse
8	Table 1-1	“Modified subgrade” – This option should be modified basecourse?? A basecourse option should also be for where the existing layer remains but is modified. Suggest three options. i.e. can have new basecourse material unmodified, new material that is modified and existing material modified. Possibly an option as well for the subbase layers.	Beca	Modified subgrade changed to modified basecourse. We believe a new unmodified basecourse and new material that is modified have the same function.
8	Table 1-1	“Upper subbase” – The options here seem ok (I am no pavement expert) but don’t they align with the dropdown options in the spreadsheet. No coarse aggregate option for example. Similar for other pavement layers although wearing course seems ok.	Beca	Materials in each of the layers have been matched across the calculator and table.

Page	Section	Comment	By	Response from thinkstep-anz
8	Table 1.1	Upper subbase Add – foam stabilisation, although expensive could be an option Add – lime stabilisation.	CD	Lime stabilisation added. Foam stabilisation not added.
8	1.3 Table 1.1	Lower subbase Add – Cement bound and lime modified.	CD	Lower subbase section has been removed.
10	Table 1-2	Replace "paving materials" with "pavement materials" CD agrees.	BP & CD	Amended.
10	Table 1-2	"Maintenance, repair, replacement and refurbishment of pavement within its service life" – See below and later but where does resurfacing sit? It does not seem clear. There just seems to be maintenance or pavement renewal. It could be considered here or as a renewal option.	Beca	Amended to include resurfacing.
10	Table 1-2	"Deconstruction of select pavement layers" – Do we consider resurfacing only i.e. mill and replace asphalt surfacing – again part of general comments regarding whether and how resurfacings are treated/included.	Beca	Yes, selected layers can be left inground at end of life to be reused, unmodified, in the next pavement.
10	Table 1-2	"(the lower layers may not be damaged)" – the tabs have only remove or leave (for an overlay) as options. Modify existing only would be a third option.		Selected layers can now be left in ground to be reused.
10	1.5.1 Time coverage	"As such, it is intended to represent paving technologies that are current at the time of writing …" this should state "pavement technologies". Throughout the document, replace 'paving' with 'pavement' so as to be accurate and avoid confusion – that this is LCA calculator only refers to 'paving' as opposed to all pavements.	BP	References of paving has been switched to pavement.
15	2.2.2 Data requirements	"Therefore, it is unlikely that material other than glass and bitumen will be imported for pavement construction." – Glenbrook slag may not be imported (yet) but is only sourced from one location. Slag is constrained in quantity from Glenbrook and Waka Kotahi may look at importing options to both improve supply and reliance on a single supplier. More of an issue for surfacing than pavement materials so may not be significant.	Beca	Noted.
17	Table 3-1	"Meter slag" – Melter slag.	Beca	Amended.
17	Table 3-1	"End of life" – does modifying existing layers sit here or is that covered above in the table?	Beca	Modifying existing layers falls under the "Maintenance, repair, replacement and refurbishment" section above.
18	Table 3-2	Aggregate (crushed rock) production from NZ quarries – should also consider 'scalping'/ aggregate wastage. For example, a specified pavement aggregate can result in up to 50% of the raw input being scalped and wasted with no viable commercial use within cost effective haulage distance from the quarry.	BP	Noted, though our calculations are based on total energy used (diesel and electricity) divided by total product sold at the site level. Any losses of material that cannot be sold are inherently captured by these calculations.
18	Table 3-2	Aggregate (alluvial sand and gravel) – should also consider 'scalping'/aggregate wastage. For example, a specified pavement aggregate can result in up to 50% of the raw input being scalped and wasted with no viable commercial use within cost effective haulage distance from the quarry.	BP	See above.

Page	Section	Comment	By	Response from thinkstep-anz
19	Table 3-2	Under Binder production, should allow for NZ-based bio-bitumen sources.	BP	Bio-based bitumen is currently out of scope due to a lack of available data. The calculator has been designed to easily include additional materials should data become available.
19	Table 3-2 Construction and paving	“Additional materials” – need to add reinforcement bars or mesh for concrete pavements.	Beca	Steel reinforcing bar has been added.
19	Table 3-2	Construction and paving: should also consider foamed bitumen which is a significant method of recycling & stabilising pavements, and has environmental benefits because of the lower bitumen content possible due to this technology.	BP	Noted. This would need to be considered in a future version of the tool.
22	4 Pavement Environmental Calculator	“25 years (Waka Kotahi’s default design life)” – Note (it may be obvious) but this is a design criteria, not an indication of when the pavement needs to be renewed.)	Beca	Amended to design criteria.
