Determining the carbon footprint of land transport infrastructure in New Zealand

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Abbreviations, acronyms and definitions

Acronyms

CNGP	Carbon Neutral Government Programme
ERP	New Zealand's emissions reduction plan
EPD	environmental product declaration
GHG	greenhouse gas
GPS	Government Policy Statement
ISC	Infrastructure Sustainability Council
LCA	life cycle assessment
NZTA	NZ Transport Agency Waka Kotahi
PEET	Project Emissions Estimation Tool
RAMM	Road Assessment and Maintenance Management

Definitions

Carbon dioxide equivalent (CO_2e): unit for comparing the radiative forcing of GHGs to carbon dioxide.

Carbon emissions: the term used throughout this report as shorthand for GHG emissions or carbon dioxide equivalent.

Embodied carbon: GHG emissions associated with the creation, refurbishment, maintenance and end-of-life treatment of an asset. Also recognised as capital carbon by parts of the industry to refer to similar life cycle stages.

Enabled emissions: GHG emissions associated with users' utilisation of an asset, network or transport system. Also recognised as user emissions or vehicle emissions.

Greenhouse gases (GHGs): gaseous constituents of the atmosphere, natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds.

Upfront carbon emissions: GHG emissions associated with the creation of an asset, network or transport system.

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Executive summary

Land transport infrastructure is a vital part of modern society, allowing for the movement of goods, services and people. However, land transport infrastructure has been identified as a major contributor to climate change through the carbon emissions generated from the infrastructure itself and the use of it. This research has sought to understand the carbon footprint of all land transport infrastructure in Aotearoa New Zealand.

This research was carried out between 2022 and 2023. It aimed to improve the understanding of the carbon footprint of New Zealand's land transport infrastructure. The research focused on embodied carbon of land transport infrastructure and analysed the whole-of-life emissions of New Zealand's land transport network, including material and construction, maintenance, operation and end of life. It excluded vehicle emissions (also referred to as enabled emissions) that arise from the use of the infrastructure.

This report uses the following terminology to define the life stages of carbon in infrastructure:

- **Upfront carbon (also referred to as construction emissions)** – emissions produced in materials' production and construction stages, including transport of materials to site.
- **Use stage carbon (also referred to as maintenance and operations emissions)** – emissions produced while the infrastructure asset is being maintained or replaced and those produced through electricity being used to operate the infrastructure.
- **End-of-life carbon** – emissions produced through demolition, deconstruction and the subsequent processing of the waste materials that occur at the end of an asset's life.

Research objectives

This research aimed to quantify the whole-of-life emissions of New Zealand's land transport network, including within the road and rail network. The objectives of the research were to:

- analyse literature and available data around the quantification of the carbon footprint
- identify and determine an appropriate methodology for quantification of the carbon footprint from New Zealand's land transport infrastructure
- determine a baseline carbon footprint for land transport infrastructure in Aotearoa New Zealand
- identify the greatest contributors to carbon emissions to inform decisions on where to target reductions
- provide a framework and data, including recommendations for addressing any data gaps, to help the sector develop tools that can assess the greenhouse gas emissions impacts of land transport investments.

To fulfil the first objective, a literature review was undertaken of research from both New Zealand and international contexts to understand if carbon quantification of infrastructure at a similar scale has taken place before. The literature review found that embodied carbon in construction and infrastructure is considered a hidden impact, with much more attention in policy and literature being given to vehicle emissions from the use of the infrastructure. The literature review found methodologies for quantifying the carbon emissions for individual infrastructure projects. However, there is limited literature or clear methodologies on undertaking large-scale carbon quantification across a whole infrastructure network. The literature available on approaching this task for individual asset types, particularly the quantification of the impacts of roads and rail such as the global standard PAS 2080:2023 *Carbon management in buildings and infrastructure*, formed the foundations for establishing a methodology at a national network scale.

The second objective was approached using a combination of methodologies presented in the literature review. Profiles representing a 'typical' infrastructure asset were developed using the NZTA Project Emissions Estimation Tool combined with research and technical knowledge from subject matter experts.

Each profile was assigned an emissions factor and asset data was obtained from New Zealand's Road Assessment and Maintenance Management (RAMM) digital asset and KiwiRail and placed within the emissions framework.

Key findings

This research estimates that the upfront carbon footprint of the road network, which includes state highways, local roads and all associated assets such as footpaths, traffic signals and signage, is **37,250 ktCO_2e (±10%)**. Maintenance emissions for the road network have been estimated at **855 ktCO_2e (+10%, -14%)** per year with operational emissions estimated at **35 ktCO_2e (+10%, -22%)** per year.

The total national upfront carbon footprint for the rail network, including tracks, structures, retaining walls and culverts, is **15,380 ktCO_2e (±15%)**. Maintenance emissions for the rail network have been estimated at **220 ktCO_2e** per year.

(Note: for an illustration of scale, New Zealand's national net emissions[2] for the 2022 year were estimated at 59,100 ktCO_2e, of which the total land transport (fuel) emissions comprise an estimated 13,600 ktCO_2e[3]).

We have summarised the key findings as follows:

- Over decades, investment into infrastructure has produced significant carbon emissions through its construction, maintenance and operation. Much of this is essentially a sunk cost that cannot be recovered or changed, but there are significant opportunities to reduce carbon by changing how we invest in, design, construct and maintain our current and future assets. However, these opportunities can only be realised if we consider whole-of-life carbon (including embodied and enabled emissions) in decision making about investment into infrastructure.
- Maintaining and optimising our current network is better from a carbon perspective than building new, and all new assets will increase carbon through upfront emissions as well as through the maintenance cycles and end-of-life impacts that are created. Optimising our current network can occur in many ways, and in the context of this research, we consider it to be when whole-of-life and whole-of-network considerations are brought to the forefront of investment decision making, with build nothing and build less being the desired outcome.
- Although gains have been made in recent years, there is a lack of information about maintenance activities on the road network and end-of-life impacts and the subsequent carbon emissions from these activities. This presents a risk to future New Zealand's infrastructure investment, particularly considering increased maintenance requirements due to more heavy vehicles on the roads and impacts from extreme weather events.
- This research looked at embodied carbon across the life cycle of infrastructure assets, but embodied carbon is only one piece of a very complex puzzle that should not be analysed alone. Enabled vehicle emissions and embodied emissions are two interrelated elements and must also be considered in conjunction with other impacts, including a just transition, community wellbeing, environmental impacts and climate resilience.
- There is significant opportunity to reduce upfront carbon emissions through innovation of new materials, technologies and processes when new infrastructure assets are required or through maintenance.

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[2] This information is provided to contextualise a reference point for a relative comparison of the scale of emissions findings only. The emissions boundaries used in the national inventory are different to those in this report (i.e. the emissions sources are different), and therefore the findings in this report should not be considered to be part, or a subset of the national inventory carbon figures.

[3] Ministry for the Environment (*2024) New Zealand's Interactive Emissions Tracker*. Available at: [NZ's Interactive Emissions Tracker (environment.govt.nz)]() Accessed May 2024.

Although quantifying emissions reduction opportunities was out of scope of this research, the significance of upfront and maintenance emissions suggests that developing, trialling, implementing and eventually mandating low-carbon materials will reduce carbon in future investments.

Recommendations

Through this research report, several recommendations have been identified that will improve understanding of the carbon footprint of land transport infrastructure and identify ways to investigate reducing the impact:

- Future land transport investment decisions should consider whole-of-life carbon (embodied and enabled) in the context of New Zealand’s net-zero by 2050 reduction target. Particular focus should continue on improving information available on maintenance, operations and end of life activities.
- Future land transport investment decisions should consider the whole transport network and other related horizontal infrastructure. Consideration of optimising existing infrastructure before new construction is important.
- Technological and process innovations that reduce embodied carbon should continue to be researched, trialled and implemented to reduce emissions when new assets are needed or maintenance is occurring.
- Asset databases should be standardised and improved (particularly in how maintenance is recorded).

Abstract

This research aimed to improve the understanding of the embodied carbon impact of New Zealand’s land transport infrastructure. The need to reduce transport emissions is well documented in policy and research. However, focus has predominantly been on emissions generated by using infrastructure (enabled vehicle emissions) or project-specific quantification. This research project has sought to fill this gap by quantifying the estimated whole-of-life embodied emissions for land transport infrastructure. By developing profiles that represent a typical asset, this research was able to calculate the construction, maintenance, operation and end-of-life emissions associated with New Zealand’s transport infrastructure. It estimates that the upfront impact of the road network (including state highways, local roads and associated assets) is **37,250 ktCO_2e (±10%)** and continues to produce **890 ktCO_2e (+10%, -14%)** per year due to maintenance and operational emissions. The upfront impact of the rail network is **15,380 ktCO_2e (±15%)**, and maintenance emissions for the rail network are estimated at **220 ktCO_2e** per year. Although these are significant quantities, upfront emissions represent a sunk cost that cannot be changed. Focus on emissions reduction in our land transport should be placed on how we maintain and optimise our current transport network and how we consider the embodied and enabled vehicle emissions in tandem in our investment decision making.

1 Introduction

This research was commissioned by NZ Transport Agency Waka Kotahi (NZTA) to determine the carbon footprint of land transport infrastructure in Aotearoa New Zealand. The research was carried out between 2022 and 2023. It was commissioned in part to fill a knowledge gap about the carbon footprint of New Zealand's land transport infrastructure, particularly horizontal infrastructure such as road and rail. The purpose of this research is to provide a robust foundational understanding of the whole-of-life (construction, maintenance, operation and end of life) footprint of New Zealand's transport infrastructure and provide a high-level, whole-of-life carbon footprint for transport infrastructure across Aotearoa New Zealand.

The objectives of the research were to:

- analyse literature and available data around the quantification of the carbon footprint.
- identify and determine an appropriate methodology for quantification of the carbon footprint from New Zealand's land transport infrastructure
- determine a baseline[4] carbon footprint for land transport infrastructure in Aotearoa New Zealand
- identify the greatest contributors to carbon emissions and inform decisions on where to target reductions
- provide a framework and data, including recommendations for addressing any data gaps, to help the sector develop tools that can assess the greenhouse gas (GHG) emissions impacts from land transport investments.

Current understanding of carbon in infrastructure is largely limited to individual projects, and this research project sought to understand the carbon footprint at a national level, forming a baseline from which emissions reduction initiatives can be targeted to help meet emissions reduction targets.

1.1 Structure of the report

This report is divided into the following parts:

- This **introduction** establishes the purpose of the work and provides some context to the background. It also seeks to define some of the key terms within the context of this research.
- The **literature review** explores peer-reviewed research on different methods used to estimate carbon, particularly those that feature carbon estimation at regional or national scales. It also provides some background to carbon assessments, including existing standards and methods.
- The **methodology** defines the scope and boundaries of this study and provides an overview of the methodology used to calculate the national footprint.
- The **results** section provides tables and images describing the results (the national footprint) calculated during this research.
- The **recommendations and discussion** section provides a summary of the findings of this research and offers recommendations for future work areas and/or research.

1.2 Background to the research

Climate change is one of the most urgent and important issues of our times. On 22 April 2016, Aotearoa New Zealand was one of more than 190 countries to become a signatory to the Paris Agreement, an international treaty on climate change with the goal to limit global warming to well below 2 °C, and preferably to 1.5 °C,

[4] In this context, the term 'baseline' means an estimation of the carbon footprint that will allow the emissions produced by New Zealand's land transport infrastructure to be understood and assessed and to support spatial comparisons.

compared to pre-industrial levels. Most signatory countries have developed legislation and policies to drive significant changes with their domestic emissions. For example, Aotearoa New Zealand developed the New Zealand Emissions Trading Scheme (NZ ETS) and passed the Climate Change Response (Zero Carbon) Amendment Act in 2019 (the Climate Change Act), which set the requirement for a national emissions reduction plan (ERP) (Ministry for the Environment, 2022b).

The Climate Change Act requires Aotearoa New Zealand to reach net-zero carbon emissions (excluding biogenic methane) by 2050 and set emissions budgets as the stepping-stone targets for getting there. It also defines the role of He Pou a Rangi | Climate Change Commission to provide independent, evidence-based advice to government on New Zealand's transition to net-zero carbon emissions (Ministry for the Environment, 2021).

In May 2022, the New Zealand Government proposed the first three emissions budgets for 2022–25, 2026–30 and 2031–35. Table 1.1 shows the required reductions against the 2019 reference year.

Table 1.1 New Zealand Government's proposed emissions budgets (Ministry for the Environment, 2022b)

	2019 (reference year)	2022–25	2026–30	2031–35
All gases, net (AR5)[5]	-	290 $MtCO_2e$	305 $MtCO_2e$	240 $MtCO_2e$
Annual average	78.0 $MtCO_2e$	72.5 $MtCO_2e$	61 $MtCO_2e$	48 $MtCO_2e$

Following the release of the first three emissions budgets, the first ERP was published, outlining the strategies, policies and actions for achieving the first 2022–25 emissions budget (Ministry for the Environment, 2022b). Sector-specific reduction plans were included in the ERP to provide details on emissions reduction initiatives for each sector.

Chapter 10 of the ERP outlines the plan for reducing New Zealand's transport emissions and includes targets relating to reducing vehicle kilometres travelled (VKT) by light vehicles and reducing emissions associated with freight. This points Aotearoa New Zealand towards a mode shift[6] where more journeys will need to be taken by active modes, rail or buses instead of cars and more freight will need to be moved by rail or sea instead of trucks. Although this research project does not include enabled vehicle emissions, these reduction targets will impact the way we design, construct, maintain and use our transport infrastructure.

Chapter 12 of the ERP is aimed at the building and construction sector and states that, in 2018, emissions relating to the construction of buildings and infrastructure were responsible for 7.4 $MtCO_2e$ and an additional 2.9 $MtCO_2e$ of embodied emissions resulting from the production of imported materials occurring outside of Aotearoa New Zealand. This represents 9.4% of domestic carbon emissions or 15% if biogenic methane is excluded (Ministry for the Environment, 2022b). Chapter 12 also outlines initiatives to reduce by 0.9 $MtCO_2e$ to 1.7 $MtCO_2e$ for the first budget. Without the reduction initiatives, the total emissions contribution from this sector (including both vertical and horizontal infrastructure) for the first emissions budget are modelled at 8.1 $MtCO_2e$ per year (Ministry for the Environment, 2022b).

In 2021, the Climate Change Commission provided advice on the first emissions budget and made the recommendation for Crown agencies and Crown-owned companies to incorporate climate change into their decision making, with a particular focus on investments into housing and infrastructure to help achieve emissions reductions. Following this advice, the Government announced the Carbon Neutral Government

[5] The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) set carbon budgets – an accumulated amount of carbon emissions over time. The AR5 identifies a GHG emissions budget of 840 $GtCO_2e$ for the world to have a 50% chance of staying below 2 °C of warming by 2100.

[6] Change in demand of a transport mode relative to another.

Programme (CNGP). The CNGP aims to accelerate the reduction of emissions in the public sector by requiring participants to:

- measure, verify and report emissions annually
- set gross emissions reduction targets in line with a 1.5 °C reduction pathway and set longer-term reduction plans to reduce emissions
- offset remaining scope 1, scope 2 and mandatory scope 3 emissions from 2025 to achieve carbon neutrality.

CNGP participants[7] are required to prepare emissions inventories in accordance with ISO 14064-1:2018 (International Organization for Standardization, 2018) and/or the Greenhouse Gas Protocol. GHG reporting standards require organisations to define the organisational boundary, set a base year, apply appropriate emissions factors to all emissions sources and measure changes in emissions over time.

The built environment has a vital role in meeting the emissions reduction challenge in line with the Paris Agreement and Climate Change Act. The World Green Building Council (2019) states that carbon emissions associated with the manufacturing and transportation of construction materials, construction of buildings and infrastructure and the end of life of these assets contribute approximately 11% of all global carbon emissions, and this proportion is higher when the operation of buildings and infrastructure assets is included.

The purpose of this research is to calculate a high-level, whole-of-life carbon footprint for transport infrastructure across Aotearoa New Zealand. The research will contribute to wider pieces of work that are taking place within the industry and assist NZTA and other transport authorities in targeting emissions reductions.

The research is seeking to calculate the carbon footprint of land transport infrastructure rather than offering solutions to reduce carbon emissions. Understanding a carbon footprint is a crucial step in planning and budgeting to meet New Zealand's net-zero target by 2050. It is also important to understand the carbon impacts of various transport infrastructure asset types to support identification, management and implementation of carbon reduction opportunities.

1.3 Carbon in this context

Emissions are produced over the life cycle of an infrastructure asset, including during its construction, maintenance, operation, use and end of life. This research project is focused on the embodied and operational emissions of land transport infrastructure, which includes the construction, maintenance, operational and end-of-life emissions, but does not include those that are created by people and vehicles using the infrastructure.

