Lifetime liabilities of land transport using road and rail infrastructure

December 2011

N Mithraratne
Landcare Research, Auckland

NZ Transport Agency research report 462

ISBN 978-0-478-38073-6 (print)
ISBN 978-0-478-38072-9 (electronic)
ISSN 1173-3756 (print)
ISSN 1173-3764 (electronic)

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NZ Transport Agency (2011) Lifetime liabilities of land transport using road and rail infrastructure. *NZ Transport Agency research report 462.* 100pp.

Keywords: bus, carbon footprint, construction, contaminants, environment, freight transport, GHG, greenhouse gas emissions, LCA, life cycle assessment, life cycle energy, maintenance, passenger transport, rail, roads, road run-off, rolling stock, vehicles

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Acknowledgements

The author acknowledges funding received from the NZ Transport Agency for this research.

The project would not have been possible without support and advice from Professor Robert Vale (Victoria University of Wellington) and the contributions from the project steering group – Andrew Guerin (MWH Global Inc.), Dr Bryan Pidwerbesky (Fulton Hogan Ltd), Tony Miguel (Waitakere City Council), Peter Steel (KiwiRail), Leah Murphy (Ministry of Transport), Carl Reller (NZ Transport Agency), Karl Check (KiwiRail), and Kieran Helm (KiwiRail). Their support and advice are greatly appreciated.

Many organisations and individuals provided data for the project. The author is especially grateful to Nicholas Manson (KiwiRail) for sharing his personal knowledge of rail operations, and Neil Bennett (Fulton Hogan Ltd) for answering numerous questions on road construction.

The author would also like to express sincere thanks to the reviewers Dr Helen Murphy (VicRoads, Australia) and Martin Ward (Ward Wilson Research).

Abbreviations and acronyms

ARC	Auckland Regional Council
ARTA	Auckland Regional Transport Authority
CO_2e	carbon dioxide-equivalent
EE	embodied energy
EIO	economic input–output
EIO-LCA	economic input–output life cycle assessment
GHG	greenhouse gas(es)
GJ	gigajoule
Gtkm	gross tonne-kilometre
Km	kilometre
LCA	life cycle assessment
LCV	light commercial vehicle
LPV	light passenger vehicle
MJ	megajoule
MVR	motor vehicle register
Ntkm	net tonne-kilometre
NZTA	NZ Transport Agency
NZTS	New Zealand Transport Strategy
OGPA	open graded porous asphalt
pkm	passenger-kilometre
p/v	passengers per vehicle
SUV	sports utility vehicle
tkm	tonne-kilometre
vkm	vehicle-kilometre
vpd	vehicles per day

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Executive summary

In 2009, the NZ Transport Agency (NZTA) commissioned Landcare Research to study the lifetime environmental and financial liabilities of providing transport services that use road and rail infrastructure. The study was undertaken between October 2009 and March 2011 in New Zealand, using transport data for the year beginning July 2007 and ending June 2008.

The purpose of this research was to establish the baseline environmental and financial liabilities of passenger and freight transport that uses land transport infrastructure systems – roads and rail. This knowledge could then be used to evaluate any future measures to improve the performance of the transport system in terms of the selected indicators.

The initial project goal was to identify the environmental and financial liabilities of land transport in New Zealand through the following indicators:

- total life cycle energy consumption
- life cycle greenhouse gas (GHG) emissions
- life cycle stormwater contamination
- life cycle costs.

However, establishing the total life cycle cost of transport was difficult due to commercial sensitivity, and the data on stormwater contamination proved to be unsatisfactory for a detailed assessment.

Limitations, scope and methodology of study:

The study is based on the current industry best practices in road and rail construction, maintenance and operation and is a simplification of actual transport operations in New Zealand. The transport services were evaluated using the 2008 data for the vehicle fleet, rolling stock and services – the most up-to-date data at the time of the study. Therefore the actual performance of real-life transport infrastructure projects could be somewhat different from the results reported here, although the relative performance of contributory components and transport modes could be expected to be similar.

Road and rail infrastructure systems were limited to carriageway (pavements and bridges) and rail track (track formation, bridges and tunnels) respectively. Street lighting, roadside barriers, embankments, cycleways, traffic signals, railway stations, bus shelters, etc were not included. The impacts of terrain and ground conditions on the construction requirements of road and rail infrastructure were ignored. The life stages included were initial construction, maintenance, replacements and operation. As demolition and disposal of large infrastructure systems such as roads and rail are uncommon, they were not considered. It is very likely that passengers (and freight) have to use other means to get to the station to board the train and to get to the actual location from the destination station. These additional transport requirements were ignored.

The study used the product-based Life Cycle Assessment (LCA) method and considered material use, transport requirements, on-site machinery and fuel use. The impact of traffic delays and rolling resistance were not considered. Road and rail infrastructure are shared by both passenger and freight transport activities. Since damage to infrastructure and the consequent maintenance are functions of the total load transported, weight mass allocation based on the gross-tonne-kilometre performance was used to allocate infrastructure to the services provided.

Results:

At the time of this research, a third of the New Zealand road network (especially on rural roads) had an unsealed finish. The high maintenance needs of an unsealed pavement means that over 40 years, it consumes four times the energy and releases four times the GHG emissions than a sealed pavement, if infrastructure alone is considered (ie excluding the vehicles that run on the roads, and their fuel use).

Two common pavement constructions – unbound granular and structural asphalt – were considered in the study. When infrastructure alone is considered, the lifetime energy use (excluding the earthworks) for the structural asphalt construction (which is used for motorways), is 75% higher than that for unbound granular construction (which is used for state highways). In terms of GHG emissions, motorways contribute 56% more than state highways. The average energy use of the road network is 193GJ/lane-km/annum, while the average GHG emissions are 12tCO_2e[1]/lane-km/annum.

The results also indicated that earth-moving for a pavement lasting 40 years can add 16–127GJ/lane-km annually, depending on whether the pavement is constructed on a flat site with easy construction conditions or on a hilly site with difficult construction conditions. In terms of GHG releases, earth-moving contributes 1.1–9tCO_2e/lane-km annually, depending on the condition of the terrain over the 40-year period.

Fuel use for transport of materials and machinery to the construction site is a significant contributor to the total energy use and GHG emissions of a pavement. The fuel consumption of large vehicles used in New Zealand is 33% more than that for similar vehicles in Europe, while for smaller vehicles it is about 64% higher.

The average annual energy use for the rail track (ie excluding the trains that run on the tracks and their fuel use), without the energy use for bridges and tunnels, is 196GJ/km, while annual GHG emissions, including the emissions from bridges and tunnels, are 18.5tCO_2e/km. The majority of energy use and emissions are due to the steel rails used for track construction.

When passenger and freight transport by road is considered (including road infrastructure, the vehicles that run on roads, and their fuel use), fuel use for vehicle operation is the most significant contributor to the total energy use and GHG emissions. The contribution to the total energy use and GHG emissions by the infrastructure is small, while the contribution by vehicles (manufacture and maintenance) is moderate. For freight transport by road, the highest energy and emissions intensity is for the light commercial vehicle, while the energy and emissions intensities of trucks decrease as the size of truck increases. The energy intensity and GHG emissions of light commercial vehicle use for freight transport are twice those for large trucks. For road passenger transport, operational energy use and GHG emissions are significant and increased vehicle occupancy could lead to noticeable improvements.

For passenger services using rail (including rail infrastructure, rolling stock and its fuel use), operation (fuel and electricity use) is the most significant contributor to the total energy use (more than 71%) and GHG emissions (more than 70%). The contribution to the total energy use and GHG emissions from rolling stock (manufacture and maintenance) is marginal (up to 3%), and for rail infrastructure it is moderate (up to 25%). For freight transport using rail, rail infrastructure contributes 20% to the total energy use and 28% to the total emissions.

Conclusions:

The study suggests that the choice of construction type significantly alters the energy use and GHG emissions for the pavement constructions that are commonly used in New Zealand. The unbound granular

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[1] Carbon dioxide-equivalent.

construction system provides an environmentally friendly pavement solution, provided a sealed wearing course is used. The contribution from earthworks to the energy use and GHG emissions for pavements is moderate on flat terrain, but significant on hilly terrain. The wearing course construction type has a considerable impact on the energy use and GHG emissions for pavements. Sealing the unsealed length of the network could therefore significantly reduce the resource use associated with the existing road infrastructure.

Steel rails for rail track construction are responsible for nearly half the lifetime GHG emissions and energy use for rail tracks. Sourcing rails from a best-practice factory in China could only moderately reduce the lifetime emissions and energy use for rail tracks. Therefore, if the environmental impacts of rail track infrastructure are to be reduced, alternative sources of steel rails need to be investigated.

For passenger transport services by road, fuel use is the most significant contributor to energy use and carbon intensity, so using lighter/smaller vehicles and increasing vehicle occupancy can make a significant difference. However, for freight transport services by road, the choice of vehicle and infrastructure is as important as the fuel used.

The use of rail for passenger and freight transport, however, leads to far greater reductions in energy and carbon emissions, when compared against all modes of road transport. Suburban passenger transport using electrified rail is far better than the same using diesel rail.

The main purpose of this research was to generate New Zealand-specific transport data. As the study found the results derived using New Zealand data were drastically different from those derived using European data, it is essential that any attempts to quantify the impact of transport policies and actions are based on New Zealand data.

Recommendations:

The following practices are recommended to reduce the environmental impacts of the transport sector:

- the use of sealed wearing course as the standard practice for pavements
- the use of more durable pavements on hilly terrains
- local sourcing of steel rails for rail tracks.

In order to improve the reliability of transport data, further research into the following areas is recommended:

- long-distance and suburban bus services in New Zealand
- New Zealand freight movements, including vehicle fleet composition and average fuel use
- the current manufacturing practices and energy mix used in Chinese steel-manufacturing factories
- the quantity of contaminant transported by various vehicle types
- the cost of transport infrastructure construction, maintenance and operation.