23	4.1	“The pavement parameters include the physical area of the pavement, the design life of the pavement and a variable to define the environmental discount rate. The design life of the pavements can be entered as either years of use or equivalent standard axles.” Subsurface pavement life is designed in terms of ESA, but chip seal surfacings are not – seals are designed considering all light & heavy traffic loading. This calculator should separate out the surfacing life from the pavement life.	BP	The maintenance section of the tool has now been reworked to help improve maintenance per pavement layer; however, there is still one overall design life. As such, this change may not fully address your comment.
23	4.1	“In the instance where the design life is entered in equivalent standard axles, this is converted to years of use by multiplying by 1.62/365. This factor accounts for the proportion of heavy vehicles within the national fleet.” Don’t understand why 365 is in the calculation? Is that just coincidence that there are 365 days in a year?	BP	Terminology amended. Multiplying by 1.62 coverts AADT to expected ESA across NZ. Dividing the ESA design life by the daily ESA and 365 provides the design life in years.
23	4.2.4 Pavement Design	“The first compulsory section within the raw materials section of the calculator is detailing the physical design of each investigated pavement.” – As mentioned before (if not the case already) use of the tool will be greatly increased if renewal for existing pavement layers are included (e.g. similarly to the renewal approach) rather than just new materials only.	Beca	Though the tool is set up for a new pavement, it can also be applied for renewal of existing pavements.
24	4.2.4 Pavement Design	“For example if 5% of a 250mm aggregate base course is intended on being substituted with recycled crushed concrete then the thicknesses would be 253.5mm of aggregate.” – Should this be 250-5% of 250 = 237.5mm? - Agreement between Beca and BP.	Beca & BP	Correct, amended
24	4.2.5 Construction process	The impacts of constructing the pavement from the respective raw materials is assumed to be entirely due to the combustion of diesel in machinery. Diesel consumption is the single largest impact on construction, but what about the huge electrical input to the project and site offices required for supporting the construction of a greenfields project, where they have to be established on site specifically for the project? Is that excluded?	BP	Electricity for offices is currently out of scope.
24	Table 4-1 caption	“Default diesel consumption factors for pavement construction” – Unbound granular pavements?? Modified pavements?? I see chipseal is in which is a surfacing layer.	Beca	These literature values were reviewed against the data that we received from industry. Overall, they correlated reasonably well; however, we did not receive enough data to be able to

Page	Section	Comment	By	Response from thinkstep-anz
		If we are having a standard litres/m2 rate then is there much difference between an asphalt surfacing which maybe 40mm thick and a structural asphalt layer which maybe 150mm thick?		disaggregate them further. We encourage contractors to use their own data rather than the defaults wherever they are available.
25	4.3 Pavement maintenance	"Six forms of maintenance have been included within the calculator and include.." – Are we missing surfacing renewal as part of pavement maintenance or are renewals separate to maintenance?	Beca	Currently renewing the entire surface would be considered separate to maintenance and would be part of a new pavement life. Just replacing the wearing course can be selected so not to capture the intensity of having to replace the entire pavement. For partial replacements of surface courses and or other layers, this would fall under "Dig outs".
25	4.3 Pavement maintenance	Six forms of maintenance have been included within the calculator and include: • Crack Sealing • Fill Cracks (Potholes) – this should just be Potholes repair • Patch Stabilisation • Dig Outs • Lay Over – should say Overlay (Beca also noted this) This is grossly over-simplified and needs much more work and input from practitioners before being released for wider consultation – there are a much wider range of maintenance activities that do consume substantial resources and energy. This is a very significant issue that needs much attention because most of the NZ road network has been developed in a low initial capital cost – high maintenance regime.	BP	The term "fill cracks" was included after discussions with NZTA to keep the terms consistent with their internal documents. NZTA's NPV document lists 10 forms of maintenance. The processes missing are: • Milling – now added • Minor levelling • Rip and remake – now added • Surfacing defect repairs – now added • Water blasting – material impacts assumed to be negligible, traffics delays can be covered • Shoulder maintenance – now added.
25	4.3 Pavement maintenance	"To increase the granularity of the results, the maintenance impacts are reported later in the calculator under the two groups: life extension and replacement maintenance." – Minor comment – the tab requires M2 quantity – would a % area be easier for the user? Some maintenance options might be more continuous i.e. over 60 year, one would have more than 3 "years" or applications of digouts. Not sure how this could be done but might need a change in the format of the tab if felt necessary. The Waka Kotahi NPV analysis for example has an annual type approach. I think the mtce part might require a review in how it is set up in terms of scheduling the maintenance activities. Or possibly repairs have an annual quantum and then a more specific quantity at resurfacing reflecting preseal repair activity??? The examples in the spreadsheet might need to be reviewed as they seem, to me anyway, to not be options adopted in the field e.g. 45mm of bitumen emulsion.	Beca	m2 was used as this is the same format for outlining maintenance schedules in the Waka Kotahi's NPV document. The number of maintenance cycles can be altered if desired. Three was chosen as a starting point but this can be extended. We will discuss with a pavement expert around a suitable number of maintenance cycles for each process.