For the purpose of this research, we have aligned the categorisation of emissions sources with PAS 2080:2023 (British Standards Institution, 2023) and used the following terminology to describe the different life cycle stages of carbon (see Figure 2.1) adapted from the World Green Building Council (2019):

- **Upfront carbon** – emissions caused in materials' production and construction stages of the life cycle before the building or infrastructure begins to be used (A1–A5).
- **Use stage carbon** – emissions associated with materials and processes needed to maintain the building or infrastructure during use such as for refurbishments. In this research, the use stage refers to emissions generated from maintenance and operation of the asset (B2–B5 and B6).

[7] Participants in the CNGP are divided into three tranches: Tranche 1 includes government departments, departmental agencies and executive branches; Tranche 2 includes Crown agents; Tranche 3 includes tertiary institutions, legislative branches, Offices of Parliament and state-owned enterprises.

- **End-of-life carbon** – emissions associated with deconstruction/demolition (C1), transport from site (C2), waste processing (C3) and disposal (C4) of a building or infrastructure that occur after its use.

Figure 1.1 shows the activities that fit into each of the three categories.

Figure 1.1 Explanation of the life cycle stages of carbon that are captured in this research (adapted from Waka Kotahi NZ Transport Agency, 2023a)

Upfront carbon	Use stage carbon (enabled emissions excluded)	End-of-life carbon
Production of construction materials	Production of maintenance materials	Fuel used during deconstruction and demolition
Transport of materials	Maintenance fuel use	Emissions generated during processing of the waste materials
On-site fuel and electricity use	Electricity use (streetlights and traffic signals)	Transport of waste from site

1.4 Links to other research

This project is connected to research into the impact of infrastructure investment on carbon (including embodied and enabled carbon) as part of the wider NZTA research programme:

- Swithinbank (2022) developed carbon emissions baselines for construction, operation and maintenance of land transport infrastructure. This research used existing datasets from Aotearoa New Zealand, Australia, the UK, Ireland and the USA to calculate a carbon emissions baseline for infrastructure assets using standard metrics (CO_2e per lane km and CO_2e per m^2). The findings of this research were incorporated into the Project Emissions Estimation Tool (Waka Kotahi NZ Transport Agency, 2023b), described further in section 2.3.1, which has been utilised for the calculations in this research project.
- As yet unpublished work undertaken by IDS (n.d.) on GHG modelling for the National Land Transport Plan (NLTP) focuses on establishing modelling emissions scenarios as part of the national level pavement deterioration modelling to assess maintenance and renewal levels for the NLTP. The modelling looks at maintenance budget scenarios and the impact on network condition to inform the government’s funding commitment to the NLTP. The work by IDS applies a carbon emissions lens to the model with the resulting forward work programmes enabling comparisons between funding levels on carbon and condition. The results work by IDS is incorporated into this research project to inform the carbon footprint of maintenance and renewal activities for pavements and surfacing.
- Lee et al. (2024) have researched integrated land use and transport planning. This is a critical component of reducing transport emissions and creating an urban environment that achieves broader social, economic and environmental outcomes. Their paper discusses the necessary pre-conditions required to achieve this in Aotearoa New Zealand and introduces a tool to quantify the emissions impacts of transport and land-use decisions in the New Zealand context. Although links are still to be confirmed, the results of this carbon footprint project will contribute to this tool to support whole-of-life carbon consideration in land-use planning.

2 Literature review

The purpose of this literature review is to inform the methodology by analysing literature and data from Aotearoa New Zealand and abroad. The following aims have been established to guide the literature review to achieve this purpose:

- Establish the context for researching the carbon baseline of land transport infrastructure, including the policy context.
- Summarise existing standards, frameworks and methodologies that direct the approach to carbon emissions quantification and carbon management.
- Review existing literature to understand how large-scale emissions estimation has occurred in either New Zealand or international contexts, with a particular focus on the methodology undertaken and boundary setting.
- Analyse asset data and design information to understand how assets can be organised and standardised.

These aims seek to guide the literature review to cover the background and context for undertaking the research project through to methodologies and data sources that are available or have been used in similar projects or settings.

2.1 Context

Infrastructure is critical to all aspects of modern society. It is an interconnected network of physical assets that enables the movement of both people and goods and underpins many aspects of our quality of life (Griffiths, 2014; New Zealand Infrastructure Commission, 2022). Land transport infrastructure in Aotearoa New Zealand is part of a category of economic infrastructure consisting also of energy, telecommunications, waste and water (New Zealand Infrastructure Commission, 2022).

In Aotearoa New Zealand, NZTA has a role in transport regulation, infrastructure, planning, investment management and other general functions and has a primary objective of contributing to an effective, efficient and safe land transport system in the public interest (Waka Kotahi NZ Transport Agency, 2021). New Zealand’s land transport and associated infrastructure is also guided by the Government Policy Statement on Land Transport (GPS), which sets the government priorities for investment over a 10-year period (New Zealand Government, 2020). Organisations such as NZTA must ensure that investment in transport reflects the priorities outlined in the GPS, which includes a strategic priority to develop a low-carbon transport system that supports emissions reductions.

2.1.1 Infrastructure carbon in literature

As stated in section 1.2, the built environment has a vital role in meeting the emissions reduction challenge in line with the Paris Agreement and the Climate Change Act.

The need to reduce transport emissions is well documented in policy and government strategies, including in the Rautaki Hanganga o Aotearoa | New Zealand Infrastructure Strategy (New Zealand Infrastructure Commission, 2022) and the ERP (Ministry for the Environment, 2022b). In Aotearoa New Zealand, transport makes up 38% of the national non-agricultural emissions, with most of these being emissions derived from fossil fuels used to power vehicles (New Zealand Infrastructure Commission, 2022). Jackson and Brander (2019) stated that the infrastructure industry has acknowledged that there is a need to understand, manage and reduce emissions from the sector. However, research, data, plans and strategies have primarily focused on emissions from use of the infrastructure asset (enabled emissions) rather than those created during infrastructure construction, maintenance and end of life (Swithinbank, 2022).

This gap in literature and policy, as identified by Swithinbank (2022), is set against trends of rising demand for construction materials and a decarbonising electricity grid, which together make research into whole-of-life carbon vital to meet any carbon reduction targets (World Green Building Council, 2019).

The carbon emissions of transport infrastructure, reported in terms of carbon dioxide equivalent (CO_2e), occur at each stage of the infrastructure's life cycle (Ministry of Business, Innovation and Employment, 2022). This includes the emissions of the materials and products used across their life cycle, transportation and construction processes, maintenance activities and the end-of-life emissions. For the purposes of this research, carbon emissions are reported as carbon emissions ($kgCO_2e$) and include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other gases that have a global warming effect such as refrigerant gases (Ministry for the Environment, 2022a).

2.2 Existing standards and frameworks for carbon management

International standards and frameworks have been developed to establish methodologies and/or best practice for quantifying, managing and reducing carbon in infrastructure assets. This section outlines the international standards and guidelines for managing and quantifying carbon in infrastructure.

2.2.1 PAS 2080 – carbon management in buildings and infrastructure

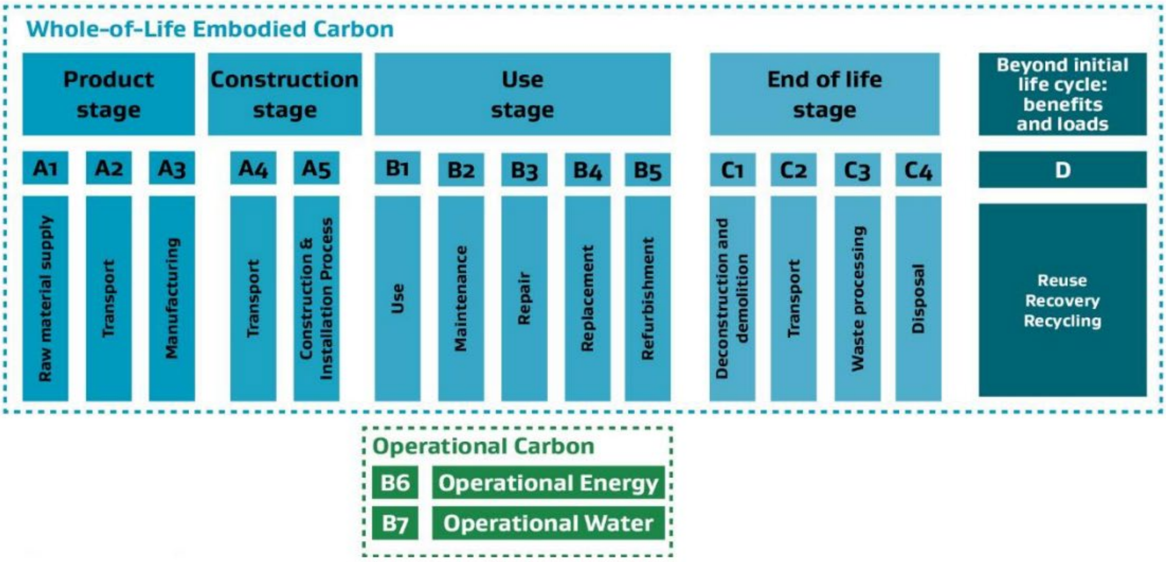
PAS 2080:2023 (British Standards Institution, 2023) sets out the principles and processes for carbon management of infrastructure assets. It establishes five fundamental principles that underpin the carbon management process:

- Relevance: Data and assessment methods relevant to the defined boundary of carbon management and assessment are to be selected, documented and used.
- Completeness: All life cycle carbon emissions arising within the defined infrastructure system boundary that provide a material contribution to the management and assessment of carbon emissions are to be included.
- Consistency: Consistent methodologies and data sources for carbon management and assessment are to be used to allow comparisons of emissions over time. Any changes to methodologies, assumptions or data sources are to be transparently documented.
- Accuracy: The quantification of carbon emissions is to neither overestimate nor underestimate actual emissions as far as can be judged, and uncertainties are to be reduced as far as reasonably practicable. A sufficient level of accuracy is to be achieved to enable users to make decisions with reasonable assurance as to the integrity of the reported information.
- Transparency: Where the outputs of a carbon management approach carried out in accordance with the PAS are to be disclosed to a third party, information shall be made available on the methodology and data sources used and any relevant assumptions to allow such a third party to make associated decisions with confidence.

PAS 2080:2023 notes that all activities leading to carbon emissions relevant to the life cycle boundary should be assessed, including emissions from the product stage (A1–A3), construction stage (A4–A5), use stage (B1–B5) and end-of-life stage (C1–C4), as outlined in Figure 2.1. It is optional to include module D, the beyond initial life cycle benefits and loads stage, in a whole-of-life carbon assessment. Figure 2.1 illustrates the life cycle stages and emissions boundaries of embodied carbon and operational carbon as defined by the Ministry of Business, Innovation and Employment. This is consistent with the life cycle stages defined by

PAS 2080:2023 while illustrating the embodied carbon and operational carbon boundaries that have been defined in this literature review.

Figure 2.1 Stages of whole-of-life assessments (reprinted from Ministry of Business, Innovation and Employment, 2022, p. 6)



2.2.2 Greenhouse Gas Protocol

The GHG Protocol provides a series of standards that create a consistent framework for businesses, governments and other entities to measure and manage carbon emissions and report and understand GHG information.

The GHG Protocol corporate standard (World Business Council for Sustainable Development & World Resources Institute, 2012) defines the boundaries for reporting carbon emissions, including the consolidation approach for organisations' reporting of carbon emissions and the emissions scopes. The corporate standard allows two distinct approaches to consolidate carbon emissions: equity share or operational control (financial or operational). Under the equity share approach, an organisation accounts for carbon emissions from its operations based on how much equity it has in that operation. Under an operational control approach, an organisation accounts for the carbon emissions from operations it has control over (ie, it has full authority to introduce and implement its operating policies).

Under an operational control approach, 100% of emissions from operations should be accounted for, including emissions from the following scopes:

- Scope 1 direct emissions from owned or operated assets (vehicle fleet emissions).
- Scope 2 indirect emissions from purchased electricity.
- Scope 3 indirect emissions from suppliers, distributors, subcontractors and so on.

The GHG Protocol product standard (World Resources Institute & World Business Council for Sustainable Development, 2011) sets out the requirements and guidance for companies to quantify and report on GHG emissions inventory for a specific product. It provides a framework for companies to make informed choices to reduce carbon emissions from the products that they design, manufacture, sell, purchase or use. The product standard has the same five principles that are included in PAS 2080:2023 and described in section 2.2.1. Two important steps within the product standard are establishing the scope of a product inventory and setting the appropriate boundaries.

Methods for quantifying scope 1, 2 and 3 emissions are set out in the GHG Protocol and ISO 14064 suite of standards (detailed in section 2.2.4).

2.2.3 ISO 14040 and ISO 14044 – life cycle assessments

ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization, 2006a, 2006b) set out the principles and framework and requirements and guidelines for doing a life cycle assessment (LCA). These international standards are focused on the process of undertaking an LCA for a product and following the impact (which typically goes beyond the carbon impact to consider a wider range of environmental impacts) covering:

- upstream processes (cradle to gate) covering raw material production (A1–A3 in Figure 2.1)
- core processes (gate to road), including transport of material to site (A4) and construction of the asset (A5)
- downstream processes (road to grave) covering maintenance (B2–B5), end of life (C1–C4) and any potential credits from future use of recycled materials (D).

As these standards provide a framework for doing an LCA rather than setting rigid rules and prescribing datasets to use, Huang et al. (2013) state that this has allowed LCA tools and datasets to be developed that have slightly different focuses – for instance, some are more focused on materials selection whereas others support carbon quantification at a project level. Some LCA-based tools that are in use within the market are described in section 2.3.

2.2.4 ISO 14064 and ISO 14067 – carbon emissions reduction

The ISO 14064 suite of standards (International Organization for Standardization, 2018a, 2019a, 2019b) are commonly used to measure and report carbon emissions at an organisational level, and ISO 14067:2018 (International Organization for Standardization, 2018b) is used for products. These international standards are predominantly used for operational or organisational footprints and used for reporting and transparency. Complying with these standards gives confidence in how carbon emissions can be measured, allowing for comparison.

An inventory can be verified to the ISO 14064 suite of standards, which is a requirement of New Zealand's CNGP. (Alternatively, CNGP participants can use the GHG Protocol corporate standard.) These standards provide a framework for defining the scope and boundaries of a GHG assessment but are limited in their capacity to provide guidance on how emissions are to be measured.

The ISO 14064 suite of standards provides a consistent framework for quantifying, monitoring and reporting carbon emissions and therefore is commonly used for carbon reporting. ISO 14064-1:2018 details the principles and requirements for designing and developing organisational-level GHG inventories. Despite being organisationally focused, it provides guidance on inventory management and reporting necessary for best-practice reporting and verification activities.

2.3 Background to carbon assessments

This section defines the methods and tools for assessing the whole-of-life carbon emissions of land transport infrastructure.

The embodied emissions of materials or products are calculated using the LCA methodology. This uses life cycle inventory (LCI) data to understand the total energy and resource impact of materials and products over their lifetime. The life cycle stages of materials or products include the product stage (A1–A3), construction stage (A4–A5), use stage (B1–B5), end-of-life stage (C1–C4), and benefits and loads stage (D), as presented in Figure 2.1. Environmental product declarations (EPDs) are verified outputs of LCAs and outline the emissions generated over the product's life cycle.

The embodied carbon of infrastructure is the sum of the embodied carbon of materials and products used across the infrastructure's life cycle, the transportation and construction processes, maintenance activities and end-of-life emissions (Ministry of Business, Innovation and Employment, 2022).

LCA and carbon footprinting tools have been progressively developed and adopted by the infrastructure sector to assess whole-of-life carbon (Jackson & Brander, 2019). Some of these were developed to support the assessment methods for sustainability rating tools, which were first developed to assess the sustainability of buildings and infrastructure in the 1990s and 2000s. Table 2.1 provides a summary of some carbon calculation tools used in Aotearoa New Zealand and internationally for assessing carbon at various life cycle stages. This list is not exhaustive. However, the tools mentioned here are the most commonly used in horizontal infrastructure and are referred to within literature – for example, Griffiths (2019), Liu et al. (2019) and Jackson and Brander (2019).

The tools presented in Table 2.1 vary in terms of system boundary, ranging from cradle to gate to cradle to grave. Carbon calculators require the correct application to quantify carbon for specific life cycle stages. The main carbon calculator tools for horizontal infrastructure in Aotearoa New Zealand include the NZTA Project Emissions Estimation Tool (PEET) and the Infrastructure Sustainability Council IS Materials Calculator for civil infrastructure.