Abstract

The aim of the project was to establish the whole-of-life environmental performance of passenger and freight movement that uses roads and rail. The performance indicators selected were life cycle energy consumption, life cycle stormwater contamination, and life cycle GHG emissions. This study was based on process assessment and considered material use, transport requirements, on-site machinery use, and fuel use. The impacts of traffic delays and rolling resistance were not considered. The study was undertaken in New Zealand between October 2009 and March 2011 using data for the year beginning July 2007 and ending June 2008.

The results suggest that the environmental impact of pavements can be altered by earthworks (especially in hilly terrains), choice of construction system, and wearing-course construction. Rail emissions can be influenced by the source of the steel rails used. For passenger transport, fuel use is the dominant factor; for freight transport, infrastructure, vehicles and fuel are equally important. However, the use of rail for passenger and freight transport leads to far greater reductions in energy and carbon emissions when compared against all modes of road transport.

The results derived using New Zealand data are significantly different from those using European data. It is therefore essential to use local data in evaluations of transport policies and actions.

1 Introduction

In 2009, the NZ Transport Agency (NZTA) commissioned Landcare Research to study the lifetime liabilities of providing transport services that use road and rail infrastructure in New Zealand. The study was undertaken between October 2009 and March 2011.

1.1 Purpose and objective of research

The purpose of this research was to establish the baseline environmental and financial performance of passenger and freight transport that uses land transport infrastructure systems – road and rail. The goal of the research was to identify the environmental and financial performance of land transport in New Zealand through the following indicators:

- total life cycle energy consumption
- life cycle GHG emissions
- life cycle stormwater contamination
- life cycle costs by including:
  - construction, operation, maintenance and demolition of roads and rail infrastructure
  - manufacture, maintenance, use and disposal of vehicles.

However, the unit costs for the proprietary products and systems and unique construction and maintenance practices that the road and rail sectors use were commercially sensitive and not publicly available. Because it was not possible to use secondary sources to establish life cycle costs, this aspect was excluded. Further, the quality of data available on stormwater contaminant loads in New Zealand was found to be unsatisfactory for a detailed assessment.

The objectives of the study were to enable:

- a better understanding of environmental externalities in the land transport sector
- targeting of efforts to reduce greenhouse gases (GHGs), in order to manage New Zealand’s liabilities in line with the country’s international commitments
- the assessment of implementation decisions designed to meet targets in the New Zealand Transport Strategy (NZTS)
- better management of energy cost risks in New Zealand transport planning.

1.2 Background

Efficient land transport decision making requires accurate evaluation of whole-of-life costs. These include impacts that may be beyond the direct mandate of the responsible agency but create significant benefit or liability for others. Although recognised in project evaluation methods (NZTA 2008), a number of these externalities are still poorly quantified and methods for including them are relatively rudimentary. As such, the environmental externalities (eg embodied energy, GHG emissions, and contaminant delivery to stormwater systems) associated with transporting passengers and freight using road and rail infrastructure in New Zealand are unknown.

In economic terms, these particular externalities are significant. Oil currently plays an important role in the transport sector as the main fuel (petrol and diesel) used to power vehicles, and as the main raw material used in the production of road pavement materials (asphalt and bitumen). Oil prices, therefore, directly influence the cost of construction, maintenance and operation of road transport services, and the cost of operating rail services with a high use of diesel-powered locomotives. Any increase in transport costs has a negative impact on the economy. In recent times, oil prices have sometimes risen well above the rate of inflation, and remain extremely difficult to predict.

Climate change is a global issue. New Zealand's international commitments to GHG reduction are a significant issue for the land transport sector. The transport sector accounts for 19% of New Zealand's GHG emissions (Treasury New Zealand Government 2009, p25). In 2006 the total GHG emissions of the road transport sector in New Zealand were 64% above the 2012 Kyoto target[2], with the potential for a further 30% increase by 2030 under a business-as-usual scenario (MoT 2008a, p8), creating a significant economic liability[3]. However, the above estimates ignore the production of fuel and are based only on GHG emissions that are due to fuel combustion. An account of life cycle GHG emissions can support policy directed at meeting existing and future commitments.

A significant focus of the *New Zealand energy strategy 2050* (NZES) is transport (MED 2007, p11), which is responsible for 44% of the nation's total annual energy usage. (Note: The NZES has been updated since this research. The NZES 2011–2021 and the New Zealand Energy Efficiency and Conservation Strategy 2011–2016 were released in August 2011, setting the strategic direction for energy in the New Zealand economy.) Furthermore, New Zealand's GHG emissions from transport are relatively high on a per-capita basis. The New Zealand Energy Strategy has two main objectives in relation to transport:

- to reduce GHG emissions from transport
- to reduce dependency on imported oil as an energy source for transport.

Under a continuation of the current trend, it is predicted that by 2030, the total energy use by transport will increase by approximately 40%, with similar increases predicted for transport emissions. Three-quarters of this growth will be from road transport. Given the threat of climate change and the uncertainty surrounding the future oil supply, this path will not be economically or environmentally sustainable (MED 2007, pp6, 11).

Life cycle assessment (LCA)-based studies have already been used in Europe to inform decisions on transport infrastructure investment. Norway now has a policy of preferring bridges to tunnels when roads or rails must cross fiords, reportedly as a result of LCA (The Economist 2009). A report commissioned by the UK Department for Transport to investigate the impact of a new rail line connecting London to Manchester and London to Glasgow/Edinburgh also used the LCA approach to estimate the carbon emissions of the proposed new line on which the recommendations were based (Booz Allen Hamilton Ltd 2007).

The NZTS[4] (MoT 2008b) provides the overarching direction and policy for the New Zealand transport sector, with increased focus on associated energy and emissions. The NZTS identifies that long-term

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[2] 5.6 million tonnes of carbon dioxide above the target.

[3] Road transport emissions in 2008 were 68% above the 1990 level (MfE 2010).

[4] The NZTS has been reviewed since this research. 'Connecting New Zealand' is a more current summary of the government's transport policy and intentions. It is largely focused on the government's direction for the next decade, and draws on government documents that have different time horizons, including up to 20 years for the National Infrastructure Plan.

environmental gains could be made from a mode switch that would encourage the transfer of freight from road to rail. Strategy targets include halving per-capita transport emissions by 2040 and reducing single-occupancy car travel in major urban areas on weekdays by 10% per capita (ibid, p5). The National Infrastructure Plan (NIU 2010, p7) vision is to enable transport mode choices based on full social costs, and infrastructure investment based on smart procurement and whole-of-life costs. Information from this project will support the evaluation of opportunities to meet targets in the NZTS and the National Infrastructure Plan[5].

This research builds on several earlier studies of the environmental impacts of road construction practices, which focused on the construction-stage costs and the environmental impacts of roading infrastructure. A recent study by Browne (2008) assessed the carbon footprint of the construction phase of five construction projects at various stages of development (design, in progress and completed), while the use of recycled materials has been the subject of a number of others (Herrington et al 2006; Patrick et al 2006). McGimpsey et al (2009) studied the sustainability of New Zealand's rail system and the opportunities and barriers around achieving more sustainable outcomes. They found that rail has many inherent advantages related to sustainability, such as energy efficiency, lower GHG emissions and land use, on a unit (passenger-kilometre – pkm, or tonne-kilometre – tkm) of transport service provided. Therefore, wider use of rail for national transport, especially to carry freight, was advocated. European studies (Smith 2003; RSSB 2007) have shown that compared with other modes, rail can provide transport services at a fraction of the energy and emissions.

Some impacts, particularly stormwater pollution and GHG emissions, extend well beyond the initial construction activity, to operation, maintenance and demolition (where applicable). These can be significant. Australian research established that in the 40-year life cycle energy account of a rural road in Australia, vehicle manufacture and maintenance (28%) and vehicle use (62%) are dominant factors (Treloar et al 2004). In 1999, Lenzen identified that embodied energy (EE) use by the transport sector contributed up to 65% of the total energy use for passenger transport and up to 50% of the total for freight transport in Australia[6].

Current practice, as set out in the NZTA *Economic evaluation manual* (EEM) (2008; NZTA 2009b), does not fully account for the externalities. For example, while the cost of GHG emissions from vehicle operation (based on fuel consumption) is included in the EEM, GHGs embodied in the construction, maintenance and disposal of the infrastructure and vehicle fleet are excluded. Lenzen's 1999 research found that these embodied GHG emissions could constitute up to 65% of a life cycle emissions account for transport in Australia. Similarly, the costs of stormwater pollution generated by the land transport sector, such as wearing of road-surfacing materials, road-marking paint, and vehicle tyres and brake pads etc are not considered in the EEM, except when it is identified that a project threatens critical habitat or other ecologically sensitive areas. Timperley et al (2005) reported, however, that stormwater pollutants from roads are a significant source of ongoing contamination in receiving waters.

1.3 Limitations of the study

This study is based on the industry best practices in road and rail construction and operation, and is a simplification of actual transport operations in New Zealand. Therefore the actual performance of real-life

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[5] An updated National Infrastructure Plan was released in July 2011.

[6] Lenzen's estimates were based on a 20-year useful life for Australian passenger cars – in recent times, this is reported to have been reduced to 12 years. This would further increase the EE of passenger transport.

projects could be somewhat different from the results reported here, although the relative performance of contributory components and transport modes could be expected to be similar. New Zealand data on suburban bus services and freight operations was not available, and therefore the reported estimates, which are based on overseas data, may not represent the actual performance of these operations in New Zealand. Similarly, the quality of available data on stormwater contamination due to road vehicles proved to be unsatisfactory for a quantification of contaminants from different vehicle types used on New Zealand roads.

1.4 Report structure

The report sets out the research scope and approach and the results of the study, and is divided into the following eight sections:

1. Introduction
2. Road transport system in New Zealand
3. Rail transport system in New Zealand
4. Goal definition and scope of study
5. Road and rail infrastructure lifetime liabilities
6. Road and rail transport service lifetime liabilities
7. Conclusions
8. Recommendations.