25	Table 4-2	"Lay Over" – Is this Overlay?	Beca	Correct, Lay over was simply the terminology we were provided by Waka Kotahi.

Page	Section	Comment	By	Response from thinkstep-anz
25	4.4 Maintenance induced traffic delay	(Heading) – Why is this just for maintenance?? – the renewal/end of life treatments should be included also.	Beca	Terminology has been amended. It is meant to, and is capable of, covering maintenance, replacement and end of life treatments. Capturing the impacts of additional idle times does not depend on the process in question. The materials impacts of maintenance and replacements are captured earlier.
27	4.5 Vehicle-pavement interactions	(Heading) – These may need to be looked at given the outputs. Deflection induced fuel consumption does not register so is it worth including? Roughness induced fuel consumption is quite critical and may need more consideration – see comment below).	Beca	Both sections are being reviewed and trying to work with the author of some papers which cover both sections. Depending on traffic flow and stiffness the deflection induced impacts can be just as impactful.
27	4.5.1 Pavement deflection	This section seems to completely ignore relevant extensive research done in NZ in the 1990's by Opus (now WSP) central labs. Why was that not referenced? Most NZ pavements are relatively high deflection compared with international Western pavements, so impact of deflection on vehicle fuel consumption is higher.	BP	As covered by email, could you pass on the research? We have been unable to find this.
28	4.5.2 Surface roughness	(Heading) – This makes up half the impact in the example in the spreadsheet but the discussion here is very light. I think it needs much more discussion given the weighting it has on the results. (Conversely about pavement deflection has no impact and has nearly two pages including some impressive formulas!)	Beca	Both sections are being reviewed and we are trying to work with the author of papers which cover both sections. Depending on traffic flow and stiffness the deflection induced impacts can be just as impactful.
29	4.5.2 Surface roughness	"The IRI is a well-documented metric for the measure of user comfort during transit." – The tab shows some pretty low roughness numbers to start (IRI 2 – 2.5). This is typical of asphalt expressway type pavements. Much of the network including existing pavements will be much rougher than this so saving/impact could be significantly higher. I would be keen to understand how this is calculated over the life of the pavement.	Beca	We are currently working towards finalising the roughness calculations. We'll pass them on when complete.
29	4.6 Pavement end-of-life and relaying	"At the end of a pavement's useable working life, there are two options available for selection within the tool: leaving the pavement in-ground or removing it. Leaving a pavement in-ground is used in cases where the next pavement will be laid directly over the original" Agreement between Beca and BP. Beca comments: – Very simplified. As before there is a third option which is modifying existing layers. The tab does not specify when the end of life is scheduled (for both the initial replacement and secondary replacement) – is there a reason for this.? Given the lifecycle analysis periods, I would think resurfacing fits in here as an option. These options should also be considered in the traffic delay calculation as well. BP comments: – Incorrect – in NZ there 3 main options – remove & replace, overlay, and recycle in situ. Recycling in situ has become the most common form of treating the pavement at the end of its life. This is also the most environmentally sustainable option. There are a range of recycling options available, and each has its own unique material & fuel consumption parameters. This section needs substantial re-work by pavement experts.	Beca and BP	The maintenance section of the calculator has been reworked and hopefully now provides greater ability to consider recycling in situ. If further changes are still needed, these will need to be made as an update in consultation with Waka Kotahi.

Page	Section	Comment	By	Response from thinkstep-anz
35	5.6 Aggregates:	"In the instance where melter slag is included within a project, we recommend it be modelled as crushed aggregate for the time being." – Glenbrook melter slag is not used in pavements as an unbound aggregate. It is used in chip seal surfacing and asphalt surfacing only as a high value skid resistant aggregate.	Beca	Crushed aggregate was chosen as a proxy as no environmental data was available. The physical properties of the chip do not matter here and are specified independently later in the surface roughness section.
35	5.7 Asphalt plant	"Recycled Asphalt Pavement (RAP)" – RAP is not a separate asphalt type, it is recycled aggregate/bitumen that can go as a percentage of the aggregate in the four types of asphalt noted above.	Beca	Noted. This has been left in the current version of the calculator so that we can set different default energy use, though it could potentially be removed in future.