Table 2.1 A non-exhaustive summary of available carbon calculation tools for infrastructure projects (adapted from Jackson & Brander, 2019)

Developer and tool	Focus area	Region	Life cycle stages measured – most comprehensive to least
BRANZ – LCAQuick	Life cycle assessment, predominantly used for vertical infrastructure	NZ	Cradle to grave
Environment Agency – Carbon planning tool	Carbon impact of infrastructure projects, used for design comparison	UK	Cradle to grave
Mott MacDonald – Moata Carbon Portal	Modelling upfront and operational carbon of new infrastructure assets during design	Worldwide	Cradle to grave
Athena Sustainable Materials Institute – EcoCalculator	Life cycle assessment of mainly vertical infrastructure	North America	Cradle to gate or cradle to grave
NZTA – Project Emissions Estimation Tool (PEET)	Carbon impact for comparison of design options and high-level carbon assessment	NZ	Cradle to completed construction, with maintenance and operational
Railway Safety and Standards Board – Rail Carbon Tool	Measuring, managing and reducing embodied carbon from the construction of rail	UK	Cradle to completed construction, use optional
Atkins – Carbon Critical Knowledgebase	Tool for calculating and evaluating low-carbon options on infrastructure projects	Worldwide	Cradle to completed construction, use optional
International Road Federation – Calculator for Harmonised Assessment and Normalisation of Greenhouse Gas Emissions for Roads (CHANGER)	Estimation of carbon emissions of road construction activities and allows comparison of techniques and materials	North America	Cradle to completed construction

Developer and tool	Focus area	Region	Life cycle stages measured – most comprehensive to least
Swedish Transport Administration – Klimatkalkyl tool	Life cycle assessment for infrastructure projects and road maintenance	Sweden	Cradle to gate, with operation and maintenance
Infrastructure Sustainability Council – IS Materials Calculator NZ v2	Evaluation of the environmental impacts of materials and transportation	NZ	Cradle to gate plus material transportation
Highways England – Carbon Emissions Calculator	Tool for collecting data on carbon emissions from the supply chain for road infrastructure	UK	Cradle to gate plus construction

2.3.1 NZTA Project Emissions Estimation Tool (PEET)

NZTA, in collaboration with Auckland Transport, KiwiRail and AECOM, developed the Project Emissions Estimation Tool (PEET) as a GHG emissions estimation tool for use in the early stages of land transport infrastructure projects (Waka Kotahi, 2023b). PEET uses standard design examples and industry research to calculate the estimated carbon emissions through a project's life cycle but with particular emphasis on the upfront carbon emissions. The purpose of PEET is to inform decision making while a project is going through a business case or design optioneering.

The standard design examples that are included in PEET provide an emissions estimation for the key materials that make up that asset type. It does not provide a detailed emissions analysis of specific project elements but provides an assessment of significant emissions sources.

PEET uses emissions factors for key construction materials from:

- BRANZ CO_2NSTRUCT v2 (BRANZ, 2023)
- construction material EPDs
- IS Materials Calculator NZ v2
- ICE database v3 (Circular Ecology, 2019)
- Ministry for the Environment emissions factors (Ministry for the Environment, 2022a)
- Greenhouse Gas Assessment Workbook for Road Projects (TAGG, 2013)
- KiwiRail report 2021
- expert advice.

These sources are periodically updated.

2.4 Analysis of research on emissions estimation

Carbon accounting is not a new scientific topic. However, in academic literature publications, a whole-of-life approach to emissions for transport infrastructure has been rare until recently (Mirhashem & Ravanshadnia, 2022). Prior to this and still appearing to have prominence in academia and policy, estimation studies have focused on tailpipe emissions produced during the use of the infrastructure rather than the construction and operation of the infrastructure (Lokesh et al., 2022b). Potential reasons for this are that it may be because responsibility for reducing tailpipe emissions and embodied emissions often sit with different government organisations (Lokesh et al., 2022b), and the varied nature of civil infrastructure (consisting of assets from tunnels to bridges, rail and roads) creates challenges in establishing robust methodologies for any type of sustainability assessment (Liu et al., 2019). However, studies on whole-of-life emissions for vertical and horizontal infrastructure are increasing, with Mirhashem and Ravanshadnia (2022) stating that, between 1999 and 2019, scholarly articles on embodied carbon in roads increased from zero to 15 articles per year.

The following paragraphs review and analyse key pieces of research that have taken place in Aotearoa New Zealand and internationally from 2013 to 2022. While this is not an analysis of all research conducted on this topic, these sources have similar objectives but varied focuses within the context of infrastructure and methodologies. The analysis of these sources seeks to find similarities and differences in the approach and to provide direction for the methodology to be used for this research project. A research methodology for vertical infrastructure is also included because carbon assessments for buildings have progressed further than horizontal infrastructure and may offer valuable insights.

Lokesh et al. (2022b) assessed the whole-of-life embodied emissions of a typical road in the United Kingdom using LCA methods recommended in ISO 14040 and ISO 14044 that are coherent with the Highways England guidance. For this study, whole of life was considered to include embodied and operational carbon but exclude emissions generated from the disposal or decommissioning of an asset because this was an unlikely occurrence for roading infrastructure and excluded use (or enabled) emissions. Lokesh et al. used a series of assumptions to calculate the whole-of-life carbon footprint of a 1 kilometre section of a single-2 lane, dual-2 lane and dual-3 lane road, which includes materials used in the construction of the road, construction energy uses, electricity used in road lighting and maintenance (relating to resurfacing). The assumptions related to the design life of the asset (assumed to be 40 years) and the material type of surfacing (assumed to be asphalt). The results are summarised in Table 2.2. The findings suggest that material production contributes approximately 70% to the overall carbon footprint of the road, material transport 10%, road operation 13%, maintenance 4% and construction averages 2%.

Table 2.2 Summary of the whole-of-life carbon footprint of different road types (Lokesh et al., 2022b, p. 23)

Road type	Total whole-of-life carbon
1 km dual-3 lane	2,658.9 tCO_2e
1 km dual-2 lane	2,014.1 tCO_2e
1 km single-2 lane	880.3 tCO_2e

Research by Huang et al. (2013) takes an international approach, analysing road widening in the UK, highway construction in the United Arab Emirates (UAE) and highway upgrades in India. Their methodology tests the use of CHANGER (Calculator for Harmonised Assessment and Normalisation of Greenhouse Gas Emissions for Roads) as a tool for measuring and benchmarking the carbon footprint of road construction. CHANGER was developed in accordance with ISO 14044, and Huang et al. found it to be a useful tool for measuring carbon in large projects where it may be impractical to model every process in detail, although this will result in a trade-off between improving consistency between projects and losing some accuracy in detail. This study sets similar boundaries to Lokesh et al. (2022b) for estimation of materials and construction activities but adds preconstruction or site clearance, cut and fill as well as deforestation and does not include maintenance or operational emissions. Similar to Lokesh et al., Huang et al. excluded end of life and decommissioning from their study. The research provides the results of the three case studies and shows the contribution of materials, transport and construction to the overall carbon footprint, with the percentage for each life stage shown. The results found that materials sourcing and manufacturing account for the largest portion of carbon emissions from road construction. However, there was significant variation in the total carbon per kilometre between and within the case studies. The results from the UK trunk road widening (2,047 tCO_2e/km for a 2-lane dual carriageway) are comparable to the results described by Lokesh et al., which estimated the carbon footprint of a dual-2 lane road to be 2,014 tCO_2e/km. However, the relative impact of each life stage varies from Lokesh et al.'s research, with materials contributing 50%, transport contributing 22% and construction contributing 28%. This may be due to the different boundary conditions or methodology used.

Table 2.3 Carbon footprint of road construction (adapted from Huang et al., 2013)

		Length (km)	Materials (tCO_2e/km)	Transport (tCO_2e/km)	Construction (tCO_2e/km)	Total (tCO_2e/km)
UK	Trunk road	28	743	236	1,069	2,047
UAE	Option A	250	5,018	3,169	1,439	9,626
	Option B	250	4,525	2,511	1,522	8,559
India	WEP1	52.4	2,982	82	163	3,227
	WEP2	75.3	461	255	181	897
	WEP3	38.58	496	140	938	1,574
	WEP4	73.8	565	363	319	1,247
	WEP5	28.6	589	549	499	1,637
		Average %	50%	22%	28%	

Swithinbank (2022) used carbon footprints that had been previously calculated for infrastructure projects from Aotearoa New Zealand and internationally to establish a carbon baseline for infrastructure projects in this country. This work analysed previously completed carbon footprints/GHG inventories for motorways, state highways, shared paths and railways across the construction and operational and maintenance life cycle stages. Using standard metrics, these datasets were used to calculate a carbon baseline for construction and operation of infrastructure assets. Similar to Lokesh et al. (2022b) and Huang et al. (2013), Swithinbank excluded end-of-life emissions in this assessment but acknowledged this as a gap that should be addressed rather than end-of-life emissions being an unlikely occurrence. The research investigated the impact of different construction conditions on the overall carbon footprint of the project, and the results suggested that major structures and earthworks have a large impact on the overall carbon footprint of a project, particularly roading and shared path projects. Swithinbank's analysis found that 73% of total emissions in roading projects came from embodied emissions in materials. This is similar to the study completed by Lokesh et al. (70%), although the results should be taken with caution as material transport may have been allocated to different categories in different footprints. Lokesh et al., Huang et al. and Swithinbank all use specific project information to assess the carbon footprint of infrastructure assets. Lokesh et al. and Huang et al. used design and construction information to calculate the asset footprint, and Swithinbank used previously calculated carbon assessments of assets to establish a carbon baseline.

While Lokesh et al.'s (2022b) study described the whole-of-life impact of roading infrastructure, they undertook a similar study to research the whole-of-life carbon impact of rail infrastructure (Lokesh et al., 2022a). This research used a similar approach in that the whole-of-life carbon of 1 kilometre of track was modelled. The research found that track maintenance was the most material and energy-intensive stage in the life cycle of a rail track, contributing approximately 70% of the track's whole-of-life carbon. They discussed the benefits for operational emissions of a decarbonising grid, including reducing carbon emissions from the overhead lines operation and in stations. They noted that, even in optimistic decarbonisation scenarios, embodied carbon in materials remains a 'stubborn' and significant component (22–48%) of whole-of-life carbon that is hard to remove (Lokesh et al., 2022a, p. 7).

Other studies on emissions estimation have researched specific elements of transport infrastructure. As an example, Gallagher and Bearsley (2021) sought to understand carbon emissions arising from the construction of different pavement types. Their methodology first estimated the embodied carbon for pavement construction materials (aggregate, cement and bitumen). The carbon estimates in this work were based on expected carbon footprints at the production plant and therefore do not include transport of materials to the construction site. The research draws upon EPDs, the IS Materials Calculator and industry estimates to calculate the scope 1 (estimated direct carbon emissions arising from supply chain companies), scope 2 (emissions from electricity generation and third-party transport operators) and scope 3 (bitumen manufacture and transportation to Aotearoa New Zealand) emissions. Pavement models based on design specifications were developed, and the carbon emissions for each pavement type were estimated. The estimated carbon emissions for each pavement type varied from 24.3 $kgCO_2e/m^2$ to 83.7 $kgCO_2e/m^2$, as shown in Table 2.4.

Table 2.4 Estimated carbon emissions for 5x 10^6 ESA (equivalent standard axles) structurally equivalent pavements (adapted from Gallagher & Bearsley, 2021, p. 7)

Pavement type	Units	Total ($kgCO_2e$)
Granular basecourse	m^2	24.3
Cement modified basecourse	m^2	31.4
Foamed bitumen stabilised basecourse	m^2	29.7
Structural asphalt	m^2	38.3
High modulus asphalt	m^2	35.4
Inverted cement stabilised sub-base	m^2	46.1
Continuously reinforced concrete pavement	m^2	83.7

As summarised by Mirhashem and Ravanshadnia (2022) and Lokesh et al. (2022b), embodied and whole-of-life carbon research into buildings far exceeds horizontal infrastructure. A recent report by the Green Building Council of Australia and thinkstep-anz sought to calculate the embodied carbon and embodied energy in Australia’s commercial and residential buildings (Green Building Council Australia & thinkstep-anz, 2021). Similar to tailpipe emissions for horizontal infrastructure, this report acknowledges that carbon emitted from the use of the building is much more visible and has been the focus of more research than embodied carbon, making embodied carbon (predominantly upfront emissions) the hidden carbon impact of buildings.

This research used process LCA as its baseline method and three main steps to calculate a national baseline (2019) and a forecasted impact (2050), which were:

- a bottom-up hotspot assessment (process LCA)
- top-down material flow analysis (MFA) for the top five material categories
- refined bottom-up hotspot assessment using MFA data and supplementary data.

The scope of the study considered the embodied carbon and energy within manufacture of building materials, transportation of materials to site, construction processes, maintenance of buildings, demolition and disposal at end of life and recycling credits. The research estimated that the total carbon emissions from Australia’s buildings was 137 $MtCO_2e$ in 2019, which will reduce to 29 $MtCO_2e$ in 2050, largely due to a decarbonising grid. The research found that, for all building types, materials had the largest contribution to the overall embodied carbon of the building and that, under a business-as-usual scenario, embodied carbon emissions are estimated to increase between 2019 and 2050. The research also found that, over time, the relative impact of materials to the whole-of-life carbon footprint will increase as the national electricity grid decarbonises, with the research estimating that embodied carbon, which contributed 16% of total emissions from the building stock in 2019, will represent 85% in 2050.

2.5 Key findings of the literature review

Most research to date on the carbon footprint of infrastructure (both horizontal and vertical) has focused on carbon emissions during the use stage of the asset by vehicles using the road. However, there has been growing awareness of the upfront carbon that is produced through the construction of infrastructure, which has been seen through an increasing number of studies that seek to understand the whole-of-life carbon footprint of infrastructure types.

Despite the increasing number of carbon estimation studies, they remain limited to major asset types such as the road network and rail and do not encompass the entire land transport network. Notable asset types that do not feature heavily in carbon estimation research include structures (such as bridges and tunnels) and footpaths.

Of the relevant carbon estimation studies, there is variation in the scope, boundaries and methodologies. Estimation of the carbon footprint of material production, transport and construction processes (life cycle stages A1–A3 and A4–A5) feature within most research. However, there are variations between these elements. The inclusion of other life cycle stages such as maintenance and operational emissions also varies between research.

End-of-life impacts (life cycle stages C1–C4) have been excluded from most studies on horizontal infrastructure with the justification provided being that decommissioning is not a common occurrence for infrastructure assets.

3 Methodology

The objective of the methodology was to draw upon the findings of the literature review, including quantification methods, data, scope and boundary setting, to steer the quantification method. Although the literature review did not result in a clear methodology for undertaking a carbon assessment at this spatial scale, findings from the review have been used to set boundaries around life cycle and assets and in the overall approach. The overall approach to the methodology takes an asset profile that presents a typical asset, quantifies the carbon associated with it and aggregates that across the number (or length) of this asset in Aotearoa New Zealand. This approach follows the methodology set out by Gallagher and Bearsley (2021) – New Zealand researchers who used a similar method for quantifying the carbon emissions of pavements (with a detailed summary provided in section 2.4). The following sections detail the scope and boundaries of the research and provide a summary of the methodology, with further detail provided in Appendix A.

3.1 Scope of research

This research project sought to quantify the carbon footprint of existing land transport infrastructure, providing a high-level, whole-of-life carbon footprint that addresses construction, maintenance, operation and end-of-life carbon emissions. This study was exploratory and aimed to establish a basic understanding of the carbon footprint of New Zealand's land transport infrastructure over its lifetime. Assessing the emissions associated with a typical asset is a different process from assessing the carbon footprint of a specific infrastructure development or a product where the individual components are well documented.

3.1.1 Life cycle stages

The scope of this study covers embodied carbon and embodied energy across the full life cycle of New Zealand's land transport infrastructure. It does not include enabled emissions. Table 3.1 presents the life cycle stages that have been included in this research to meet the scope of the project, and Table 3.2 provides additional detail on the variation between specific infrastructure types. The recovery stage (module D) has been excluded across all infrastructure types.

Table 3.1 System boundaries for this research project based on the modules in EN 15804

	Product stage	Construction process stage		Use stage							End-of-life stage			
	Raw material supply Transport Manufacturing	Transport process	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction, demolition	Transport	Waste processing	Disposal
Module	A1–A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Modules declared	✓	✓	✓	ND	✓	✓	✓	✓	✓	ND	✓	✓	✓	✓

ND = not declared.

Table 3.2 System boundaries for specific infrastructure assets used for this research project based on the modules in EN 15804

Asset type	Product stage	Construction process stage		Use stage							End-of-life stage			
	Raw material supply Transport Manufacturing	Transport process	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction, demolition	Transport	Waste processing	Disposal
Footpath/ cycleways	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	ND	ND	ND	ND
Drainage	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	✓	✓	✓	✓
Kerb and channel	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	✓	✓	✓	✓
Pavements	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	ND	ND	ND	ND
Railings	✓	✓	✓	ND	ND	✓	ND	✓	ND	ND	✓	✓	✓	✓
Road marking	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	ND	ND	ND	ND
Signage	✓	✓	✓	ND	ND	✓	ND	✓	ND	ND	✓	✓	✓	✓
Streetlights	✓	✓	✓	ND	ND	✓	ND	✓	✓	ND	✓	✓	✓	✓
Structures	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	✓	✓	✓	✓
Traffic islands	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	✓	✓	✓	✓
Traffic signals	✓	✓	✓	ND	ND	✓	ND	✓	✓	ND	✓	✓	✓	✓
Bus shelters	✓	✓	✓	ND	ND	✓	ND	✓	ND	ND	✓	✓	✓	✓
Rail structures	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	✓	✓	✓	✓
Rail tracks	✓	✓	✓	ND	✓	✓	✓	✓	ND	ND	✓	✓	✓	✓

ND = not declared.