2 Road transport system in New Zealand

2.1 Road transport network

In New Zealand, a road is defined as the land between the legal road boundaries and typically includes the carriageway, footpaths and other accessways, berms[7] and unpaved areas constructed for public use. The pavement is the portion of the road that supports the vehicular traffic (Transit NZ RCA and Roading NZ 2005, pp41–48). New Zealand has 90,783 kilometres of roads, of which 10,894 kilometres are state highways and 79,889 kilometres are local roads (Treasury New Zealand Government 2009, p18).

2.1.1 Road classification

Depending on the data source selected, the road classification may vary. For example *Network statistics* (LTNZ 2009) divides the roads into state highways (including motorways) and local roads. Local roads are further divided into urban, rural and special-purpose roads. Urban roads are those with a speed limit of 70km/h or less, while rural roads are those with a speed limit of more than 70km/h. Special-purpose roads can be either urban or rural local roads, but are mainly rural (Fong 4 December 2009, pers comm).

According to the EEM (NZTA 2008, pSP3-8), roads are divided into 'urban arterial', 'rural strategic', 'urban other' and 'rural other'. This classification depends on their function, which is related to their strategic value, total traffic usage, speed environment, etc (Pidwerbesky 27 November 2009, pers comm). The definitions are as follows:

- urban arterial – arterial and collector roads within urban areas carrying traffic volumes greater than 7000 vehicles per day (vpd)
- urban other – urban roads other than urban arterial
- rural strategic – arterial and collector roads connecting main centres of population and carrying traffic of more than 2500vpd
- rural other – rural roads other than rural strategic.

If the two classifications used in *Network statistics* (LTNZ 2009) and the *EEM* (NZTA 2008) are compared:

- urban arterial roads are arterial and collector roads within urban areas carrying traffic volumes greater than 7000vpd, which could include both state highways and urban local roads
- rural strategic roads are arterial and collector roads connecting main centres of population and carrying traffic of more than 2500vpd – both state highways and rural local roads could include 'rural arterial roads'.

Another classification used by researchers in New Zealand and overseas is 'self-explaining roads' (Charlton 27 November 2009, pers comm), where roads are classified as 'through roads', 'distributor roads' and 'access roads'.

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[7] Raised barrier between two lanes of traffic travelling in opposite directions.

Table 2.1 Road classification based on self-explaining roads (Charlton 2005)

Category	Sub-category	Speed (km/h)	Lane width (m)/no.
Through	Urban	60–70	3.75/2+2
	Rural	100–110	3.5/2+1 or 2+2
Distributor	Urban	50	3.5/1+1 or 2+2
	Rural	80	3.25/1+1 or 2+1
Access	–	30–40	2.5/1 or 1+1

2.1.2 Road network statistics

Details of the road network in New Zealand according to *Network statistics* (LTNZ 2009) are shown in table 2.2. Unsealed pavements make up only 0.5% of the total lane length for state highways, but they form 37% of the total lane length for local roads. Although rural local roads are of lesser strategic value, they form 67% of the total lane length of New Zealand roads and could therefore be vital in terms of road infrastructure externalities, primary energy use, and emissions.

Table 2.2 Road network statistics (end of June 2008) (LTNZ 2009)

Category	Sub-category	Total length (lane-km)	Sealed length (lane-km)	Unsealed length (lane-km)	% of unsealed length
State highway	–	22,644.8	22,531.9	112.9	0.5%
	Motorway	431.0	431.0	0	0%
Local road	Urban	34,638.8	34,015.4	623.4	2%
	Rural	117,913.7	62,692.5	55,221.2	47%
	Special-purpose	1000.6	729.2	271.4	27%

2.2 Pavements

The structural design of pavements depends mainly on the site soil characteristics, climatic conditions, axle loads of heavy vehicles using the road, and construction material properties. This means that roads can have similar pavement design irrespective of the road classification (Pidwerbesky 27 November 2009, pers comm).

Pavements can be classified into two categories: flexible and rigid (Transit NZ RCA and Roading NZ 2005). Over 90% of New Zealand roads use flexible unbound granular pavements (Oeser et al 2008). Rigid structural asphaltic pavements are used mainly for urban motorways and heavy industrial traffic zones (Gundersen 2008). A typical sequence of layers in New Zealand pavements, from the bottom, is sub-grade, sub-base, base course and wearing course. Pavement may or may not have a surfacing/sealing layer, depending on the type and volume of traffic. Both 'urban arterial' and 'rural strategic' roads should be sealed because of the heavy traffic volume associated with these roads (Fong 16 December 2009, pers comm).

The two main types of seals used on New Zealand roads are chipseal and asphalt (NZTA 2009a). According to a survey of 33 road controlling authorities in New Zealand (which included 6 major urban areas, 4 large provincial townships and 19 small rural provincial townships) the type of seal predominantly used (on 78% of urban sealed roads and 99% of rural sealed roads) is chipseal (LTNZ 2004, p3). Chipsealed roads require resealing every 10 years with premium-quality aggregates, and an annual application of bitumen at the rate of 1.5l/m^2 (Ferry 1998, p59).

An unsealed pavement carrying traffic of about 100vpd can be constructed with a 50mm thick wearing course. Erosion due to vehicle traffic and weathering means that 8–15mm (average 12mm) of surface material is lost annually. Therefore unsealed pavements need grader blading four times a year to reshape and smooth the surface, combined with replacing the wearing course at a rate of 15mm/year (Ferry 1998, pp56, 60).

2.2.1 Pavement construction types

Pavement design can be similar, irrespective of whether it is sealed or unsealed (Pidwerbesky 27 November 2009, pers comm). Bennett (2008) published construction details and maintenance requirements for two pavement construction types: unbound granular pavement and structural asphaltic concrete. In terms of the time period required for initial construction, the two pavements are equal. However, structural asphaltic concrete pavements can be opened for traffic as individual layers are placed, and therefore the disruption to traffic flow is minimised.

2.2.1.1 Unbound granular pavement

This consists of a 250mm thick sub-base layer constructed on a sub-grade. A 150mm base course is constructed on the sub-base layer and a 25mm thick wearing course is added with grade 3 (16mm chips) chipseal. A year after the initial construction, a second coat of grade 5 (8mm chips) chipseal is added.

The maintenance regime includes stabilisation using foam bitumen and cement after 14 years, and resealing after 4, 19 and 28 years with grade 2 (19mm) chips, and after 15 and 25 years with grade 5 (8mm) chips.

2.2.1.2 Structural asphaltic pavement

This consists of a 200mm thick sub-grade improvement layer constructed with 3% lime-stabilised sub-grade. A 125mm structural asphalt layer is constructed on the sub-grade improvement layer, and a 40mm thick open-graded asphalt wearing course is added. The wearing course is milled and replaced at 11 and 21 years after the initial construction. All milled material is recycled into asphalt for later use.

2.2.2 Pavement useful life

The useful life of pavements (and other transport infrastructure) depends mainly on the damage caused by vehicles, and is a function of the useful life of contributory components.

The NZTA's *EEM* (2008) specifies a design life of 30 years for pavements. Chipseal surfaces have a shorter design life and need to be replaced several times during the life of the pavement. Design life varies with the grade of chipseal (which depends on the size of chips used) and the traffic load on the pavement. According to Austroads (2008), two-coat seals have a longer life (8–15 years) than single-coat seals. Chipseal useful life estimates by *New Zealand road asset maintenance management system* are cited in Gundersen (2008) (see table 2.3).

Table 2.3 Useful life of various chipseals at different traffic loadings (vpd) (Gundersen 2008)

Surfacing type	<100vpd	100–500vpd	500–2000vpd	2000–4000vpd	4000–10,000vpd	10,000–20,000vpd	>20,000vpd
Voidfill seals							
Grade 6	6	5	4	3	2	1	1
Grade 5	8	7	6	5	4	3	2
Grade 4	12	10	8	7	6	5	4
Grade 3	14	12	10	9	8	7	6
First-coat seals							
Grade 5	1	1	1	1	1	1	1
Grade 4	3	2	1	1	1	1	1
Grade 3	4	3	2	1	1	1	1
Grade 4/6	6	4	3	2	2	1	1
Grade 3/5	8	6	5	4	3	2	1
Grade 2/4	10	8	6	5	4	3	2
Reseals							
Grade 5	8	7	6	5	4	3	2
Grade 4	12	10	8	7	6	5	4
Grade 3	14	12	10	9	8	7	6
Grade 2	16	14	12	11	10	9	8
Grade 4/6	14	12	10	9	8	6	4
Grade 3/5	16	14	12	11	10	8	6
Grade 2/4	18	16	14	13	12	10	9

In practice, the design life is taken as a period shorter than the actual useful life, in order to avoid any litigation.

As a comparison in terms of terrain, Swiss roads[8] could be regarded as similar to those in New Zealand. Spielmann et al (2007, p75) estimated the useful life of Swiss roads as follows:

- subgrade – 100 years
- foundation (base and sub-base) – 40 years
- surfacing – 15 years.

2.2.3 The GHG emissions of pavements

A New Zealand study (Browne 2008) on initial construction emissions from pavements found concrete to be the source of the highest emissions, followed by the fuel consumption for material transport and on-site machinery. Treloar et al (2004), in a hybrid LCA[9] of Australian rural roads, found that in the total life cycle, the energy embodied in the pavement construction was small, compared with the manufacture and operation of vehicles over the 40-year period.

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[8] Swiss roads are subjected to much lower winter temperatures, which could impact the useful life of pavement layers.

[9] An LCA that uses a combination of process assessment and economic input–output assessment.

Although most LCA studies concentrate mainly on material extraction and production, Santero and Horvath (2009a) identified rolling resistance, traffic delays, transportation and materials as factors that determine the life cycle emissions of pavements. Estimates of GHG emissions reported by LCA studies of pavements that have this type of focus are shown in table 2.4. These studies considered the construction and maintenance of pavements, and the operation of vehicles (including maintenance and repair of those that used the pavement) during the estimated pavement lifetime.[10] The GHG emissions shown in table 2.4 range from 80 to 498t/lane-km.[11] Climate, traffic loading, maintenance strategy and material type were identified as factors determining the emissions due to materials (ibid).