36	5.8 Asphalt mix designs	This section should be renamed, as chip seal is not an asphalt mix design. Potentially surfacing mix designs.	CD	Have renamed to "wearing course mixtures".
36	Table 5-8	"Chip Seal" – Chip Seal is not an asphalt type. It is a separate class of thin surfacing. Also noted by CD: table should be renamed.	Beca & CD	Renamed.
36	5.8	Waka Kotahi have trialled epoxy chip seals, these should be added as they will likely be an option for surfacing.	CD	This wasn't included as part of the desired materials by Waka Kotahi but could be included if they request it. It could potentially already be included by constructing the relevant layers out of included materials.
37	5.10 Background data	'Concrete?' (underneath table) – Do we need a section on concrete to allow for concrete pavements?	Beca	Concrete is modelled based on the cement used. More detail has now been added to section "5.1.5 Cement".
38	6.1 Example pavements	Some of the example pavements are obviously very specific and from a specific greenfield project and should have a wider range of options and scenarios to make them more relevant and acceptable to a wider range around NZ. This needs the input of a pavement design practitioner with national exposure.	BP	The section has been reworked and simplified to make it clearer that these are illustrative examples only.
38	Table 6-1 caption	"Example pavement designs" – We should have an example of concrete pavement design. Why has it been left out?	Beca	We chose not to include a concrete example as the purpose of this section is to illustrate how to use the tool rather than to try to make definitive comparisons. We suggest comparisons be made at the project level.
39	Table 6-2	"Pavement" (column 2 heading) Comment 1: Is this supposed to be Pavement Surfacing? It is different to Pavement type. Comment 2: I agree with Bruce here – there seems to be no separate consideration of surfacing life and pavement life. Chipseal (and the asphalt wearing course layer as well) is a surfacing layer, essentially sacrificial, compared to the pavement structure underneath.	Beca	Changed to pavement surfacing.
39	Table 6-2	"Expected Life of Pavement (years)" (column 3 heading) – Important to clarify that surfacing life is not pavement life.	Beca	Amended

Page	Section	Comment	By	Response from thinkstep-anz
39	Table 6-2	“30” (value for Asphalt (AC) – for low volume low speed should be 25 years.	Beca	Now 25 years.
39	Table 6-2	“6” (value for Gravel) – Why only 6 years? Would expect at least 20 years?	Beca	Gravel now removed.
39	6.1 Example pavements	“Even after a pavement is removed at the end of its design life” – Do you mean removed or rehabilitated. If it stays there it will be rehabilitated to reset life for another design period. Note design life – should this read expected life as design life is a different thing.	Beca	Section has now been simplified.
39	6.1 Example pavements	“To convey any potential environmental benefits of a pavement lasting beyond the required design life the results are also presented using an indefinite time horizon.” – Sort of agree. 99.9% percent of the time a road remains a road. I am not sure therefore an infinite timeframe is therefore the answer though. The 100 year cycle is probably plenty for that scenario. The issue is having all the maintenance and surfacing renewals scheduled within the analysis period. I don’t think the current tool has that correct yet.	Beca	Terminology has been amended to describe the impacts clearer. They are annualised across the respective design lives of the pavements.
40	Figure 6-1 (caption)	“Low volume, low speed pavement, 25-year horizon” – These are much different from the spreadsheet example. I think the lifecycle costs will increase with better reflection of maintenance, renewals (including traffic delay) and roughness fuel consumption.	Beca	Caption changed.
42	6.2.1 Bitumen Content	This still a limited range of options containing bitumen. For example foamed bitumen stabilised aggregate (FBS) typically at 2.7% - 3% and bitumen treated base (BTB) at 3-3.5% are very common construction techniques not covered in this section.	BP	Noted. This may need to be reserved for a future version of the Calculator.
44	6.2.3 Recycled Content	“Glenbrook Melter Slag” – GM Slag is not used in pavement structures, only in surfacing, therefore it would be part of reclaimed asphalt pavement or reclaimed chipseal pavement.	Beca	GM slag has been removed.
44	6.2.3 Recycled Content	“Recycled Asphalt Pavement” – Reclaimed?	Beca	We have chosen to use “Recycled Asphalt Pavement’ rather than the more common “Reclaimed Asphalt Pavement” to ensure consistent terminology, eg with “Recycled Crushed Concrete”.
45	Table 6-4	“Base Course, Sealing Chip” – GM Slag is not used in Base Course. It has too high a value for skid resistance use in surfacings, so is put back into Asphalt Aggregate or Sealing Chip.	Beca	GM slag has been removed.