3.1.2 Infrastructure assets

The scope of this study includes the infrastructure and asset types that are listed in Table 3.3, with a further breakdown of the components and exclusions for each asset type. This is not an exhaustive list as there are several very minor asset types that would not impact the overall result. This list should be looked at on an asset-by-asset basis rather than as a comparison between assets. Complex asset types have more exclusions than those included in this list. The rationale for asset inclusions and exclusions is included in Appendix D.

Table 3.3 Scope of infrastructure and asset types within the scope of this study and asset exclusions

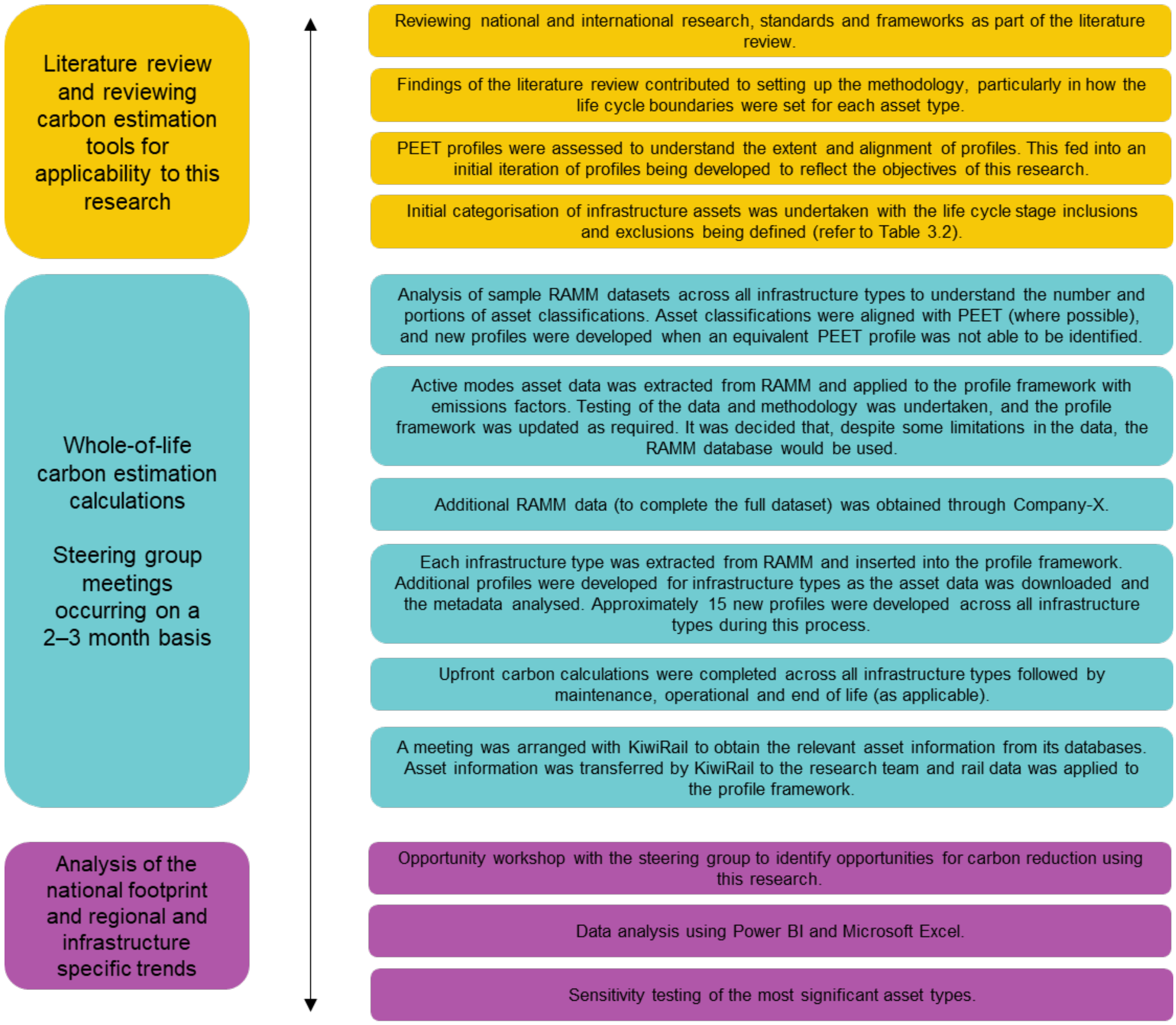
Asset type	Further asset breakdown and inclusions	Asset exclusions	Reasoning for exclusion
Road network			
Footpath/cycleways	Footpaths Cycleways	Handrails Street furniture, including seating	Handrails and other minor materials were not included in this assessment due to a lack of information in RAMM
Drainage	Catchpits Culverts Subsoil drains Manholes	Piped water network Fixings	The piped water network was out of scope for this study as it was considered separate to transport infrastructure drainage
Kerb and channel		Rural kerb and channel	Due to the limited data in RAMM on kerb and channel, rural kerb and channel was assumed to have a high portion of surface water channels, which do not have a material impact
Pavements	Pavements	Network utilities Revegetation or replanting	Network utilities such as electrical and telecommunication infrastructure were out of scope for this assessment Revegetation considered immaterial
Railings		Handrails Fixings	Limited data in RAMM on handrails and fixings
Road markings	Paint	Zebra crossings	Limited information in RAMM database and considered immaterial
Signage	Structure	Fixings	Considered immaterial
Streetlights	Structure Operational energy	Bulbs	Considered immaterial
Structures	Bridges Underpasses Culverts	Tunnels Fixings Operational energy that is not covered in other asset profiles (eg, ventilation)	Limited data on the carbon footprint of tunnels and the number of tunnels in Aotearoa New Zealand

Asset type	Further asset breakdown and inclusions	Asset exclusions	Reasoning for exclusion
Traffic islands	Structure	Fixings	Considered immaterial
Traffic signals	Structure Operational energy	Fixings Bulbs	Considered immaterial
Public transport			
Bus shelters	Bus stops	Vertical infrastructure relating to bus and public transport assets (eg, bus stations) Bus infrastructure that is located on private land (eg, bus depots) Operational energy	Limited data on the building typologies of public transport stations in Aotearoa New Zealand
Rail			
Structures	Bridges Retaining walls Culverts	Tunnels Fixings	Limited data on the carbon footprint of tunnels and the number of tunnels in Aotearoa New Zealand
Tracks	Rails Tracks Ballast Fixings	Related infrastructure such as yards	

3.2 Research assessment

This research took an asset categorisation approach to calculate the emissions for each infrastructure type, which was then aggregated to calculate the national footprint. Figure 3.1 provides an overview of the steps taken to develop the national footprint. Further details on specific elements of the methodology are provided in Appendix A and an in-depth discussion on using New Zealand's Road Assessment and Maintenance Management (RAMM) for this process is provided in Appendix B.

Figure 3.1 Overview of the methodology in calculating the carbon footprint of land transport infrastructure in Aotearoa New Zealand



3.3 Summary of asset profiles

The methodology used for the carbon calculations was based around the development of profiles that represented a typical asset. This is similar to the approach taken by Gallagher and Bearsley (2021) who modelled different pavement types used in Aotearoa New Zealand and the methodology for design comparison in PEET. Details on the profiles that were developed for each infrastructure type are provided in Appendix C with an overview provided below.

3.3.1 PEET standard design

PEET v3 uses standard design examples and industry research to provide a high-level estimation of the carbon emissions of an asset that can be used across an entire infrastructure project at the early stages of design. The standard design examples included in PEET were used as the first iteration of the asset profiles for this research. The PEET standard design examples consider the most significant emissions sources of a project's life cycle and do not provide a detailed emissions analysis of project elements. Three asset types are shown in Table 3.4 as an example of how the standard designs are developed in PEET.

Table 3.4 Three examples demonstrating how PEET standard designs are developed using the materials that make up individual components of an asset

Asset	Asset component	Materials making up component
Light pole – 8 m	Concrete foundation	In situ concrete 30 MPa (ordinary Portland cement) Aggregate
	Pole	Steel coil
Standard concrete footpath – 100 mm depth, 1 m width	Concrete slab	In situ concrete 20 MPa (ordinary Portland cement)
	Basecourse	Aggregate
	Sub-basecourse	Aggregate
	Earthworks	
Minor roundabout – 10 m diameter, centre raised bed	Basecourse	Aggregate
	Concrete slab	Precast concrete Steel reinforcing bar
	Mountable concrete kerb	Precast concrete Steel reinforcing bar
	Concrete splitter islands	Precast concrete
	SAC allowances	Hot mix asphalt 0% reclaimed asphalt pavement Aggregate Bitumen Lime

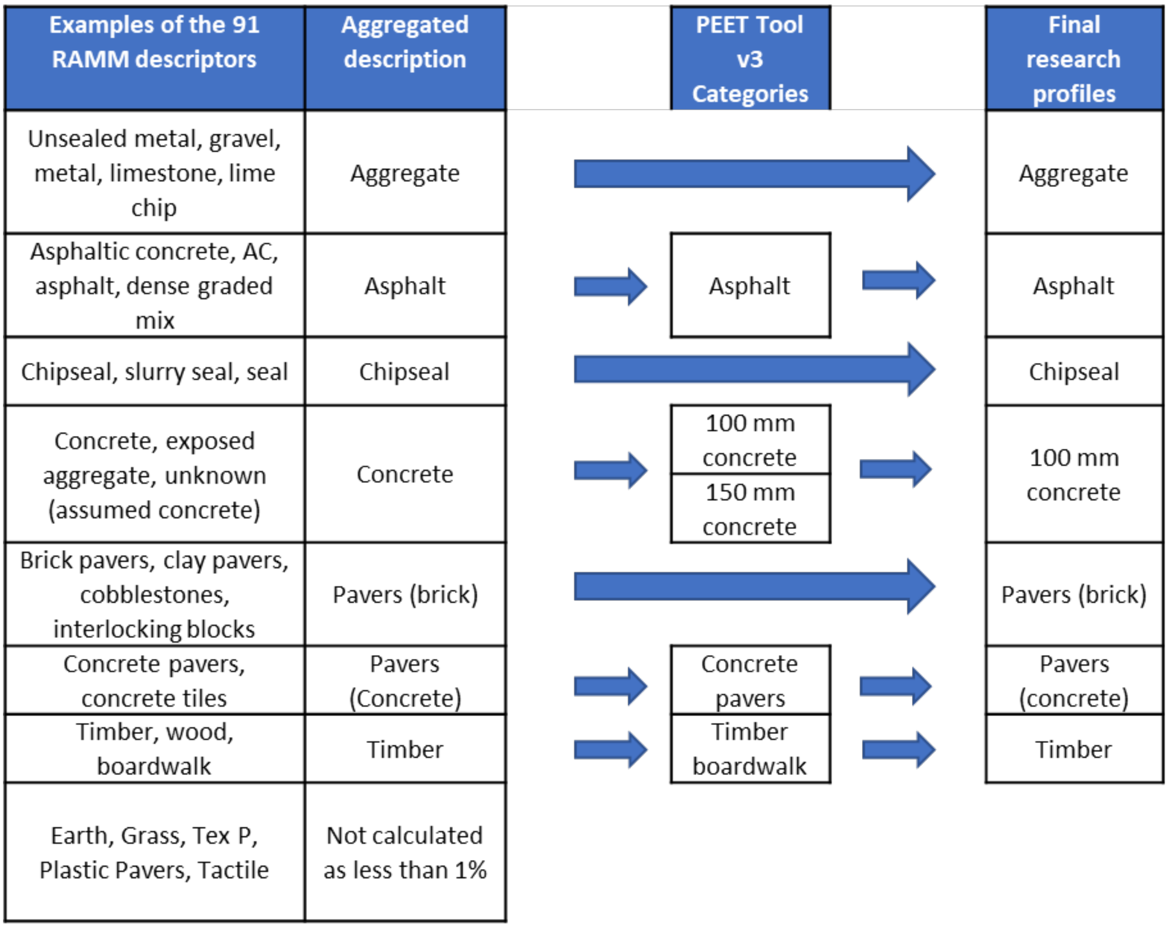
PEET uses these standard designs to estimate the carbon emissions by calculating the quantity of material required for each component and multiplying by the relevant emissions factor for that material. As discussed in section 2.3.1, emissions factors in PEET have been obtained from a range of sources.

3.3.2 Developing PEET standard designs into profiles

The standard designs that have been previously researched and included in PEET became the first iteration of profiles for this research project. PEET standard designs across all different infrastructure types were collated into Excel workbooks based on the infrastructure type (for example, footpath/cycleways, pavements and structures). A sample of RAMM asset data was downloaded and compared to the PEET standard designs. The RAMM database has a large amount of data representing asset categorisation, spatial information, material composition, quantity or treatment lengths, asset owners, construction dates and many other elements. Asset categorisation and material composition information were used to align the RAMM assets with PEET standard designs to inform the asset profiles. Infrastructure types required varying levels of effort, with some infrastructure types being relatively simple to align with the PEET standard designs and others requiring significant recategorisation due to the use of free-text boxes to describe materials.

Figure 3.2 provides an example of how the footpath/cycleway infrastructure type was developed from the PEET standard design to profiles used in this research. The source data from RAMM had 91 varying descriptors of footpath surface type. PEET had five standard design profile types. For the purposes of the study, the different footpath surfacings were firstly categorised into aggregated families such as asphalt, chipseal and concrete in alignment with PEET. The concrete surfacings were calculated based on the 100 mm profile from PEET as thickness data was not available in RAMM. Profiles for chipseal and unsealed (aggregate) footpaths were added to align with those footpath sections in RAMM that were numerous enough to justify an additional profile.

Figure 3.2 An example of how PEET standard designs for footpath/cycleways infrastructure were aligned with RAMM data to develop profiles for this research project



Like the examples provided in Table 3.4, the profiles developed for this research project were split into individual components, and the materials that make up those components were assigned an emissions factor.

3.4 Key assumptions

Table 3.5 provides a summary of the calculation method and key assumptions for each life cycle stage. Refer to Appendix C for more detail on the specific profile assumptions.

Table 3.5 Key assumptions across the different life cycle stages

Life cycle stage	Calculation method	Key assumptions
Embodied emissions in materials A1–A3	Applying profile emissions factors	• RAMM data was taken as accurate unless null measurements were supplied, in which case average asset measurements were applied. • Asset profiles were assigned based on keywords from the asset data classification. • Carbon sequestration potential of materials (such as timber and concrete) has not been factored into these calculations.
Transportation of materials to site emissions A4	PEET default factor of 16% applied to total embodied carbon of materials	• Due to lack of data on material supplier locations, the PEET default factor was used derived from Swithinbank (2022).
Construction installation emissions A5	PEET default factor of 17% applied to total embodied carbon of materials	• Due to lack of data on construction methods and fuel use, the PEET default factor was used derived from Swithinbank (2022).
Maintenance emissions B2–B5	Maintenance emissions were applied based on an average year of maintenance across the asset's valuation life	• The maintenance emissions of pavements covered emissions associated with results aligned with the IDS modelling work assigning carbon footprints to pavement renewals and maintenance activities (IDS, n.d.).This work was completed for NZTA using the national state highway network data and Southland District Council network. • The maintenance emissions of asset types replaced at the end of life (eg, streetlights, bus shelters) were calculated based on the embodied emissions of materials and the construction installation emissions represented in net present value (average emissions per year based on the average valuation lives). • Average valuation lives were sourced from a variety of road controlling authorities' roading valuations and the New Zealand Infrastructure Asset Valuation and Depreciation Guidelines (Āpōpō, 2006).
Operational energy use B6	Average kWh per year taken for assets that require electricity The emissions factor for electricity was taken from Ministry for the Environment (2022a) and applied to assets' electricity usage for 1 year Modelling the total operational energy and emissions over the lifetime of the assets was not performed	• Average hours of the day for streetlight use assumed 11.5 hours per streetlight. • LED streetlights were assumed to be 100 W. • Non-LED streetlights were assumed to be 250 W. • It was assumed 78% of the national streetlight inventory are LED and 22% are non-LED. • Traffic lights were assumed to have 1.2 lights operating 24 hours a day. • Traffic lights were assumed to be 200 W.
Deconstruction C1	The deconstruction (demolition) of pavements was captured in the maintenance emissions factors for pavements	• Emissions resulting from fuel consumption in the deconstruction and demolition of assets (eg, bridges) were not included in this assessment due to lack of data on the fuel quantities involved per asset type.
Transportation, processing and disposal of	The assets' material quantities calculated were applied end-of-life waste	• Emissions from waste disposal were included in the analysis and included processes of collection, transportation and landfill emissions (gate to grave).