Table 2.4 GHG emissions from selected LCA studies of pavements (Santero and Horvath 2009b)

Source	Country	Pavement structures (no.)	Pavement lifetime (years)	CO_2e^a emissions (t/lane-km)	
				Min	Max
Häkkinen and Mäkelä (1996)	Finland	5	50	80	345
Mroueh et al (2000)	Finland	7	50	132	281
Stripple (2001)	Sweden	3	40	135	268
Athena Institute (2006)	Canada	20	50	213	498
Chan (2007)	US	24	Variable	99	472

a) Carbon dioxide-equivalent.

Several factors could influence emissions through pavement construction. The emissions due to material transportation are determined by aggregate (as the single material with the largest mass in a pavement), transport distance and mode. In New Zealand, the cost of aggregate doubles at every 30km of distance it is transported (Richard Paling Consulting 2008b), so it is unlikely to be transported over distances in excess of 100km.

The energy use of on-site equipment used for placing pavement layers has been estimated to comprise 1–3% of the life cycle energy use (Athena Institute 2006; Zapata and Gambatese 2005). Browne (2008, pp3–5) reported 1.6% as the EE in plant for New Zealand road construction projects studied. On-site equipment use for pavement construction in the US, reported by Santero and Horvath (2009a), is shown in table 2.5. Based on these, Santero and Horvath estimate that life cycle emissions due to on-site equipment for construction and demolition are up to 10tCO_2e/lane-km if embodied emissions of fuels are included.

Table 2.5 On-site equipment use for pavement construction (Santero and Horvath 2009b)

Material	Equipment	Model	Fuel consumption (l/hour)
Concrete	Slipform paver	Wirtgen SP500	21.5–32.2
	Texture/curing machine	Wirtgen TCM950	7.8–11.8
Asphalt	Asphalt paver	Dynapac F121W/D	~35
	Pneumatic roller	Dynapac CP221	~20
	Vibratory roller	Dynapac CG233HF	~20
Aggregate base	Pneumatic roller	Dynapac CP221	~20
Demolition	Drop hammer	8600 Badger breaker	~35
	Milling machine	Wirtgen W1900	56–84

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[10] Although emissions depend on the pavement type, this was not discussed.

[11] One lane-kilometre covers an area of 3600m^2.

The impact of traffic delay (due to the initial construction period, and periodic maintenance) on the carbon emissions is site-dependent. Häkkinen and Mäkelä (1996) estimated traffic delay to contribute less than 5tCO_2e/lane-km over a pavement's 50-year life, while Chan (2007) (cited by Santero and Horvath 2009a) estimated emissions resulting from delays to vary from negligible to 600tCO_2e/lane-km, depending on the location for initial construction. Santero and Horvath used 1000tCO_2e/lane-km as the upper limit for life cycle emissions due to traffic delay. This suggests that life cycle studies that concentrate only on material extraction and production, and disregard traffic delays, could be accounting for only half the emissions.

Rolling resistance is the energy lost through tyre–pavement contact and depends on pavement structure, vehicle mass, pavement temperature, road roughness, road grade and vehicle speed (ibid).

2.2.4 Contaminant delivery by pavements

ARC (1992) cited by Kennedy (2003, p11) identified wear and breakdown of the road surface (including aggregate and other materials used in the base course and surface, bitumen and concrete) and other materials used on the road surface (eg marking paint) as the main sources of contaminants from pavements. Timperley et al (2005) estimated that 90g of suspended solids are delivered to water bodies by a square metre of pavement area in a year.

2.3 Bridges

In addition to roads, the network also includes a significant number of bridges (and cycleways). Bridges are an important component in the road network, with a significant resource use for construction and maintenance. The statistics for bridges are shown in table 2.6.

The total length of state highways in New Zealand is 10,906km, and this includes 4024 bridges with a total length of 142km (LTNZ 2009). Therefore the length of bridges as a percentage of the state highways is 1.3%. The total length of urban road is 17,298km, including 232km of bridges. Therefore, the urban road-bridge length as a percentage of urban road length is also 1.3%. The total length of special-purpose roads is 513km, with the length of bridges being 3.7km, or 0.7%. This indicates that the total length of bridges is less than 2% of the total length of any road type in New Zealand. Therefore detailed analysis of the resource use of bridges may not be warranted.

However, an Australian study (Maguire and Ryan 2009), has reported the carbon footprint of road construction as 190tCO_2e/lane-km (or 760tCO_2e/km) and 1.5tCO_2e/m^2 of bridge deck. On this basis, if the lane width is assumed to be 4.75m (3.5m wide lane with 1.25m wide shoulder), the carbon footprint due to construction of bridge deck per km is 7125tCO_2e, or 37.5 times that of the road.

Table 2.6 Bridges statistics (end of June 2008) (LTNZ 2009)

Road category	Bridge category	No.	Total length (m)
State highway	–	3807	127,651
	Single-lane	188	12,648
	Speed-restricted	11	682
	Weight-restricted	3	324
	Timber	15	843
Total state highway bridges		**4024**	**142,148**
Urban local road	–	4726	61,525
	Single-lane	7316	140,882
	Speed-restricted	183	4489
	Weight-restricted	511	13,577
	Timber	990	11,786
Total urban local road bridges		**13,726**	**232,259**
Special-purpose local road	–	50	800
	Single-lane	63	2597
	Weight-restricted	1	26
	Timber	6	305
Total special-purpose local road bridges		**120**	**3728**

Although the GHG emissions from bridge construction in Australia are not applicable to New Zealand because of inherent differences in the economies of the two countries (eg energy mix, building materials production practices/technologies, transport distances), it is reasonable to assume that the emissions due to roads and bridges in New Zealand would be similar in ratio to those in Australia. On this basis, bridges in New Zealand will add 49% to the total emissions due to state highways, even though they comprise only 1.3% of the total length of state highways. Similarly, bridges add 50% and 27% respectively to the total emissions due to urban roads and special-purpose roads, while representing only 1.3% and 0.7% of their total length. This suggests that although the bridges are insignificant in terms of the total length of the road network, their contribution to GHG emissions could be significant.

An important point is that the road construction considered in the Australian study was a combination of new build and rehabilitation and included a new motorway interchange bridge (Maguire 2010), which could be regarded as the most extreme scenario. It could therefore be argued that the relativity between roads and bridges in terms of carbon footprint would usually be lower than suggested by this comparison.

Material use (concrete and steel) for bridges in Switzerland, as reported by Spielmann et al (2007), is shown in table 2.7. These estimates are based on the material expenditure for rail bridges in Germany (assuming double track, ie a track in each direction) reported by von Rozycki et al (2003). Spielmann et al assumed that in the Swiss road network, 75% of the bridges were ‘glen bridges’ (ie bridges crossing valleys or rivers), with the other 25% being road/railway bridges. In New Zealand all bridges except those on special-purpose roads (and timber bridges) are likely to be similar in nature to the category ‘road/railway bridges’ in table 2.7. However, an assessment based on material consumption alone could underestimate the total environmental impact, as the fuel required to operate machinery and equipment during the construction and maintenance could be significant (although the environmental impacts of machinery use for bridge construction could be negligible).

Table 2.7 Material consumption for the construction of road bridges (Spielmann et al 2007)

Material	Absolute consumption		Lifespan	Specific consumption	
	Concrete	Steel		Concrete	Steel
Unit	**t/bridge km**	**t/bridge km**	**Years**	**kg/bridge m/year**	**kg/bridge m/year**
Glen bridges	55,000	3000	100	550	30
Road/railway bridges	89,000	4900	50	3560	196
Average bridge	–	–	–	1302.5	71.5

2.3.1 Useful life of bridges

Bridge life is determined by functional obsolescence as a result of increasing traffic and societal demands, rather than by structural failure. Horvath and Hendrickson (1998) estimated the useful life of steel bridges to be 80 years. Furthermore, steel bridges need repainting every eight years as preventive maintenance. Veshosky and Nickerson's 1993 estimates (cited by Horvath and Hendrickson 1998, p113) for the useful life of various bridge types were as follows:

- steel bridges: 47–76 years
- reinforced concrete bridges: 47–86 years
- pre-stressed concrete bridges: 21–86 years.

Itoh and Kitagawa (2003) reported the service life of Japanese bridges as 60 years. The useful life of bridges in New Zealand has been estimated to be 50–60 years (Treasury New Zealand Government 2009, p23).

2.4 Cycleways

The statistics for cycleways are shown in table 2.8.

Table 2.8 Cycleway statistics (end of June 2008) (LTNZ 2009)

Category	Sub-category	Total length (lane-km)
Local roads	Urban	480.5
	Rural	90.8
	Special-purpose	-

Compared with the total length of pavements, cycleways are negligible and therefore have not been included in the estimates of road network liabilities.

3 Rail transport system in New Zealand

3.1 Rail network

New Zealand's national rail network includes over 4000km of rail tracks (Treasury New Zealand Government 2009). Approximately 40% of the existing network is subject to heavy traffic volumes, and the rest operates below its capacity. This study uses the categorisations 'primary rail' (tracks carrying a heavy volume of traffic) and 'secondary rail' (tracks carrying a low volume of traffic), although these are not formally used by KiwiRail.

Rail infrastructure in New Zealand is divided into two categories: 'above rail' (those parts that travel on the rails) and 'below rail' (those parts that do not travel on the rails). 'Below rail' infrastructure includes tracks, bridges, tunnels and culverts, stations, and signal and communication systems, while 'above rail' infrastructure includes rolling stock such as locomotives, freight wagons and passenger carriages.

3.1.1 Rail tracks

Tracks consist of:

- two steel rails on which rail vehicles move
- a series of timber or concrete sleepers (ties)
- a track bed consisting of crushed stone ballast.