Life cycle stage	Calculation method	Key assumptions
materials C2–C4	disposal emissions factors from UK Government GHG conversion factors for company reporting[8]	• Material types were applied closed loop factors if they are commonly recycled in Aotearoa New Zealand (eg, steel and aluminium) or landfill factors if they are commonly sent to landfill (eg, aggregate, plastics, concrete, wood). • The future state of material recycling was not considered (ie, the expected rates of concrete, wood or aggregate recycling in the future). • UK Government GHG conversion factors were assumed because Ministry for the Environment (2022a) factors only provide GHG emissions factors for landfill gases and do not include collection, transportation and processing.

3.5 Sensitivity testing

A sensitivity analysis was undertaken to test the assumptions that were made across the major asset types. An overview of the method for doing the sensitivity analysis is provided in Table 3.6.

Table 3.6 Overview of sensitivity testing method

Sensitivity analysis step	Further detail
Define variables	• Select independent variable/s that will impact the dependent variables. • Select the asset/material types that will be tested. • Define the experimental model.
Create assumptions	• Create assumptions from the database.
Define the scenarios	• Setting the boundaries: define scenarios (low/medium/high) under which the assumptions will be applied on the variables.
Sensitivity analysis	• Perform the analysis and observe the results under different scenarios and assumptions. • Correlation analysis: defining the relation between independent and dependent variables. • Subjective sensitivity analysis: analyse individual parameters.
Results and charts	• Summary of the results with charts for better visualisation. • Draw conclusion.

3.6 General considerations and limitations

Our aim has been to provide a reasonable estimation of the carbon footprint of land transport infrastructure in Aotearoa New Zealand. Given the scale of this task, several approximations have been put in place. The following is a list of assumptions that have been adopted into the general analysis and reporting of results:

- This study is exploratory in nature, attempting to understand the significance of carbon within infrastructure assets. The profiles that have been developed represent a typical make-up of material type, material quantity and construction methods. However, every infrastructure asset is different and is constructed with a unique set of conditions impacting the construction methods and material make-up. The profiles have been aligned with PEET where possible to maintain consistency with current tools.
- The assets in this research were assumed to have been constructed using the materials, material manufacturing processes, construction techniques and transportation methods that are used today.

[8] https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting

Historical differences in the way materials were manufactured, construction methodology and the natural build-up of infrastructure assets over time (for example, roads that were originally gravel roads and were built up and sealed) has not been factored into this research. Emissions factors of materials have been based on current data (including EPDs and manufacturer information) and may not reflect the manufacturing processes that took place at the time the asset was constructed.

- Current electricity and diesel emissions factors have been applied to construction and maintenance emissions, despite the year of construction. Current emissions factors have also been applied to future activities, including maintenance, operational and end-of-life activities, and this research has not incorporated reduced carbon emissions from grid electricity, improved energy efficiency in manufacturing plants or electrification of the transport fleet.
- This research provides a high-level estimation of the carbon emissions of land transport infrastructure. The results may help inform but should not be used to report under the requirements of the CNGP or annual GHG reporting requirements.
- Asset data was obtained using national and organisational databases, including RAMM. RAMM includes a significant amount of information about individual assets or treatment lengths of road and footpaths. The asset information contained in RAMM was assumed to be correct and categorised accordingly to develop the national footprint. However, given RAMM as a database has been used for decades, it has a lot of variability in the way that data has been entered between and within regions. The data within RAMM has been taken on face value. It is outside the scope of this project to validate the RAMM data. The known limitations however have been detailed.
- NZTA publicly available bridge number and length data was used to extrapolate missing structure data (this was the only exception to using RAMM data). The data obtained from RAMM and KiwiRail was assumed to be accurate (as confirmed above). However, when data was null, the average for that asset class was used to add it to a profile and calculate the carbon emissions. Metrics in RAMM that were frequently null included heights and widths (for example, the height of a sign or width of a bridge). In these situations, the average sign height or average bridge width were used.
- The profiles in this research were based on the profiles developed as part of PEET. These profiles and the emissions factors associated with them, as determined in PEET, are assumed to have been developed through best practice and represent an accurate assessment.
- This research presents a GHG-only inventory and does not present the overall environmental performance of infrastructure.
- This research has not considered the impact of calcium carbonation in concrete and the effect this has on carbon sequestration.
- This research has excluded the impact of fuel use for deconstructing assets (ie, life cycle stage C1) due to the limited data available on decommissioning transport infrastructure assets. This data is not able to be assessed given uncertainty over assessing the distance from the asset location and the location post deconstruction.

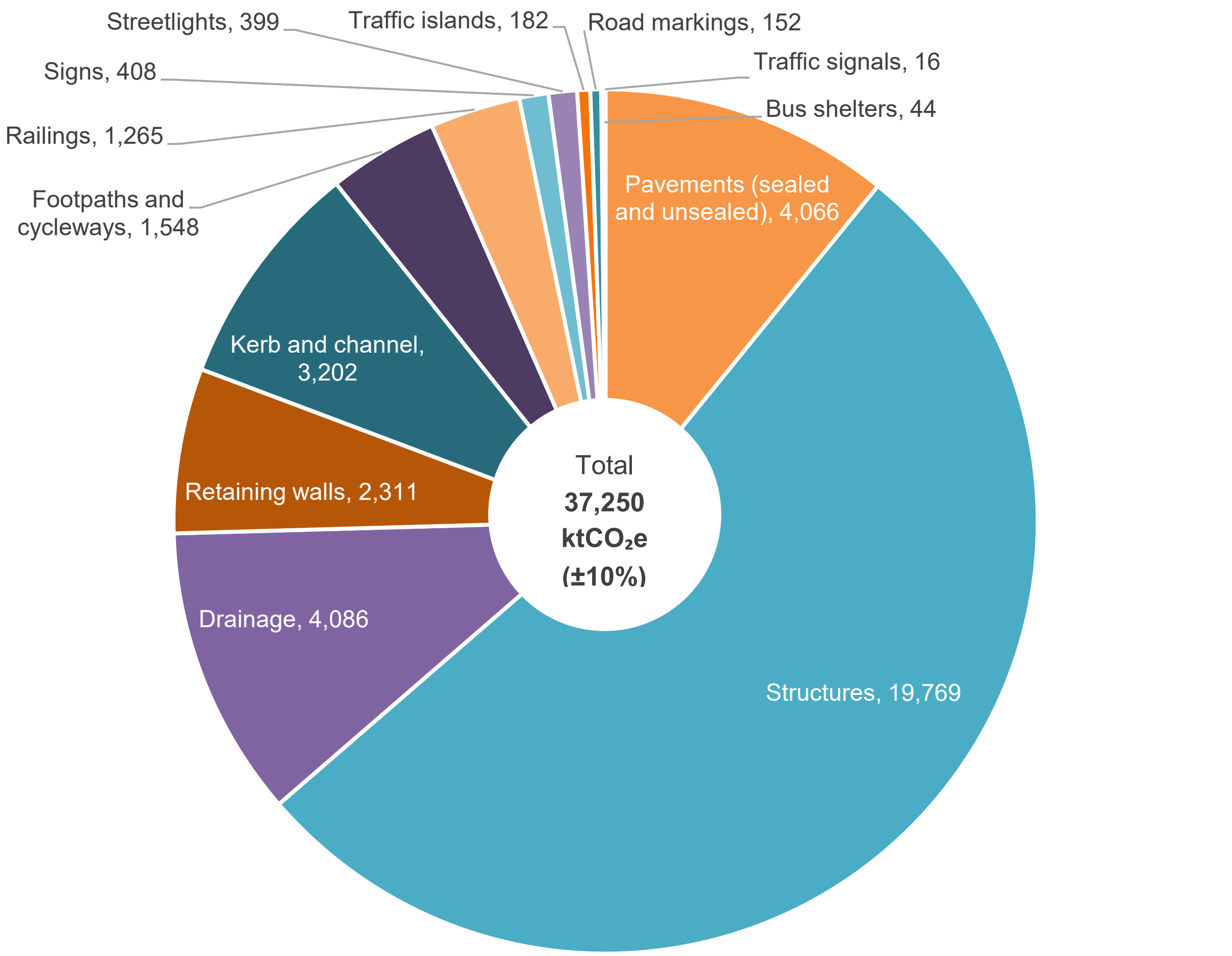
4 The national footprint

This section provides an overview of the results of the national carbon footprint of land transport infrastructure in Aotearoa New Zealand. This overview is supported by a Power BI dashboard that should be used to undertake further analysis of the results and to understand variances between regions and infrastructure types.

The following results show the total upfront emissions, the expected maintenance and operational emissions on a yearly basis and the end-of-life emissions. The upfront emissions demonstrate that significant carbon expenditure has happened over decades of investment into New Zealand's infrastructure. However, this cannot be changed, and the focus should be placed on reducing emissions from maintenance, operational and end-of-life activities in addition to reducing the impact of future assets that have not yet been constructed (which have not been incorporated into this footprint).

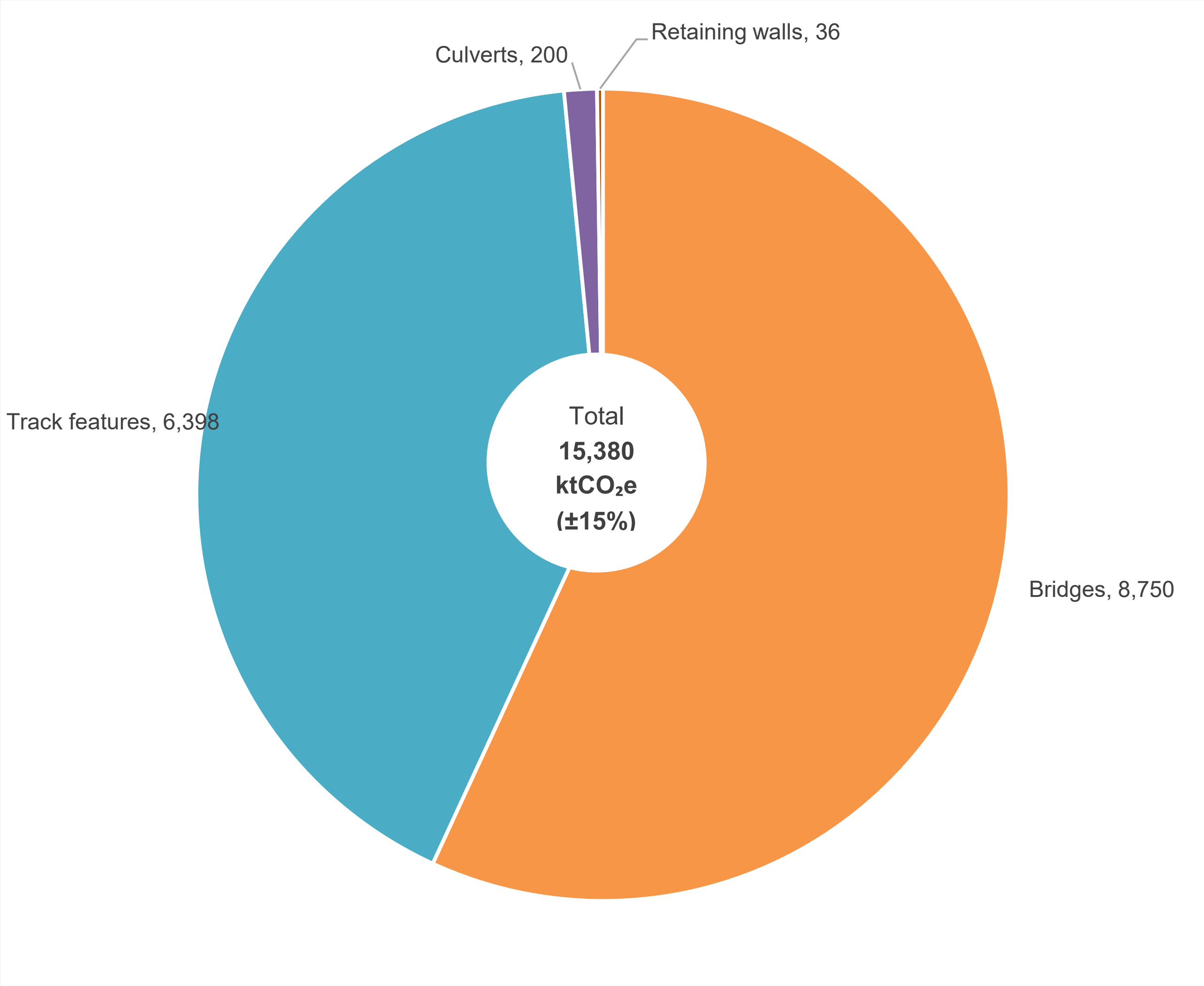
The total upfront emissions for the road network are **37,250 ktCO$_2$e (±10%)**. Figure 4.1 shows the relative contribution of the different asset types to this footprint. Structures (consisting of bridges and culverts) contribute the largest portion to upfront emissions (53% of the total national road network footprint) followed by pavements and drainage (both 11%).

Figure 4.1 Total upfront emissions for the road network (ktCO$_2$e)



The total upfront emissions for the rail network are **15,380 ktCO_2e (±15%)**. Figure 4.2 shows how the different rail asset types contribute to this footprint. Bridges contribute the largest portion to upfront emissions (57% of the total rail network) followed by track features (consisting of ballast, sleepers and tracks), which represent 42%.

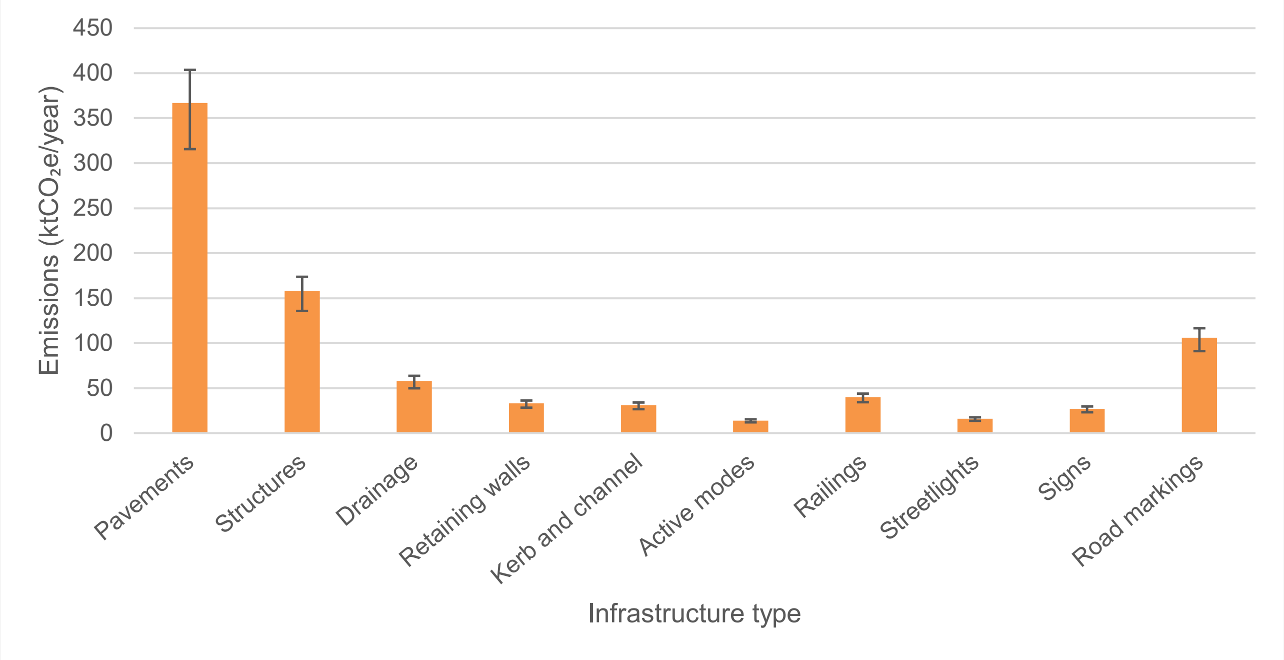
Figure 4.2 Total upfront emissions of the rail network (ktCO_2e)



Maintenance activities of our current road network contribute a total of **855 ktCO_2e (+10%, -14%)** emissions per year. Figure 4.3 shows the estimated carbon emissions associated with maintenance activities on the road network each year. Sealed pavements have the most carbon-intensive maintenance activities at **357 ktCO_2e/year**, which represents 45.30% of all yearly maintenance activities. Asset owners and managers have an obligation to maintain the assets that exist in our network, and this data demonstrates that these maintenance obligations require a significant investment in carbon each year. In addition, new assets (ie, new greenfield) are likely to add further contribution to maintenance emissions.