Standard rail tracks use two rails laid 1435mm (4ft 8½in) apart. Because of the country's difficult terrain, New Zealand railways historically used a narrow-gauge track (1067mm; 3ft 6in apart) with a light, flat bottom rail that weighed 35kg/m (Taieri Gorge Railway 2009). Modern heavy rail weighs 50kg/m (KiwiRail 2009). Tracks are laid on a mix of timber and concrete sleepers at 0.65m spacing (PWC 2004, p183) on a bed of 40mm size stone ballast (Taieri Gorge Railway 2009).[12]

Tracks wear out because of the tonnage they support rather than through rust, and rails laid on straight tracks last longer than those laid on curves (Shughart 2010).

3.1.2 Sleepers

The properties of standard timber sleepers used in New Zealand rail tracks are shown in table 3.1.

Table 3.1 Properties of standard-sized pine and hardwood sleepers (Manson 8 February 2010, pers comm)

Timber type	Species	Length (mm)	Width (mm)	Depth (mm)	Volume (m^3)	Approx dry density (kg/m^3)	Sleeper weight (kg)
Softwood	Treated *pinus radiata*	2100	200	150	0.063	510	32
Hardwood	Ironbark	2100	200	150	0.063	1170	74
Hardwood	Jarrah	2100	200	150	0.063	820	52

Sleepers are usually made of concrete, apart from those on non-ballast-bridges, which are made from timber. Timber sleepers could be either softwood or hardwood, with hardwood sleepers being preferred

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[12] According to Milford and Allwood (2010), UK railways use three standard ballast depths: 150mm, 200mm and 280mm.

on bridges. The size of timber sleepers used under track structures such as turnouts and on bridges is different from the standard sleepers shown in table 3.1.

In New Zealand, concrete sleepers are manufactured by Busck Prestressed Concrete Ltd (KiwiRail 2009). The composition of concrete sleepers used in New Zealand is as follows:

- Pandrol cast steel rail-fixing shoulders – 3.536kg
- steel reinforcement – 6.504kg
- concrete – 214.96kg (of which 39.6kg is cement).

Owing mainly to the greater strength of concrete sleepers, sleeper spacing can be increased from 600mm (timber) to 700mm (concrete). However, the first four sleepers either side of a rail joint are spaced closer, while on curves tighter than 300m, radius concrete sleeper spacing is reduced to 600mm (Manson 8 February 2010, pers comm).

Unlike timber sleepers, concrete sleepers tend to shatter during derailments as they cannot absorb the drag of derailed wheels along the tracks (Shughart 2010). However, depending on the traffic, a rail line with timber sleepers may need frequent re-gauging, whereas a line with concrete sleepers rarely does (ibid).

3.1.2.1 Sleeper fastenings

The sleeper-fastening systems used for timber[13] and concrete sleepers are shown in table 3.2. The concrete sleepers are fixed in place using Pandrol e-clips (steel) with a plastic wear pad between the rail and the sleeper (White 2010, pers comm). Plastic wear pads are imported from Australia.

Table 3.2 Properties of sleeper-fastening systems for timber and concrete sleepers (Manson 25 March 2010, pers comm)

Fastening type	No./ sleeper	Weight (kg/no)	Bedplate type	No./ sleeper	Weight (kg/no.)	Notes
Timber sleeper fastenings						
Canted bedplate with N clip (screw spike)	4	0.5	Canted bedplate	2	6	No pads but four N clips and washers weighing 4×(0.1+0.5)
Pandrol clip – timber sleeper (screw spike)	4	0.77+0.5	Bedplate	2	10	No pads or other components
NZR spring clip assembly (screw spike)	4	0.5	–	–	–	No pads but four spring clips weighing 4×0.1
Ribbed bedplate and rubber pad with N clip (screw spike)	4	0.5	Ribbed bedplate	2	10	Two natural rubber pads 0.15kg each, four N clips and washers weighing 4×(0.1+0.5)
Ribbed canted bedplate with N clip (screw spike)	4	0.5	Ribbed canted bedplate	2	6	No pads but four N clips and spring washers weighing 4×(0.1+0.5)
Concrete sleeper fastenings						
Pandrol e-clip – concrete sleeper	4	0.77	–	–	–	Two natural rubber pads 0.15kg each, four nylon insulators 0.06kg each

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[13] These are systems that were used historically, but not on the new track.

3.1.2.2 Overseas practices

Crawford (2009) has reported the weight of concrete and timber (River Red Gum) sleepers used in Australia as 299 and 80.2kg/sleeper respectively. These sleepers are heavier than those used in New Zealand (225kg/sleeper). In Australia, concrete and timber sleepers are spaced at 714mm and 685mm respectively. As reported by Kiani et al (2008), railways in the UK use rubber pads with concrete sleepers (each weighing 0.66kg/sleeper).

3.1.3 Ballast

Ballast track bed in New Zealand consists of a mix of aggregates with an average density of 1569kg/m^3. Initial construction includes ballast spreading for sub-base and foundation. Ballast maintenance includes tamping, cleaning and changing. During tamping and cleaning, 5% and 30% (respectively) of new ballast material is added to the track bed.

3.1.4 Useful life of rail tracks

3.1.4.1 Rails

In their LCA study of railways in the UK, Kiani et al (2008) estimated a maximum 30-year life for rail. However, anecdotal evidence, based on the existing rail track condition in New Zealand, suggests this estimate is too low for this country.

On average, rail tracks can carry 200 million gross tonnes during their life (Manson 30 July 2010, pers comm). This can be used to estimate the theoretical useful life of rail tracks on straight sections. On this basis, 1600km (~40%) of the existing network with a heavy volume of traffic (‘primary rail’) needs to be replaced after 40–60 years, while the remaining track with a lower volume of traffic (‘secondary rail’) should theoretically last for at least 80 years.

However, rails on tight curves wear out faster, and those in damp tunnels corrode more quickly. Fatigue can also shorten rail life in some cases. If these factors are taken into account, then 50% of the network will last for 50 years and the rest will last for 80 years. However, the above estimate of theoretical rail life based on gross tonnage assumes constant traffic over time, which is highly unlikely, given traffic growth and other fluctuations (ibid).

3.1.4.2 Sleepers

In his LCA of sleepers used in Australia, Crawford (2009) estimated the useful life of timber sleepers as 20–30 years, and concrete sleepers as 50 years. Shughart (2010) estimated 10–40 years for timber, and 40–60 years for concrete, metal and plastic sleepers used in the US. Kiani et al (2008) estimated the life of concrete sleepers used in the UK as 20–30 years.

3.2 Rail bridges and tunnels

Because of terrain conditions in New Zealand, the rail network includes a considerable number of rail bridges and tunnels. In recent times, some rail bridges have been replaced with culverts. At the time of this research, the network included 1636 bridges, with a total length of 63.8km. More than 93% of bridges (in terms of number or length) carried rail traffic, while the remainder were used as subways (that carried rail tracks on top) and stock underpasses. In addition, there were footbridges, stock overbridges, and other miscellaneous structures that were an integral part of the rail network.

Recently, four tunnels have been day-lighted[14], while another has been bypassed to cater to the changing freight demands. At the time of this research there were 145 tunnels, with a total length of 87.4km. Rail bridges and tunnels comprised 2% each of the total rail network length (Manson 20 December 2010, pers comm).

3.2.1 Useful life of rail bridges and tunnels

KiwiRail has estimated the useful life of bridges as 100 years (KiwiRail 2009, p14), with replacements needed after 80–100 years (ibid, p24).

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[14] This is to remove its 'roof' of overlying rock and soil and expose the rail tracks, so that trains with taller freight wagons can use the track.

4 Goal definition and scope of study

The purpose of this research project was to establish the baseline performance of the current road and rail infrastructure used for the transport of passengers and freight in New Zealand in terms of primary energy, CO_2e GHG emissions, and contaminant delivery to water bodies. This baseline performance could then be used to evaluate any future measures that are taken to improve the performance of the transport system in terms of the selected indicators.

Existing road and rail networks have evolved over a long period and therefore it is not possible to accurately trace the resource uses and construction methodology utilised at the time of construction, or the maintenance practices used in the past. It is also impossible to accurately estimate the changes in the vehicle fleet and rolling stock over the years. The estimates in this study were therefore based on the current construction and maintenance practices used in the road and rail sectors in New Zealand, and the implications of these actions being continued throughout the anticipated useful lives of the various parts of the infrastructure. Similarly, the transport services were evaluated using the current vehicle fleet and rolling stock. The year 2008 was selected as the base year, as that was the date of the latest transport data at the time of this study.

The study used the product-based LCA method (ISO14040 2006; ISO14044 2006). However, the results were limited to GHG emissions, cumulative energy demand, and quantity of contaminants delivered to water bodies. Although traffic delays and rolling resistance could influence GHG emissions and cumulative energy demand, these were not quantified.

4.1 System boundary

The system boundary in this study covered the extraction of raw materials through to disposal of waste materials (or recycling), reasoning that all life cycle inputs and outputs were relevant for consideration, regardless of their physical location or the time period considered. ISO14040 recommends that ‘resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study’. All unit processes within the system boundary that were likely to make a material contribution to cumulative energy demand, GHG emissions, and quantity of contaminants were included.

Road and rail infrastructure systems were limited to carriageway (pavements and bridges) and rail track (track formation, bridges and tunnels), respectively. Street lighting, roadside barriers, embankments, cycleways, traffic signals[15], railway stations, bus shelters, etc were not included. The impacts of terrain and ground conditions on construction requirements of road and rail infrastructure were ignored – ie, for the purposes of comparison it was assumed that infrastructure was constructed on flat ground with equal soil-bearing properties.[16]

The life cycle stages that were included were initial construction, maintenance, replacements and operation. The preliminary design of the infrastructure and project-management activities was not included. As the demolition and disposal of large infrastructure systems such as roads and rail are

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[15] Signals and telephone lines are estimated to be 5% of the initial construction cost for Swedish railways, while a hybrid life cycle study of passenger transport in the US (Chester 2008) showed that street lighting contributes around 1% and 3%, respectively, to the total energy use and GHG emissions of road transport.