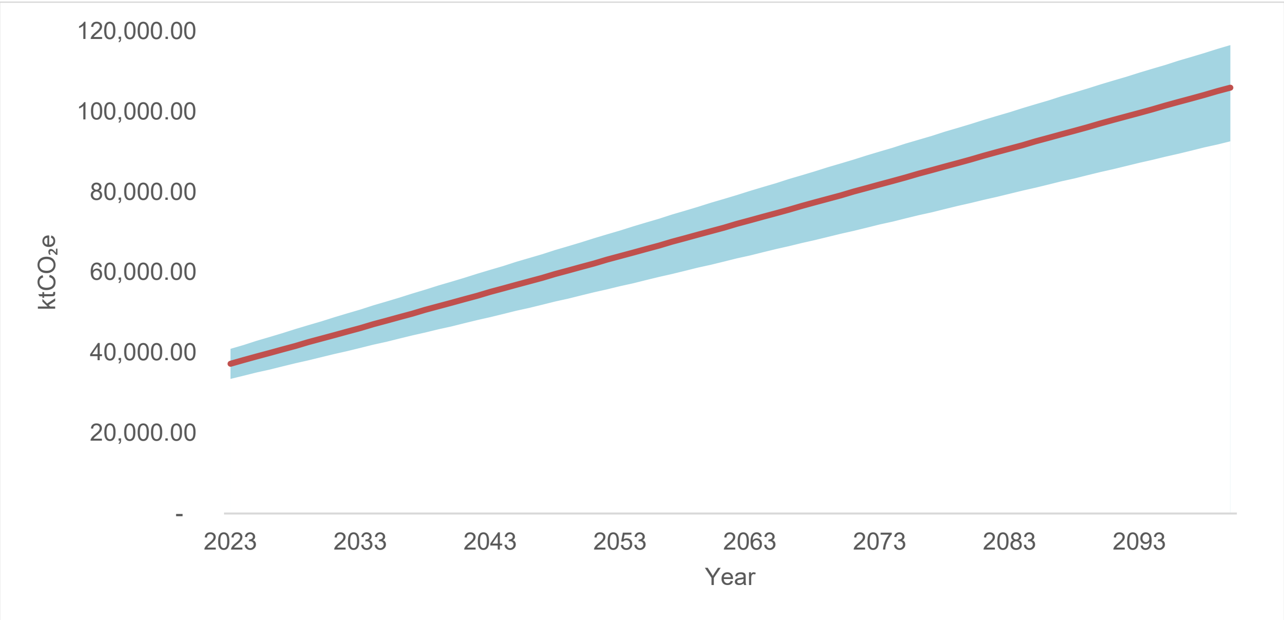
Operational activities for the road network contribute a total of **35 ktCO_2e (+10%, -22%)**.

Figure 4.3 Maintenance emissions per year for infrastructure types on the road network ($ktCO_2e$/year) (+10%, -14% for all infrastructure types)



Total embodied and operational emissions for the road network are shown in Figure 4.4, demonstrating the estimated impact that the current network will have over its lifetime. With the current upfront emissions being estimated at **37,250 $ktCO_2e$ (±10%)**, this graph shows that emissions required to maintain, operate and eventually demolish (or deconstruct) our road infrastructure are creating carbon emissions of **890 $ktCO_2e$ (+10%, -14%)** per year.

Figure 4.4 Representation of embodied emissions (including upfront, maintenance and end of life) and operational emissions per year for the road network ($ktCO_2e$) ((±10%) upfront (+10%, -14%) maintenance, operational and end of life)



The end-of-life emissions for the road and rail network are estimated to create a total of **133 ktCO_2e** and **175 ktCO_2e** respectively. Based on the valuation life of the assets, this is estimated to create **1.81 ktCO_2e** and **4.44 ktCO_2e** per year.

End-of-life emissions for the road network are lower than for the rail network due to the boundaries set in this research for the pavement asset types. Pavements are considered to not have an end of life. However, they are regularly milled down, resurfaced and resealed as part of the maintenance process, which does create waste. The emissions associated with pavement maintenance waste has been included in the maintenance calculations and not included in the end-of-life calculations.

A summary of the embodied and operational emissions of each infrastructure type is included in Table 4.1. The sensitivities as detailed in section 5 were assessed on the significant contributors for each emissions type and included in the table below.

Table 4.1 A summary of the carbon footprint of different life stages for all infrastructure types included in this research

<table>
<tr><th></th><th>Asset type</th><th>Upfront carbon emissions (ktCO_2e)</th><th>Maintenance emissions (ktCO_2e/year)</th><th>Operational emissions (ktCO_2e/year)</th><th>End-of-life emissions (ktCO_2e)</th></tr>
<tr><td rowspan="4">Rail</td><td>Bridges</td><td>8,750 (±18%)</td><td rowspan="4">220</td><td rowspan="4">NC</td><td rowspan="4">175</td></tr>
<tr><td>Track features</td><td>6,400</td></tr>
<tr><td>Culverts</td><td>200</td></tr>
<tr><td>Retaining walls</td><td>36</td></tr>
<tr><td rowspan="13">Road</td><td>Structures</td><td>19,770 (±18%)</td><td>160</td><td>NC</td><td>7</td></tr>
<tr><td>Pavements (sealed and unsealed)</td><td>4,770</td><td>370 (+23%, -34%)</td><td>NC</td><td>NC</td></tr>
<tr><td>Drainage</td><td>4,090</td><td>58</td><td>NC</td><td>8</td></tr>
<tr><td>Retaining walls</td><td>2,311</td><td>33</td><td>NC</td><td>57</td></tr>
<tr><td>Kerb and channel</td><td>3,200</td><td>31</td><td>NC</td><td>16</td></tr>
<tr><td>Footpaths and cycleways</td><td>1,550</td><td>14</td><td>NC</td><td>42</td></tr>
<tr><td>Railings</td><td>1,265</td><td>40</td><td>NC</td><td>1</td></tr>
<tr><td>Signs</td><td>410</td><td>27</td><td>NC</td><td>0.5</td></tr>
<tr><td>Streetlights</td><td>400</td><td>16</td><td>30 (+10%, -22%)</td><td>0.3</td></tr>
<tr><td>Traffic islands</td><td>180</td><td>2</td><td>NC</td><td>1</td></tr>
<tr><td>Road markings</td><td>150</td><td>105</td><td>NC</td><td>NC</td></tr>
<tr><td>Bus shelters</td><td>44</td><td>2</td><td>NC</td><td>0.3</td></tr>
<tr><td>Traffic signals</td><td>16</td><td>1</td><td>4</td><td>0.02</td></tr>
</table>

NC = not calculated.

4.1 Emissions Context

To provide a comparative reference point for the magnitude of the estimated emissions in this report, some data from New Zealand's emission inventory for the 2022[9] year are displayed below.

- New Zealand's national net emissions for the 2022 year were estimated at 59,100 ktCO2e.
- New Zealand's land transport emissions for the 2022 year were estimated at 13,600 ktCO2e.

This data is provided for illustrative purposes to contextualise the relative scale of the totals from this research. The emissions boundaries used in the national emission inventory are different to those in this report, and there is no literal or comparative relationship between this information and the emissions estimates in this report (i.e. one is not a subset of the other).

4.2 Sensitivity analysis

The sensitivity analysis was performed on the upfront emissions, operational emissions and maintenance emissions to check the assumptions applied to the RAMM dataset and the impact these have on the final results.

4.2.1 Upfront emissions

The upfront carbon emissions were found to be most sensitive to the structure assumptions, including:

- the assumption used to determine the small, medium and large bridge emissions profiles
- the assumption used to determine the abutment size.

These assumptions were tested within the realistic upper and lower bounds (±30%) to check the impact on total upfront emissions.

Structure emissions were found to be sensitive to the assumptions by approximately ±18%, resulting in a sensitivity of ±10% to the total upfront emissions.

4.2.2 Maintenance emissions

The maintenance carbon emissions were found to be most sensitive to the pavement maintenance assumptions, including:

- the reseal renewal rate (ie, percentage of the network resurfaced each year)
- the rehabilitation renewal rate (ie, percentage of the network with pavement renewals each year).

These assumptions were tested within the realistic upper and lower bounds (±30%) to check the impact on total maintenance emissions.

Pavement maintenance emissions were found to be sensitive to the assumptions by approximately +23%, -34%, resulting in a sensitivity of +10%, -14% to the total maintenance emissions.

4.2.3 Operational emissions

The operational carbon emissions were found to be most sensitive to the lighting strength assumptions, including:

[9] Ministry for the Environment (*2024) New Zealand's Interactive Emissions Tracker*. Available at: [NZ's Interactive Emissions Tracker (environment.govt.nz)]() Accessed May 2024.

- the LED strength
- the non-LED strength.

These assumptions were tested within the realistic upper and lower bounds (±30%) to check the impact on total operational emissions.

Total operational energy emissions were found to be sensitive to the lighting assumptions by approximately +10%, -22%.

5 Recommendations and discussion

Land transport infrastructure plays a significant role in our day-to-day lives. The way we construct, maintain, manage and use infrastructure has a major impact on how we meet our commitment to the Paris Agreement and keep global warming within 1.5 °C. Literature and policy have focused on emissions from the use of infrastructure, but there has been increasing awareness of the whole-of-life impact of our infrastructure and the opportunities that exist to reduce this impact.

The research developed in this report (and associated documents and Power BI dashboard) explores the carbon footprint of land transport infrastructure in Aotearoa New Zealand with a focus on the construction (including materials), maintenance, operation and end-of-life emissions of the transport network. There are several discussion areas that have come out of this research, which are detailed in this section. A summary of the key recommendations is:

- future land transport investment decisions should consider whole-of-life carbon (embodied and enabled) in the context of New Zealand's net-zero by 2050 reduction target
- future land transport investment decisions should consider the whole transport network and other related horizontal infrastructure
- technological and process innovations that reduce embodied carbon should continue to be researched, trialled and implemented to reduce emissions when new assets are needed or maintenance is occurring
- asset databases should be standardised and improved (particularly in how maintenance is recorded).

Future land transport investment decisions should consider whole-of-life carbon (embodied and enabled) in the context of New Zealand's net-zero by 2050 reduction target

This research has shown that, over time, New Zealand's investment into infrastructure has contributed to our net consumption[10] emissions. However, historical investment can't be changed. Arguably, the functional life of some of our transport infrastructure assets offers a good return on investment from a carbon perspective given some of New Zealand's transport assets are over 100 years old.

The way Aotearoa New Zealand invests in, designs, constructs, maintains and uses future assets is where the greatest opportunity for carbon reduction lies. This research has shown that upfront and use (operational and maintenance) emissions have a large impact on carbon. As we look to the future where carbon reduction is necessary for climate resilience, we must focus our efforts on reducing carbon across the entire life of our transport network, including embodied and enabled emissions.

Throughout the literature review and methodology, it became clear that maintenance activities (and their associated carbon emissions) are much less understood than upfront activities. Timing of maintenance activities and quantities and types of materials used during these processes are not well recorded. Recent research (IDS, n.d.) has sought to understand maintenance requirements on the pavements of the state highway network. However, further analysis is needed on the remainder of the road network and other infrastructure assets. Throughout the course of this research project, the importance of understanding maintenance emissions was reinforced several times by NZTA and members of the steering group and by the extreme weather events in January and February 2023 that were seen across Aotearoa New Zealand

[10] Consumption-based emissions estimates show the emissions resulting from the economic activity required to meet a country's demand for goods and services. This reflects the carbon footprint of what is consumed by that country, including imported goods. This varies from production emissions, which are those associated with goods and services produced in a country and may or may not be consumed within the country's boundaries. Production and consumption approaches offer different insights to New Zealand's emissions profile and should be seen as complementary (Stats NZ, 2020).

and have resulted in extensive and urgent maintenance activities that were not planned. Should the frequency of climatic events increase, this may in turn change asset maintenance approaches and impact emissions profiles positively or negatively. Having a better understanding of maintenance requirements will support asset owners and operators in planning for these activities and doing them in the most carbon-efficient way.

End-of-life emissions are another area that is lacking data in an infrastructure asset's life cycle. Given the prominence of transport infrastructure across the country and the regular need to maintain or replace, the lack of readily available information about end-of-life impacts prevents an accurate picture being formed that can contribute to decision making. While end-of-life emissions are a small portion of the overall carbon footprint, the importance of considering end-of-life impacts for materials has been reinforced in chapter 9 of the ERP. This chapter sets a vision of Aotearoa New Zealand moving to a circular economy by 2050, which must be supported by an investment in data collection and research.

Enabled emissions were outside the scope of this research. However, there would be benefits in combining research and data about enabled emissions with the data presented as part of this research project in decision making about future investment. Combining embodied and enabled emissions would allow whole of life to be considered in decision making and enable a greater appreciation of transport-related emissions, which in turn could be used to inform future targets. In practice, this would mean investment into new transport infrastructure assets would consider the carbon payback period of the upfront emissions against the expected enabled emissions reduction.

Future land transport investment decisions should consider the whole transport network and other related horizontal infrastructure

Optimising our existing network is better from a carbon perspective than building new. This research has shown that upfront carbon has the biggest impact over an asset's life and that maintenance emissions are also a large contributor that must be budgeted for on a yearly basis. Constructing new assets increases carbon emissions not only through the upfront carbon produced but also through the maintenance cycles and end-of-life impacts that are created through the development of a new asset. Maintaining our current infrastructure rather than building new is a way to maximise the value of assets that had a large upfront carbon investment.

In this context, optimising our network refers to using the assets we have as a base to make better decisions on where to invest. It does not eliminate investment into new infrastructure assets but ensures that this investment is considered in the context of the whole network. Optimising our existing network, including utilising, maintaining and improving our current assets, typically has a much smaller carbon footprint than building new.

Therefore, network optimisation should be the priority for carbon reduction. Optimising the existing network means understanding the entire network (including the associated embodied and enabled emissions) when making decisions about where to invest in infrastructure and aligning investment priorities with the top two priorities of the PAS 2080 carbon emissions reduction hierarchy – build nothing and build less. In the context of infrastructure and the reduction targets of the ERP, in practice, this may result in car lanes being repurposed for busways and cycleways to reduce both VKT (enabled emissions) and upfront carbon.

This research focused only on the land transport network. As the research progressed, it became apparent that transport infrastructure is intertwined with other types of infrastructure, particularly assets relating to water and utilities, which were excluded from the scope of this study. However, due to the geographically close nature of these assets (often located in the same treatment length), benefits could be achieved by considering and managing these infrastructure assets together, particularly when it comes to the maintenance requirements. In Aotearoa New Zealand, these infrastructure types are usually owned and managed by different organisations. However, with the common goal of mitigating and adapting to climate change, a cross-sector approach would have benefits.

To do this, tools that allow for whole-of-network and whole-of-life (embodied and enabled emissions) analysis during investment decision making need to be developed. There are many tools for carbon and life cycle quantification analysis that are applicable to infrastructure. However, we were unable to find one that suited whole-network analysis at a national scale, which was required by this research. This is reflected in the results that were calculated in this research in comparison to the results of different studies presented in the literature review. Generally, the results from this network analysis estimate a lower quantity of carbon per kilometre than key studies (Huang et al., 2013; Lokesh et al., 2022b; Swithinbank, 2022). It is difficult to compare our research with these papers due to the different scope and methodologies, but a reason for the different results is likely due to the prevalence of low-volume (and less carbon-intensive) roads in the New Zealand network, which are generally not the types of developments that undertake emissions estimation.

Technological and process innovations that reduce embodied carbon should continue to be researched, trialled and implemented to reduce emissions when new assets are needed or maintenance is occurring

There is significant opportunity to reduce upfront carbon emissions through innovation of new materials, technologies and processes when new infrastructure assets are required.

The significance of upfront carbon to the whole-of-life footprint confirms that this stage of an asset's life cycle offers the greatest opportunity for embodied carbon reduction through the production and transport of materials and impacts through the construction stage. New technologies and materials are regularly coming to market, either in Aotearoa New Zealand or overseas, and opportunity to implement these on our projects should be embraced with changes to specifications where required or approvals to trial new products rewarded.

This research did not quantify carbon reduction opportunities. However, the quantities of key materials and the associated carbon emissions of these materials show that low-carbon alternatives would have a significant impact across the land transport infrastructure network.

The purpose of this research was to develop a baseline of carbon emissions in land transport infrastructure, and it is recommended that the next step is to use this research for emissions reduction planning. To achieve this, the results presented in section 4 should be further analysed to identify opportunities to reduce carbon, and these should be prioritised based on the ease of implementation and impact of opportunity, as shown in Figure 5.1.

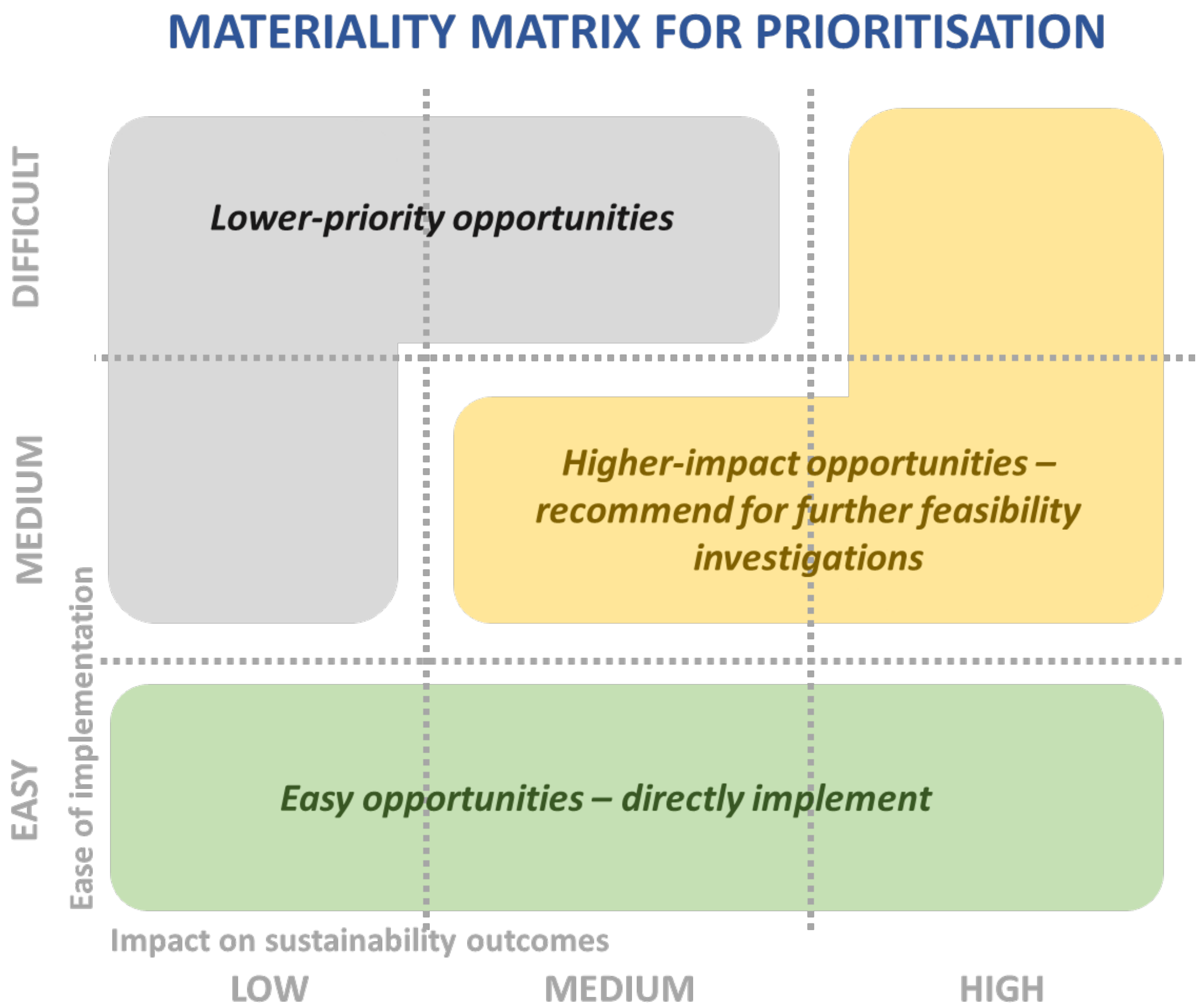
These are some opportunities to use this research to drive emissions reduction:

- Use the findings of this research to inform a base case and assist development of carbon reduction targets for new investment and maintenance requirements. Large (>$100 million) NZTA projects are currently expected to reduce upfront emissions either through an ISC assessment or through a reduction target included in the principal's requirements. This research presents opportunities for reduction targets to be developed across a larger range of infrastructure projects, including those being developed by local authorities.
- Conduct further research on key areas to improve understanding of why the results are the way they are. For instance, what is the cause of regional differences in selected asset types – is it because of investment decisions, availability of different material types, inconsistencies with data labelling on RAMM or for other reasons?
- Use this research to add additional profiles to PEET and refine those with the biggest assumptions made. Approximately 15 profiles were developed in addition to those previously determined in PEET.

These relate to pavements and footpath infrastructure. These profiles can be added into PEET to provide design teams with a more thorough understanding of the carbon footprint of design options.

- Further analysis on material impacts and alternatives within key asset types with the purpose of reducing upfront emissions in future investment.
- NZTA and other infrastructure owners have recently begun to gather carbon (and broader sustainability) data from projects in their design and construction stages. Over time, this information will assist in providing further clarity and understanding of the carbon footprint of infrastructure.

Figure 5.1 Materiality matrix for opportunity consideration



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Appendix A: Detailed methodology

The following sections expand on the methodology overview that is provided in Figure 3.1.

A.1 Categorising asset types within the profile framework

The first phase of the methodology was to develop a framework of asset types that contribute to transport infrastructure carbon emissions as defined in Table 3.2. This allowed the asset data to be categorised and standardised into the various asset types and then determine the asset type inclusions and exclusions and establish the life cycle stage inclusions and exclusions. This task was deemed to be critically important due to the quantity and variability of data that needed to be managed and analysed and the potential impact that categorisation would have on the national footprint.

Following the categorisation of asset types, sample asset data was analysed to understand the range of asset classifications within an asset type. This provided an overview of the number and portion of asset classifications within an asset type and was the basis for the determination of asset profiles.

Asset profiles were developed to represent a typical type of asset within an asset type category. Due to the bespoke nature of infrastructure assets and the large variability within an asset type category, asset profiles were necessary to define to standardise the material types and quantities that represent the range of infrastructure assets at a national scale. The findings of the literature review determined that construction materials have a significant contribution to the whole-of-life carbon impact of infrastructure assets so defining for asset profiles was important for quantifying the national carbon footprint.

In using this method, defining asset profiles needed to find a balance between being specific enough to create a carbon baseline that reflected the range of assets represented in the data but being broad enough to be applied nationally across the hundreds of thousands of bespoke assets.

A.2 Assessing PEET profiles

The NZTA PEET is a carbon estimation tool for land transport infrastructure in Aotearoa New Zealand (road and rail) that estimates emissions at the early stages of a project. Under the second order construction estimate, the tool defines typical transport asset types and specifies material types and quantities. This data and the associated carbon emissions factors became the first iteration of asset profiles that were used for this research. The PEET carbon emissions factors for the typical asset profiles were developed by quantity surveyor analysis estimates on embodied emissions depending on a selected range of asset characteristics. PEET uses embodied emissions factors for products or materials sourced from supplier EPDs, BRANZ CO_2NSTRUCT v2, IS Materials Calculator v2 and Ministry for the Environment (2022a) to determine the overall emissions factor for an asset profile based on the specific material types and quantities.

The assessment compared initial asset profiles created in the first phase with established PEET profiles to understand the extent and alignment of PEET.

A.3 Testing asset data

Land transport infrastructure asset data falls under two categories – roading asset data and rail asset data. Both categories of data are stored and kept separately and so the process of obtaining this data differed.

The majority of roading asset data is stored within the Road Assessment and Management Maintenance (RAMM) digital asset and work management software. This data was retrieved either directly from the RAMM databases that were accessible using personal logins or through the software company Company-X.

The rail asset data is held and stored by New Zealand's largest rail transport operator, KiwiRail. This data was provided directly by KiwiRail as Excel workbooks. Each row of data included information for a singular asset and included the KiwiRail area in which the asset falls, the unique asset ID, location, dimension and material information where appropriate.

Once the full asset datasets were obtained, asset profiles were tested using PEET asset profiles.

For example, PEET has the five footpath and cycleway profiles of:

- 100 mm concrete footpath
- 150 mm concrete footpath
- standard asphalt footpath
- concrete paver path
- timber boardwalk.

The first download of RAMM data showed over 70 classifications of footpaths, cycleways and shared paths (classified as 'both' in RAMM) that were labelled by an acronym relating to the surface material – for example, AC = asphaltic concrete and IB = interlocking blocks. The 70 classifications of footpaths were analysed against the five PEET profiles to understand the alignment of the PEET profiles. In this instance, it was found an additional brick path profile was required.

The test highlighted the difficulties that would be found across all infrastructure types in matching the RAMM classifications with the PEET profiles and the large number of assumptions that would be required.

The accuracy of the RAMM database was also tested during this process. Although there was no simple way to test the accuracy across country, known assets were checked within the database using street name searches. Findings of this testing were:

- on-road cycleways (for example, Nelson Street, Auckland) were not consistently labelled as a cycleway and therefore were not in the active modes data
- off-road cycleways (for example, the Kopurererua cycleway in Tauranga) were not consistently included in RAMM, which may be due to the way they were labelled (as RAMM assets are associated with road names and ID numbers) or due to them not being entered into RAMM
- inconsistent labelling by RAMM users entering records, particularly in how materials were described.

Despite these limitations, it was decided the RAMM database would be used as it was still the most comprehensive source. These limitations were either immaterial to the overall purpose of the research or could be offset through the calculation process or testing during the sensitivity analysis.

A.4 Finalising asset profiles and emissions factors

Following analysis on asset data, asset profiles and their emissions factors were finalised. Asset profiles were either assigned a PEET emissions factor when the asset type was equivalent to the PEET asset profile or a new emissions factor was created when a new asset profile was required.

The majority of emissions factors were sourced from the equivalent PEET profiles. However, several new emissions factors were created when deemed necessary. This was either because there were significant differences in emissions or when the profile contributed a significant portion to the national asset type dataset. Generally, if the PEET profiles covered 80% of the asset classifications, new profiles were not justified.

Emissions factors for new profiles were developed using the PEET template. Typical design assumptions were used to determine the material types and quantities in the new asset profile. Density factors and emissions factors for the respective materials constituting the profiles were sourced from PEET.

Smaller items such as fixings and wirings were not included in the calculations, unless included in the PEET profile, due to a lack of information. These were deemed immaterial.

A.5 Specific life cycle stage considerations

A.5.1 Material production (A1–A3)

The emissions for modules A1–A3 were quantified by applying the asset profile emissions factor to the asset dataset.

A.5.2 Material transport (A4)

This research used a multiplier of 16% to estimate emissions for material transport. This factor was researched and calculated from the NZTA infrastructure carbon baseline analysis (Swithinbank, 2022) and is used in PEET. Although the RAMM database has distance travelled for some assets, a lack of consistency in this data between regions and material types prevented more accurate numbers being used for this research. The 16% multiplier was also used while calculating the maintenance of asset types as it was assumed that materials for maintenance would be sourced from similar manufacturers and suppliers.

A.5.3 Construction impacts (A5)

This research used a multiplier of 17% to account for fuel and energy used while the asset was being constructed, except for tunnels. Similarly to transport emissions, this multiplier was determined in previous research (Swithinbank, 2022). Using this multiplier ensured that there was a consistent approach across asset types and regions. Earthworks required to construct assets, particularly for the road network, can have a significant impact on emissions generated through construction practices, and these differences are not reflected in this research. Tunnels did not use the PEET construction emissions factor due to using tier 1 carbon emissions factors, which includes construction impacts.

A.5.4 Maintenance emissions (B2–B5)

Maintenance activities on land transport infrastructure assets vary greatly in scale from mowing grass verges to clearing drains or washing signage. However, this research has only included activities that have a significant impact on the overall embodied carbon of an asset over its lifetime, which includes resurfacing and resealing for the road network and footpaths and asset replacement. This is a similar approach taken by Lokesh et al. (2022b).

A distinction was made between assets that are maintained throughout their life through resurfacing, resealing or repairs versus assets that are not maintained but are replaced at the end of their functional life (such as signage or railings). Maintenance calculations for repair, resealing and resurfacing (primarily pavements and footpaths) drew upon the research recently completed by IDS (n.d.). The research provided carbon quantities for maintenance activities bult up from contractor records. Renewal activities similarly scheduled renewal rates reflecting the expected life cycle of the pavement and surfacing components. These renewal activities also aggregated the carbon footprint of these activities that could be assigned to road sections depending on their surfacing type, pavement construction and road hierarchy. Maintenance emissions for these assets included disposal rates for the materials that were removed from the asset during the maintenance process – for example, milled asphalt that is removed from site in the process of resurfacing a treatment length.

For assets that are replaced (such as signage, traffic signals, railings and retaining walls), maintenance was calculated by dividing the total upfront emissions with the functional life. This represented the total carbon emissions for the replacement of the asset, represented by a single year. It should be noted therefore that this method is not appropriate for any annual type reporting such as for the CNGP.

A.5.5 Operational emissions (B6)

Although there are other sources of operational energy on the transport network, including tunnel ventilation, electronic road signs and other traffic management, this research limited operational emissions to traffic signals and streetlights on the road network. Streetlight operational emissions were calculated using an average of 11.5 hours and average rates of LED uptake across the country. Traffic signals were based on 1.25 lights (to account for the standard red-orange-green as well as arrows and pedestrian signalling) operating 24/7 per traffic signal. Emissions factors for lighting were sourced from Ministry for the Environment (2022a).

A.5.6 End-of-life emissions

End-of-life emissions were only calculated for infrastructure asset types that are decommissioned and removed from their location for disposal. The road network and footpaths were determined to not have an end of life, as these asset types do not frequently face decommissioning or closure and are more likely to be maintained by being milled to lower depths and resealed or resurfaced. This is aligned with the research completed by Lokesh et al. (2022b) and Huang et al. (2013). The end of life of other assets (structures, retaining walls, railings, bus shelters, street signs, streetlights and traffic signals) was calculated using disposal emissions factors for key construction materials sourced from the United Kingdom. The lack of local data is a limitation to these calculations.

Appendix B: Obtaining and managing asset data

The obtained land transport infrastructure asset data falls under two categories – roading asset data and rail asset data. Both categories of data are stored and kept separately and so the process of obtaining this data differed.

The majority of roading asset data is stored within the RAMM digital asset and work management software. This data was retrieved either directly from the RAMM databases that were accessible using personal logins or through the software company Company-X. The data obtained through Company-X covered the national data. This required some extra data manipulation due to the use of codes rather than descriptions (for example, asset material may be listed as 'C' rather than 'concrete'). The data obtained through personal RAMM logins required less data manipulation but was limited to the number of databases that we had access permissions for.

Considering the advantages and disadvantages of each process of obtaining data, it was determined that data would be obtained from Company-X first, with any remaining asset data retrieved using personal RAMM logins.

Data received from Company-X and retrieved directly from RAMM was organised in Excel workbooks, with a workbook used for each asset type (file size permitting). Each workbook had a row of data for each asset, which included the road council in which the asset falls, the unique asset ID, location, dimension and material information where appropriate.

Company-X data was then manipulated to include asset information descriptions rather than codes. First, lookup lists were created for the road councils that we had RAMM access to. The remaining road councils' lookups were then created using the following hierarchy of steps:

1. Inherit the description lookup from another road council with the same asset code.
2. Assign a description lookup where the code clearly relates to a specific description (for example, a drainage asset with the code RSUM was assumed to be a sump asset).
3. Assign a default description lookup based on common attributes of that asset (for example, a concrete material was assumed for footpaths with unclear or no material listed as concrete was the most common material within the data).

The rail asset data is held and stored by New Zealand's largest rail transport operator, KiwiRail. This data was provided directly by KiwiRail as Excel workbooks. Each row of data included information for a singular asset and included the KiwiRail area in which the asset falls, the unique asset ID, location, dimension and material information where appropriate.

Some limitations arose when collecting and working with the asset data:

- Inconsistent code and description lookups for roading asset data across different databases: Due to the lack of consistent code and description lookups, we were unable to easily categorise assets into their profiles. Therefore, to allocate assets into their various profiles, we used subject matter expert information to determine which assets could be grouped together.
- Roading asset data being stored in inconsistent RAMM tables:
  - Retaining wall data is saved either in its own RAMM table or in the RAMM minor structures table. While the former data was provided by Company-X, the latter was taken directly from RAMM using personal logins.
  - Bus shelter data is saved either in databases' own user-defined tables (UDTs) or within the RAMM minor structures table. All bus shelter data saved in the RAMM minor structures table was retrieved from the databases that we had personal logins for. Bus shelter data saved in UDTs was only

retrieved for databases we had personal logins for and for UDTs that were obviously named (ie, UDTs were only included if their name included ‘bus shelter’ or ‘bus stop’). Data from these UDTs had to be manually checked such that any records clearly listed as being only a seat were not exported and included in the analysis.

- Asset data missing dimension or type data: Some asset data was missing information required for assigning asset profiles and dimensions. Where possible, we have assigned the most common asset profile to these assets and assigned average dimensions to assets with no dimension data.
- Lack of access to all roading asset data: As described earlier, asset data that was unable to be provided by Company-X was instead retrieved from RAMM using our own personal logins. However, we did not have access to all road council databases and so we were unable to cover all the national data for these assets.

Because we did have access to the databases with larger road transport networks such as NZTA, Auckland Transport and Wellington City Council, we decided to exclude the assets for the remaining databases as these would not have a large effect on the overall carbon numbers. The assets for which we could only access partial data include bridges, traffic signals, traffic islands, bus shelters and some retaining walls. The databases included for these assets are shown in Table B.1.