[16] Liabilities associated with earthworks have been estimated based on two case studies representative of the best- and worst-case scenarios (see sections 5.1 and 5.3.1.)

uncommon, they also were not considered. Road and rail bridges were considered to be similar in construction, and rail tunnels were considered to consume three times as much resources as rail bridges (see section 5.7.2).

The following inputs were omitted from the analysis because of a lack of readily accessible data:

- earth-moving for pavement and track formation
- on-site wastage of construction materials.

It is very likely that passengers (and freight) have to use other means to get to the station to board the train and to get to the actual location from the destination station. These additional transport requirements were ignored.

4.2 Functional unit

The ISO 14040 series of LCA standards specify that a functional unit of analysis must be defined. The functional unit for this study depended on the component of transport being considered. While a unit length was used to evaluate infrastructure components, a unit of service was used to evaluate transport services.

The functional units used for this study were as follows:

- road infrastructure – a lane-kilometre of a specific type of road (motorway, state highway, urban local road, rural local road, special-purpose road) per annum (lane-km/annum)
- rail infrastructure – a kilometre length of single rail track (primary and secondary) per annum (km/annum)
- freight transport – a tonne of weight transported over a kilometre distance, using medium/heavy commercial vehicle, light commercial vehicle (LCV), or rail freight wagons (tkm)
- passenger transport – a kilometre distance travelled using a specified mode (eg car, van, bus, train, etc) by a passenger (pkm)

However, the use of a functional unit to compare the modes ignores the fact that it is not possible to interchange modes at all times and therefore neglects the purpose and value of the trip. Further, the variations in speed, comfort levels, availability, cost, etc, of the various modes are also disregarded in such comparisons.

4.3 Useful life

The useful life of transport infrastructure depends mainly on the damage done by vehicles and is a function of the useful life of contributory components. The useful lives used for this study are described in the following sections.

4.3.1 Useful life of road infrastructure

4.3.1.1 Pavements

Subgrade is assumed to have a useful life of 100 years. The foundation (base course and sub-base) is expected to last 40 years for unbound granular pavements, and 50 years for structural asphalt pavements. The useful life of the wearing course depends on the type of surfacing and the level of traffic (see table 2.3).

4.3.1.2 Bridges

Concrete bridges are assumed to have a useful life of 80 years.

4.3.2 Useful life of rail infrastructure

The useful life estimates for rail components used in Kiani et al (2008) for rail services in the UK and those suggested for New Zealand rail operations by KiwiRail (Manson 30 July 2010, pers comm) are shown in table 4.1.

Table 4.1 Comparison of UK and New Zealand rail useful lives (in years)

Rail component	Kiani et al (2008)	KiwiRail (Manson 25 February 2010*, 30 July 2010, pers comm)
Rails	30	Primary lines – 40–60 years; secondary lines – 80 years
Fastenings	20–30	40
Rail pads	30	30
Ballast track bed	20–30	40*
Ballast cleaning	10–15	30
Ballast tamping	1–2	Primary lines – every 2–4 years; secondary lines – every 8–10 years

This information suggests that the useful life of ballast track bed and rail fastenings in New Zealand is 40 years. Therefore, the useful life of primary lines was assumed as 40 years, with rail renewal (transposing rail[17], replacement of fastenings and pads, and ballast cleaning) after 20 years.

On this basis, the useful life estimates for rail infrastructure used in this study were as follows:

- rails for tracks – 40 years on primary lines and 60 years on secondary lines with less traffic
- rail fastenings – 40 years; pads – 20 years
- rail transposing – 20 years
- sleepers – timber sleepers used on bridge decks – 30 years; common concrete sleepers – 50 years
- ballast track bed – 40 years; ballast cleaning – every 20 years; ballast tamping – annually on primary lines with heavy traffic volumes and every 6 years on secondary lines (with less traffic)
- rail bridges and tunnels[18] – 80 years.

4.4 Characterisation factors

In this study, primary energy use and GHG emissions factors for New Zealand building materials were based on data published by Alcorn (2003), and New Zealand fuels and electricity factors were based on Barber (2009). Energy use and emissions due to supplementary processes such as rail forming, plastic rail-pad moulding, and steel-fastener manufacturing were estimated using ecoinvent[19] data modified with country-specific fuel and electricity data. Energy use and emissions factors for products imported from overseas (other than steel rails) were based on the ecoinvent 2.1 database.

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[17] Rails on curves wear faster and therefore are swapped from one side to the other.

[18] The useful lives of rail bridges and tunnels are likely to be determined by the requirements of the freight, rather than by their structural stability.

[19] Ecoinvent is a European life cycle inventory database.

The resource uses of transport activities (ie vehicles and road infrastructure, excluding fuel use) were assumed to be similar to those in Europe. Fuel use was based on the data shown in sections 5.1 and 5.2. Construction machinery production resource uses were estimated based on ecoinvent data for a harvester pro-rated according to machinery weight. Because of the lack of New Zealand data, maintenance of machinery was assumed to be similar to that for 16t and 40t lorry maintenance in Swiss conditions.

Contaminant delivery to water bodies was estimated based on the rates specified in Timperley et al (2005).

4.5 Allocation

Road and rail infrastructure are shared by both passenger and freight transport activities. Since damage to infrastructure and the consequent maintenance are functions of the total load transported, weight mass allocation based on the gross-tonne-kilometre (Gtkm) performance was used to allocate infrastructure to services provided.

5 Road and rail infrastructure lifetime liabilities

As a first step in this research, an inventory of resources used and emissions released by the road and rail infrastructure system over their lifetimes, as defined in sections 2 and 3, was completed. The inventory included a list of all significant quantities of materials, fuel, etc used and the resultant emissions and waste, by life cycle stage. The NZTA and Fulton Hogan Ltd were the primary data sources for the road infrastructure inventory. KiwiRail was the primary data source for the rail infrastructure inventory. Data was based on standard industry practices. Gaps in the data were filled by using secondary data from the ecoinvent version 2 (2007) database and published literature. These were limited to minor inputs.

The resource use inventory thus developed is discussed by life cycle stage in sections 5.1 and 5.2 below.

5.1 Road infrastructure inventory

5.1.1 Earthworks

The resource use for earthworks depends mainly on the terrain conditions (hilly or flat), rather than on the earth-transport distance, which is usually a few kilometres or less. (In an LCA-based study of a dam construction project (Mithraratne 2008), 91% of emissions due to earthworks were due to fuel use, while machinery and materials used (eg filter media and gravel) contributed 4% each, and transport contributed 1%.) Diesel use for earthworks in road construction range from 0.6 to 1.0l/m^3 of earth moved (Pidwerbesky 23 June 2010, pers comm). A case study approach was selected to establish the likely extremes due to earthworks. The two case studies selected to represent the extremes were Northern Gateway Alliance (hilly terrain – difficult construction condition) and Christchurch Southern Motorway (flat terrain – easy construction condition). The volumes of earth involved were 4.2 million m^3 for Northern Gateway Alliance (for 30 lane-km) and 500,000 m^3 for Christchurch Southern Motorway (for 28 lane-km).

5.1.2 Bridges

As discussed in section 2.3, although the length of bridges is insignificant overall, the resource use could be noteworthy. Owing to lack of data on the construction and maintenance of bridges in New Zealand, Australian data was used to estimate the emissions of New Zealand road and rail bridges. The Australian study (Maguire 2009) was limited to GHG emissions, and therefore primary energy use of New Zealand bridges was not estimated.

5.1.3 Pavements

5.1.3.1 Pavement width

Published data on the New Zealand road network indicates the total length of lane-km for different road categories, but not the lane width. It is assumed that all roads other than state highways and motorways use a lane width of 3.5m, while state highways and motorways use a lane width of 4.5m with a 1.0m wide shoulder.

Assuming the presence of shoulders for all lanes in state highways and motorways could have led to an overestimation of the pavement area of motorways with multi-lanes, as the middle lanes of multi-lane motorways have zero shoulders. However, the total length of multi-lane motorways in the network is small and therefore the impact of this assumption was negligible.

5.1.3.2 Pavement construction types

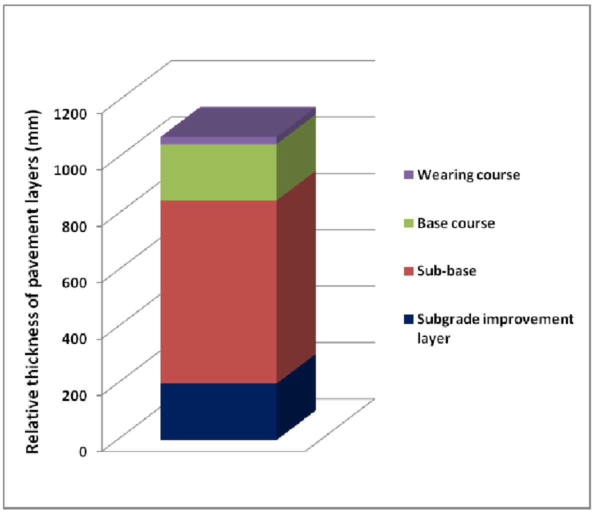
As the pavement design depends on structural requirements such as soil characteristics, climate, traffic loading and construction materials selected, rather than on the functional requirements used in the network statistics, the same pavement construction type can be used for different classes of roads. However, the thickness of the pavement is related to the level of traffic on the road.

The pavement construction types discussed in Bennett's 2008 study were those proposed to reduce the maintenance requirements rather than what was actually being constructed. For this study, it was assumed that unbound granular pavement had been used for all roads other than motorways, which use structural asphaltic concrete construction. The sequence of construction layers and the specifications used for the two pavement types is discussed below.