Table B.1 Detailed list of databases included for assets with partial data

Asset	Databases included	Notes
Bridges	Auckland Transport Buller District Council Central Otago District Council Christchurch City Council Clutha District Council DOC Roads Dunedin City Council	
Traffic signals	Gore District Council Grey District Council Hamilton City Council Hastings District Council Hurunui District Council Kaikōura District Council Matamata-Piako District Council Ōpōtiki District Council	Databases included may have no assets reported if they have none of this asset in the RAMM table.
Traffic islands	Ōtorohanga District Council Queenstown Lakes District Council Selwyn District Council South Taranaki District Council South Waikato District Council Southland District Council Stratford District Council	Databases included may have no assets reported if they have none of this asset in the RAMM table.

Asset	Databases included	Notes
Retaining walls	NZTA Tauranga City Council Waikato District Council Waipā District Council Waitaki District Council Waitomo District Council Wellington City Council Westland District Council	Partial retaining wall data only refers to retaining wall assets saved within the RAMM minor structures table. All retaining walls saved in the RAMM retaining wall table have been included.
Bus shelters	Auckland Transport Christchurch City Council Clutha District Council Hamilton City Council Hastings District Council Hurunui District Council Ōpōtiki District Council Queenstown Lakes District Council Selwyn District Council Stratford District Council Waipā District Council Waitaki District Council Wellington City Council	Bus shelter data has been retrieved from the RAMM minor structures table and database UDTs. The databases listed are those where any bus shelter data was found.

Appendix C: Asset profile assumptions

Asset	Asset profiles	Assumptions
ROADING		
Pavements	• Low Volume, Thin Surfaced Flexible, Chipseal • Low Volume, Thin Surfaced Flexible, AC • Minor, Thin Surfaced Flexible, Chipseal • Minor, Thin Surfaced Flexible, AC • Minor, Foamed Bitumen Stabilisation, Chipseal • Minor, Foamed Bitumen Stabilisation, AC • Minor, Cement Modified Stabilisation, Chipseal • Minor, Cement Modified Stabilisation, AC • Minor, Structural Asphaltic Concrete, Chipseal • Minor, Structural Asphaltic Concrete, AC • Minor, Unsealed, Unsealed • Minor, Bridge, Chipseal • Minor, Bridge, AC • Major, Thin Surfaced Flexible, Chipseal • Major, Thin Surfaced Flexible, AC • Major, Foamed Bitumen Stabilisation, Chipseal • Major, Foamed Bitumen Stabilisation, AC • Major, Cement Modified Stabilisation, Chipseal • Major, Cement Modified Stabilisation, AC • Major, Structural Asphaltic Concrete, Chipseal • Major, Structural Asphaltic Concrete, AC • Major, Unsealed, Unsealed • Major, Bridge, Chipseal • Major, Bridge, AC	• Concrete and interlocking block treatment lengths account for only approximately 0.1% of total length and so can be excluded. • If no surface material has been recorded and the treatment length is not unsealed, the asset is assumed to be chipseal. • Treatment lengths with a bridge pavement type and either a concrete or unsealed material are assumed to be valued completely within the bridge asset. • Treatment lengths that have an unsealed material type but not an unsealed pavement type have been excluded. • Treatment lengths that have an unsealed pavement type have been valued as unsealed regardless of what the recorded material is. • A percentage of treatment lengths with a thin surfaced flexible pavement type are bitumen stabilised and cement stabilised (calculated from data recorded in RAMM for minor/major, chipseal/AC, state highway/local roads).
Kerb and channel	• Standard Concrete Kerb (Type 1)	• Urban treatment lengths all have concrete kerb and channel calculated at 1.8 times the urban treatment length using a standard concrete kerb (ie, assumed to have kerb and channel along both sides of the road except for driveways and intersections). • Rural treatment lengths do not have kerb and channel. • Kerb and channel assets have a useful life that is the minimum of the rehabilitation rate of the treatment length it is associated with or 80 years.

Asset	Asset profiles	Assumptions
Road markings	• Local Low Volume Urban • Local Low Volume Rural • Local Minor Urban • Local Minor Rural • Local Major Urban • Local Major Rural • SH Low Volume Rural • SH Minor Urban • SH Minor Rural • SH Major Urban • SH Major Rural	• An area of marking per m length has been calculated for urban/rural, low volume/minor/major state highway/local roads (calculated from the Hastings and state highway databases using PEET to allocate an approximate m² paint for markings recorded on an each basis).
Footpaths and cycleways	• Concrete • Asphaltic Concrete • Pavers (Brick) • Pavers (Concrete) • Timber Boardwalk • Aggregate • Chipseal	• If an unknown or no surface material has been recorded, the asset is assumed to be concrete.
Structures	• SH Large Bridge • SH Medium Bridge • SH Small Bridge • SH Underpass/Culvert • SH Steel Pedestrian Bridge/Walkway • SH Concrete Pedestrian Raised Boardwalk • SH Hollowcore Concrete Pedestrian Bridge • SH Tunnel • Local Road Large Bridge • Local Road Medium Bridge • Local Road Small Bridge • Local Road Underpass/Culvert • Local Road Steel Pedestrian Bridge/Walkway • Local Road Concrete Pedestrian Raised Boardwalk • Local Road Hollowcore Concrete Pedestrian Bridge • Local Road Tunnel	• Small, medium and large state highway bridges (excluding underpasses/culverts) have a pier every 30 m (as per NZTA Medium Bridge in PEET v3). • Small and medium local road bridges have a pier every 17 m (as per AT Medium Bridge in PEET v3). • Large local road bridges have a pier every 23 m (as per Large AT Bridge in PEET v3). • Concrete pedestrian raised boardwalks have a pier every 19 m (as per Concrete Pedestrian Raised Boardwalk in PEET v3). • Hollowcore concrete pedestrian bridges have a pier every 19 m (as per Hollowcore Concrete Pedestrian Bridges in PEET v3). • Valuation useful lives have been shortened for large, medium and small bridges that have a recorded material of timber (50 years for timber piers and 20 years for timber deck). • Timber bridges have been assigned an emissions factor in line with a small bridge. • Councils that we could not get RAMM bridge data for have been assigned the total 2021/22 bridge length recorded for that council in the NZTA data and tools. These bridge lengths were then distributed between the different profiles in line with the distribution of the RAMM data we could retrieve.
Street signs	• Small Steel Single Post <1 m² • Medium Sign <6 m² • Large Sign <9 m² • Single Gantry <16 m² • Double Gantry <30 m²	• All street signs are assumed to be made of an aluminium sign and a steel pole with concrete foundations. • The amount of sign pole and foundation material is assumed to be related to the m² area of the sign. • If an asset has no recorded sign area, the average area for that sign type is used.

Asset	Asset profiles	Assumptions
Street lights	**Street Light Brackets:** • All Brackets **Street Light Luminaires:** • All Luminaires **Street Light Poles:** • Steel 8 m Pole • Steel 12 m Pole	• All street lights with brackets are assumed to be a 2 m steel bracket. • All street light lights are assumed to have 12.5 kg aluminium light luminaires as assumed in PEET v3. • Concrete street light poles are assumed to be powerline poles and so are not land transport assets. • Street light poles with a recorded height of <10 m are assigned an 8 m pole profile. • Street light poles with a recorded height of >10 m or no recorded height are assigned a 12 m pole profile. • Street light lights and brackets do not have recorded location information and so these assets saved under the Northland Transport Alliance are split between the three districts (Kaipara District Council, Whangārei District Council and Far North District Council) proportionally based on urban road length.
Traffic signals	**Traffic Signal Poles:** • Standard Traffic Signal Pole • JUMA Traffic Signal Pole • JUSP Traffic Signal Pole **Traffic Signal Lantern:** • 1 Aspect • 2 Aspect • 3 Aspect • 4 Aspect • 5 Aspect • 6 Aspect	• Traffic signal pole assets that are less than 5 m high are assumed a standard profile. • Traffic signal poles that are Type 3s and 5s joint arm or a 5–8 m high pole are assumed a JUMA profile. • Traffic signal poles that are steel octagonal joint use or 8–12 m high are assumed a JUSP profile. • Traffic signal pole assets that are not Type 3s and 5s joint use mast arm or joint use streetlighting poles are all assigned a standard profile. • Traffic signal pole assets are all assumed to be ground mounted with a concrete footing. • Traffic signal lights are all assumed to be non-LED. • Effect of lens size on the carbon emissions of traffic signal lights are minimal and so do not need to be considered. • All traffic signals assigned a lantern based on the respective number of aspects.
Drainage	• Box Culvert Small • Box Culvert Medium • Box Culvert Large • Circular Culvert 225 mm • Circular Culvert 300 mm • Circular Culvert 375 mm • Circular Culvert 450 mm • Circular Culvert 525 mm • Circular Culvert 600 mm • Circular Culvert 675 mm • Circular Culvert 750 mm • Circular Culvert 900 mm • Circular Culvert 1,050 mm • Circular Culvert 1,200 mm • Circular Culvert 1,350 mm • Subsoil Drain • Urban Road Manholes • Urban Road Catchpits	• The drainage assets to be included are box culverts, circular culverts, subsoil drains, manholes and catchpits. • Urban roads are assumed to have one catchpit and one manhole per 50 m of road. • Rural roads are assumed to have no catchpits or manholes. • Any drainage asset assumed to be not related to transport infrastructure excluded from the analysis.

Asset	Asset profiles	Assumptions
Traffic islands	• Conventional Traffic Island Insitu Concrete • Conventional Traffic Island Precast Concrete • Median Planting Bed. 1.8 m Width • Concrete Speed Table (includes ramps) • Asphalt Speed Table (includes ramps) • Major Roundabout • Medium Roundabout • Minor Roundabout	• Traffic islands with no recorded landscape area are given the average recorded landscape area for that profile type. • Concrete and asphaltic concrete traffic islands assumed a Conventional Traffic Island Insitu Concrete profile. • Block concrete traffic islands assumed a Conventional Traffic Island Precast Concrete profile. • Traffic islands with planting, vegetation or grass assumed a Median Planting Bed 1.8m Width profile.
Railings	• F Shape Barrier • W Beam Barrier • Steel Wire Rope Barrier • Noise Wall • Steel Wire Fence	• Railing assets that are primarily timber/wood are assumed to be carbon neutral and excluded. • Railing assets that are unknown or do not fit within their own railing profiles (eg, handrail) are included as a W Beam Barrier. • Railing assets with no type description or not directly relating to transport infrastructure (eg, aesthetic barriers, bollards or sight rails) have been excluded. • Railings on bridges have been excluded as they have been accounted for in the bridge profile.
Retaining walls	• Stone Small • Stone Medium • Stone Large • Block Small • Block Medium • Block Large • MSE Small • MSE Medium • MSE Large • Timber Small • Timber Medium • Timber Large • Shotcrete Small • Shotcrete Medium • Shotcrete Large • Timber and Steel Small • Timber and Steel Medium • Timber and Steel Large • Concrete and Steel Small • Concrete and Steel Medium • Concrete and Steel Large • Concrete Secant Pile Small • Concrete Secant Pile Medium • Concrete Secant Pile Large • L Shape Small • L Shape Medium • L Shape Large	• Retaining wall assets with no recorded length or height were assumed to have the average length or height of all retaining walls of the same material type. • Retaining wall assets that cannot inherit an average length or height (due to lack of information for that material type) have been assigned the average of all material types' average area.

Asset	Asset profiles	Assumptions
PUBLIC TRANSPORT		
Bus shelters	• Minor Bus Shelter	• All bus shelter assets are assumed to be minor bus shelters.
Train platforms	• Excluded from analysis	
RAIL		
Track features	• Standard Composite Sleeper • Standard Concrete Sleeper • Standard Wooden Sleeper • Standard Rail	• Standard rail profile assumed for all rail, including provisions for ballast and structural fill. • Concrete sleepers assumed a 700 mm spacing. • Composite sleepers assumed a 600 mm spacing. • Wooden sleepers assumed a 600 mm spacing.
Bridges	• AT Steel Pedestrian Overbridge • Large Precast Concrete Trough • Large Steel Girder (with piers)	• Large precast concrete trough bridge assumes 14 m pier spacing. • Large steel girder bridge assumes 6.5 m pier spacing. • No piers assumed for bridges <14 m long. • Bridges owned by NZTA and local authorities were assumed to be included in the RAMM database so were excluded from the rail bridge analysis.
Culverts	• Reinforced Concrete Pipe 225 • Reinforced Concrete Pipe 300 • Reinforced Concrete Pipe 375 • Reinforced Concrete Pipe 450 • Reinforced Concrete Pipe 525 • Reinforced Concrete Pipe 600 • Reinforced Concrete Pipe 675 • Reinforced Concrete Pipe 900 • Reinforced Concrete Pipe 1,050 • Reinforced Concrete Pipe 1,200 • Reinforced Concrete Pipe 1,350 • Standard 3 x 3 m Culvert	• Timber culverts and HDPE corripipe assumed de minimis and excluded. • It was assumed rail culverts were not captured in road culvert dataset.
Retaining walls	• Stone Small • Stone Medium • Stone Large • Block Small • Block Medium • Block Large • Concrete and Steel Small • Concrete and Steel Medium • Concrete and Steel Large • Timber and Steel Small • Timber and Steel Medium • Timber and Steel Large • Timber Small • Timber Medium • Timber Large • Steel Wire Fence	• It was assumed rail retaining walls were not captured in the road retaining wall dataset. • Cuttings and embankments were assumed to be covered by the 17% construction installation factor.

Appendix D: Rationale for asset inclusions and exclusions

Infrastructure type	Life cycle stages included	Life cycle stages excluded	Additional exclusions	Exclusion rationale
Pavements	A1–A3 A4 A5 B2–B5	B1 B6 B7 C1–C4 D	Vegetation clearance Stormwater systems	It was determined that the road network very rarely reaches an end of life from an LCA perspective. Once it's in existence, a road will be continuously maintained through resealing and resurfacing. However, waste disposal is created during this process, which has been included in the maintenance emissions factors. Vegetation clearance impacts the overall carbon footprint of a project, but due to lack of reliable data, we were unable to include it in our estimations. Although often geographically close, stormwater systems were determined to be outside the scope of land transport infrastructure and have been excluded from the assessment.
Footpaths	A1–A3 A4 A5 B2–B5	B1 B6 B7 C1–C4 D	Vegetation clearance Minor materials, including handrails and fixings and tactile surfaces (eg, stick-on tactile plugs)	Handrails and other minor materials were not included in this assessment due to a lack of information in RAMM. End-of-life stage (C1–C4) was excluded due to an assumption that footpaths do not reach end of life but are renewed or repurposed.
Structures	A1–A3 A4 A5 B2–B5 C2–C4	B1 B6 B7 D C1	Resurfacing Minor materials, including fixings	Resurfacing of the pavement layer is included in the road network maintenance calculations. Minor materials have not been included due to lack of reliable information and overall small contribution to the carbon footprint.
Retaining walls	A1–A3 A4 A5 B2–B5 C2–C4	B1 B6 B7 C1 D		Maintenance was excluded from the calculations as it was determined that retaining walls are replaced (either a full treatment length or individual section) when damaged rather than maintained. Minor materials have not been included due to lack of reliable information and overall small contribution to the carbon footprint. Retaining wall deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of retaining wall deconstruction.
Kerb and channel	A1–A3 A4 A5 B2–B5 C2–C4	B1 B6 B7 C1 D	Surface water channels	Surface water channels were deemed de minimis due to no materials required for construction. Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.
Traffic islands	A1–A3 A4 A5 B2–B5 C2–C4	B1 B6 B7 C1 D	Pedestrian crossing markings Car parking	Road markings have been included in the road network calculations except for pedestrian crossings. Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.

Infrastructure type	Life cycle stages included	Life cycle stages excluded	Additional exclusions	Exclusion rationale
Drainage	A1–A3 A4 A5 B2–B5 C2–C4	B1 B6 B7 C1 D		Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.
Railings	A1–A3 A4 A5 B2–B5 C2–C4	B1 B6 B7 C1 D	Timber rails Sight rails Handrails	Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.
Signage	A1–A3 A4 A5 B2–B5 C2–C4	B1 B6 B7 C1 D		Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.
Streetlights	A1–A3 A4 A5 B6 B2–B5 C2–C4	B1 B7 C1 D	Embodied emissions of light bulbs Timber post streetlights Connection cables	Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction. Timber post streetlights were considered de minimis compared to steel post streetlights. Limited data on the electrical infrastructure required to connect streetlights.
Traffic signals	A1–A3 A4 A5 B2–B5 B6 C2–C4	B1 B7 C1 D		Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.
Bus shelters	A1–A3 A4 A5 B2–B5 C2–C4	B1 B7 C1 D		Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.
Rail	A1–A3 A4 A5 B2–B5 B6 C2–C4	B1 B7 C1 D	Platforms	Limited data on the number and designs of rail station platforms. Deconstruction emissions were excluded from the assessment due to lack of data on the GHG impact of deconstruction.