Unbound granular pavement

Depending on the soil characteristics, the subgrade may require improvements in order to receive the pavement. This can be achieved by treating with lime (3% by mass) to a depth of 200mm. The subgrade improvement is generally carried out for less than 5% of the total length of a road (Pidwerbesky 22 June 2010, pers comm). (The estimates in this study assumed that the total length of the road would undergo subgrade improvement, and were therefore a conservative estimate).[20] Then a sub-base is constructed on the subgrade, a base course is constructed on the sub-base layer, and a 25mm thick wearing course is added. The thickness of the sub-base and base course layers depends on the traffic level. A year after the initial construction, a second coat of wearing course is added (see figure 5.1).

Figure 5.1 Unbound granular pavement layer sequences for all roads other than motorways



The size of the aggregates used for the two-coat wearing course depends on the site conditions and the demand created by the vehicles (ie skid resistance). The amount of bitumen required for the wearing course depends on the aggregate size. The base-case scenario (see table 5.3) in this study was based on the use of 19mm aggregate (grade 2 chips) and therefore represented the worst-case scenario with the highest use of aggregate and bitumen for the sealed wearing course.

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20 The influence of this assumption is marginal, as the subgrade improvement layer contributes only 1% and 4% to the lifetime energy and emissions, respectively, for a kilometre length of state highway.

The thickness of pavement layers and wearing course construction for different roads in the network that use unbound granular construction based on industry information[21] is shown in table 5.1.

Table 5.1 Composition of pavement structure for different road types in the New Zealand road network

Road type	Sub-base thickness (mm)	Base course thickness (mm)	Length (%)	Wearing course type/ thickness (mm)
State highway	650	200	10%	Two-coat chipseal (25)
	500	175	30%	
	250	150	60%	
Local urban roads	500	175	98%	Two-coat chipseal (25)
	250	150	2%	Unsealed (25)
Local rural roads	500	175	53%	Two-coat chipseal (25)
	250	150	47%	Unsealed (25)
Special-purpose roads	500	175	73%	Two-coat chipseal (25)
	250	150	27%	Unsealed (25)

The maintenance regime of unbound granular construction includes routine inspections, pothole fixing, and resealing. The current practice is to reseal with a two-coat seal. The resealing interval depends on the level of traffic on the pavement; the estimates used for resealing intervals in this study are shown in table 5.2.

Table 5.2 Estimates for resealing intervals for roads with different traffic loadings in the New Zealand road network

Traffic level (vpd)	Resealing interval (years)	
	Year 0–25	Year 26–40
10,000	9	7
5000	11	8
500	12	9

Initial construction resource use for unbound granular pavements

According to Richard Paling Consulting's *National freight demands study* (2008), aggregate is a low-value product and its cost doubles with every 30km distance transported. Their study estimated the average transport distance to be 20–40km, although it could be as high as 90km in Auckland (op cit, p63). Because of the large volume of aggregates involved in pavement construction, transport of aggregate over distances in excess of 100km is not cost effective. For this study, the average transport distance from the aggregate quarry and bitumen plant was assumed to be 30km.

The density of the aggregate used for the wearing course depends on the source rock used and the location of the quarry. The two main rock types used in New Zealand for chipseals are basalt and greywacke. The typical density of seal chips could therefore vary as follows:

- greywacke – 1.48t/m^3 (Grade 2) to 1.40t/m^3 (Grade 6)
- basalt – 1.90t/m^3 (Grade 2) to 1.80t/m^3 (Grade 6) (Lowe 5 April 2010, pers comm).

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[21] I Cox, Principal Operations Engineer (NZTA 26 April 2010, pers comm).

Estimates in this study were based on the use of seal chips from basalt rock.

Data used to estimate the initial construction resource use is shown in table 5.3.

Table 5.3 Details of unbound granular pavement construction used in this study

Type of data	Relevant data	Data source
Material use	Subgrade improvement layer is created by treating subgrade with 3% lime to a depth of 200mm. Density of aggregate for base course and sub-base is 2.36t/m^3. Aggregate for wearing course is spread at 75m^2/m^3. Density of wearing course aggregate is 1.9t/m^3. Bitumen for wearing course is spread at 2.1l/m^2.	Bennett 2008 Lowe 5 April 2010, pers comm
Transport	Transport distances: Lime source to site: average 50km Aggregate: average[#] 25km; max* 100km Bitumen: average[#] 30km; max[#] 200km Transport vehicles: Lime and aggregate for base course and sub-base: 28t truck and trailer; diesel use 0.55l/km Aggregate for wearing course: 15t truck; diesel use 0.5l/km Bitumen for wearing course: 10m^3 tanker; diesel use 0.55l/km	Bennett 2008 * Cox 23 March2010, pers comm [#] Pidwerbesky 22 June 2010, pers comm
Construction rates	Lime is mixed and spread at the rate of 900m^2/hr. Sub-base and base course are placed and compacted at the rate of 200t/hr and 130t/hr, respectively. Base course is prepared at the rate of 1800m^2/hr for wearing course.	Bennett 2008
Construction machinery use	Subgrade improvement layer: Lime spreader and hoe: diesel use 15l/hr Padfoot roller: diesel use 18l/hr 12H grader: diesel use 20l/hr 13-t Smooth drum roller: diesel use 18l/hr Sub-base construction: 12H grader: diesel use 20l/hr 13-t smooth drum roller: diesel use 18l/hr Water cart: 3l/hr Base course construction: 12H grader: diesel use 20l/hr 13-t smooth drum roller: diesel use 18l/hr 16-t multi- or pneumatic-tyre roller: diesel use 12l/hr Water cart: 3l/hr Base course preparation for seal: 3-part static drum roller: diesel use 12l/hr 16-t multi- or pneumatic-tyre roller: diesel use 12l/hr Seal construction: Spray truck: diesel use 2.5l/hr 3 tippers: diesel use 2.5l/hr 2 rollers: diesel use 12l/hr	Bennett 2008

Maintenance resource use for unbound granular pavements

The second chipseal layer is added to the wearing course one year after the initial pavement construction.

Routine maintenance: Routine maintenance involves regular inspections to survey pavement condition, and fixing potholes. On a network basis, 10% of the length is inspected monthly using a passenger car or a utility vehicle. Material used to fix potholes varies from asphaltic concrete to proprietary products such as EZ Street (Bennett 1 April 2010, pers comm). The distance travelled for inspections can also vary widely.

For this study, it was assumed that asphalt was used to fix potholes. Asphalt use for pothole fixing was considered to be negligible, and disregarded; however, machinery use was included. For the year following a reseal, routine maintenance needs were considered to be negligible and therefore ignored.

Resealing: Construction rate and machinery use for resealing are similar to that for the initial construction of wearing course.

Maintenance resource use was estimated based on the data shown in table 5.4.

Table 5.4 Details of unbound granular pavement maintenance requirements used in this study

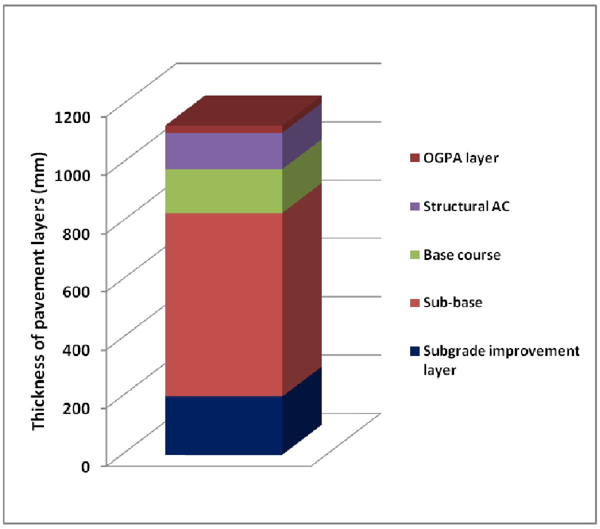
Type of data	Relevant data	Data source
Routine maintenance	Inspections to survey pavement condition: Frequency: twice a year Vehicle type: truck, fuel use 0.45l/km Distance per visit: 25km one way Maintenance activity: Frequency: 10 times a year First 25 years: use of 28t tray truck for 4h/visit After 25 years: use of 28t tray truck for 6.5h/visit Transport distance: average 25km, max 80km; vehicle: 28t truck; fuel use 0.55l/km	Bennett 2008
Resealing	Bitumen and aggregate spread rate is as follows: Bitumen 2.1l/m^2 Aggregate 75m^2/m^3, density of seal chips 1.90t/m^3 Transport distances: Aggregate: average 25km, max*100km Bitumen: average 30km, max# 200km Transport vehicles: Aggregate: 15t truck; diesel use 0.5l/km Bitumen: 10m^3 tanker; diesel use 0.55l/km Construction rate: 1800m^2/hr Machinery use: 2 multi- (16t) or pneumatic-roller: diesel use 12l/hr Spray truck: diesel use 2.5l/hr	Bennett 2008 * Cox 23 March2010, pers comm # Pidwerbesky 22 June 2010, pers comm

Structural asphaltic concrete pavement construction

This consists of a 200mm thick subgrade improvement layer (SIL) constructed with 3% lime-stabilised subgrade. A 630mm thick sub-base is constructed on the subgrade improvement layer, and a 150mm thick base course layer is added. A 120mm thick structural asphalt layer is constructed on the base course, and a 25mm thick open graded asphalt wearing course is added (see figure 5.2).

Maintenance includes routine inspections and milling and replacing the wearing course at eight-year intervals.

Figure 5.2 Structural asphaltic concrete pavement layer sequence for motorways



Initial construction resource use for structural asphaltic concrete pavements

The density of asphalt depends on the mix design and the source of the aggregate. Structural asphalt normally uses 5% bitumen[22] and 95% aggregate. Fifty percent of the aggregate is fine aggregate, and the remaining 45% consists of chips of various sizes. Seven litres of fuel is required in order to mix the ingredients and to manufacture a tonne of structural asphalt.

Open graded porous asphalt (OGPA) generally consists of 20% fine aggregates, 74% chips, and 6% bitumen. OGPA is generally made at a lower temperature (130–140˚C) than that used for structural asphalt (160–170˚C). OGPA uses more chips than structural asphalt and is therefore likely to use more fuel to manufacture, per tonne of mix. Data on actual fuel use was not available and fuel use was therefore assumed to be 7 litres for a tonne of OGPA[23]. The bulk density of the mix ranges from 2.2–2.4t/m^3.

Generally, the aggregate quarry and asphalt plant are located on the same site. Initial construction resource use for structural asphaltic concrete pavement was estimated based on the data shown in table 5.5.

Table 5.5 Details of structural asphaltic concrete pavement construction used in this study

Type of data	Relevant data	Data source
Material use	Subgrade improvement layer (SIL) is created by treating subgrade with 3% lime to a depth of 200mm Density of aggregate for base course and sub-base is 2.36t/m^3 Structural asphalt mix: 5% bitumen, 95% aggregate Density of structural asphalt is 2.41t/m^3 OGPA mix: 6% bitumen, 94% aggregate Density of OGPA is 2.3t/m^3 7 litres of fuel is used to produce a tonne of structural asphalt and OGPA	Bennett 2008

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[22] The density of bitumen is 1.01–1.03 t/m^3.

[23] However, new OGPA mixes, which use less fuel per tonne of mix (3.5l/t), have been developed.

Type of data	Relevant data	Data source
Transport	<u>Transport distances</u>: Aggregate: average 25km; max* 100km Asphalt plant to site: average 25km; max* 80km Bitumen plant to asphalt plant: average 30km; max# 200km Lime source to site: average 50km <u>Transport vehicles</u>: Lime and aggregate for base course and sub-base: 28t truck and trailer; diesel use 0.55l/km Asphalt, OGPA: 15t truck and trailer; diesel use 0.55l/km Bitumen to asphalt plant: 10m^3 tanker; diesel use 0.55l/km Lime: 28t truck and trailer; diesel use 0.55l/km	Bennett 2008 * Cox 23 March 2010, pers comm # Pidwerbesky 22 June 2010, pers comm
Construction rates	Lime is mixed and spread over 900m^2/hr Sub-base and base course are placed and compacted at the rate of 200t/hr and 130t/hr, respectively Structural asphalt is placed at the rate of 70t/hr OGPA wearing course is placed at the rate of 40t/hr	Bennett 2008
Construction machinery use	<u>Subgrade improvement layer</u>: Lime spreader and hoe: diesel use 15l/hr Padfoot roller: diesel use 18l/hr 12H grader: diesel use 20l/hr 13t smooth-drum roller: diesel use 18l/hr <u>Sub-base construction</u>: 12H grader: diesel use 20l/hr 13t smooth-drum roller: diesel use 18l/hr Water cart: 3l/hr <u>Base course construction</u>: 12H grader: diesel use 20l/hr 13t smooth-drum roller: diesel use 18l/hr 16t multi- or pneumatic-tyre roller: diesel use 12l/hr Water cart: 3 l/hr <u>Structural asphalt layer</u>: Paver: diesel use 0.3l/hr 13t smooth-drum roller: diesel use 18l/hr 16t multi- or pneumatic-tyre roller: diesel use 12l/hr <u>OGPA wearing course</u>: Paver: diesel use 0.3l/hr 13t smooth-drum roller: diesel use 18l/hr 16t multi- or pneumatic-tyre roller: diesel use 12l/hr	Bennett 2008

Maintenance resource use for structural asphaltic concrete pavements

On average, 10% of the network is inspected monthly to survey the pavement condition. At eight-year intervals, the wearing course is milled and replaced with new material. Milled material is carted away to the asphalt plant and reused in OGPA mix. For this study, the maintenance resource use for structural asphaltic concrete pavement was estimated based on the data shown in table 5.6.

Table 5.6 Details of structural asphaltic concrete pavement maintenance requirements used in this study

Type of data	Relevant data	Data source
Routine maintenance	Inspections to survey pavement condition: 10% of the network is inspected monthly Distance: 100km/year; vehicle: truck; fuel use 0.45l/km Maintenance activity: Use of 28t tray truck to fix potholes Distance: 250km/year; fuel use: 0.55l/km	Bennett 2008
Mill and replace OGPA	25mm thick OGPA wearing course is milled out, carted to asphalt plant and replaced with new OGPA product 300m^2 of OGPA is milled per hour Transport distances: Milled material to asphalt plant: average 25km, max 100km Transport vehicles: Milled material: 28t truck and trailer; diesel use 0.55l/km Machinery use for milling: Asphalt profiler: diesel use10l/hr	Bennett 2008

5.2 Rail infrastructure life cycle inventory

5.2.1 Rail track construction

New Zealand uses a narrow-gauge track with two steel rails placed 1067mm apart. New rails are generally laid on concrete sleepers, on a bed of stone ballast at least 300mm thick (TranzRail 2001).

5.2.1.1 Rail

During the period 2007–2009, virtually all new rails used in New Zealand rail tracks were manufactured in China by the Panzhihua Iron and Steel (Group) Company in Sichuan Province. Rails are transported by rail to ports in either Guangzhou (1900km) or Shenzhen (2100km) for shipping to New Zealand.

Rails are shipped in 12.8m lengths to Auckland and then transported by truck 15km from the port to Otahuhu Railweld Depot. Rails are welded at the depot into longer lengths of 76m or 153m, depending on whether they are to be transported to the South Island or the North Island, respectively. The length of rails transported to the South Island is limited by the capacity of the rail ferry. Welded rail lengths are transported to the site by rail wagons and are unloaded to the track-side using cranes mounted on the rail wagons.

5.2.1.2 Sleepers

Sleepers, other than those on non-ballast-decked bridges, are concrete and are designed to a 22.5t axle load. At the time of this research, KiwiRail Network was considering adopting an in-house design for new concrete sleepers, with the intention of designing sleepers capable of carrying 25t axle loads. Concrete sleepers are laid 700mm apart on straights and 600mm apart on curves with radius under 400m.

For the majority of bridges, hardwood sleepers are used to fix the rails to the spans. There are, however, other systems for mounting rails on bridges, including using normal concrete sleepers on a bridge deck that contains normal ballast (ballast-decked bridges), or fastening the rails direct to concrete-slab track or concrete pedestals.

Sleeper fastenings are mainly sourced from New South Wales, Australia. These are shipped in containers to Auckland or Wellington and are then transported to rail workshops, using rail (from Auckland) or truck (from Wellington). Onward distribution of fastenings to rail depots is typically by rail. In special cases (such as the 'DART project' to upgrade the rail network in Auckland) that involve laying long lengths of track, imported fastenings are delivered direct to the site.

5.2.1.3 Ballast

Ballast track bed uses a mix of aggregate smaller than 63mm in size. According to track specification (ONTRACK – New Zealand Railways Corporation – 2007), the ballast should conform to the consistency shown in table 5.7, once prepared and tested as per the requirements of NZS 4407:1991, test 3.8.2.

The average density of prepared ballast is 1569kg/m^3.

Table 5.7 Ballast aggregate consistency (ONTRACK (New Zealand Railways Corporation) 2007)

Sieve size	Percentage by weight passing each sieve
63mm	100%
53mm	82–100%
37.5mm	47–72%
26.5mm	15–40%
19mm	0–12%
13.2mm	0–3%

Aggregate is sourced from various locations in both the North and South Islands, with a major source in each island located within a rail yard. Aggregate is also delivered to rail yards by truck and transported by ballast wagons to the work site for major works (such as relaying sleepers), or by truck for smaller works (such as relaying a level crossing). Sources of ballast aggregate and mode of transport to the work site are shown in table 5.8.

Table 5.8 Ballast aggregate sources and mode of transport to the work site (Manson 7 April and 30 July 2010, pers comm)

Location	Contribution	Mode of transport to rail yard
Morrinsville, North Island	Major source	Truck
Otaki, North Island	Major source	On-site source
Whangarei, North Island	Secondary source	Truck
Auckland, North Island	Secondary source	Truck
Hunterville, North Island	Secondary source	Truck
Wellington, North Island	Secondary source	Truck
Islington, South Island	Major source	Truck (5km)
Westport, South Island	Major source	Truck
Dunedin, South Island	Major source	Truck
Hapuku (north of Kaikoura), South Island	Secondary source	Truck (~2km)
Oamaru, South Island	Secondary source	Truck

5.2.1.4 Machinery use

The various types of machinery used for track construction and maintenance purposes, and their weights, are shown in table 5.9.

Table 5.9 Machinery fleet used for New Zealand track construction and maintenance activities (K Check, Corporate Responsibility Manager, KiwiRail Network, 24 September 2010, pers comm)

Machinery type	Fleet size	Ave tare weight (t)
Ballast cleaner	1	62
Ballast regulator	3	30
Ballast regulator for beaver tamper	1	16
Beaver switch tamper	1	32
CAT 09/16 tamping machine	2	41
EM80 track-recording car	1	31
Fairmont tamper tamping machine	3	28
Low loader	1	23
Rotary scarifier	1	10
Sleeper layer	1	40
Spot tamping machine/regulator	1	16
SSP ballast equaliser	2	17
Tauranga Mk6 regulator	1	30
Tauranga Mk6 tamper	1	41
Tie crane	2	9
Tie replacer	2	16

For certain types of machinery, New Zealand track-construction times appear to be significantly different from those reported by Kiani et al (2008) for UK railways. A comparison of machinery use in New Zealand and the UK for track construction and maintenance is shown in table 5.10.

Table 5.10 Machinery use for track construction and maintenance in New Zealand and the UK

Activity/machinery	Construction speed (hours/km of single track)	
	New Zealand[a]	UK[b]
Ballast-spreading machine	1	12
Sleeper-laying machine	8	14
Rail-laying machine	8	37
Ballast-changing machine	12	17
Ballast-cleaning machine	12	17
Ballast-tamping machine	2	32

a) K Helm, Project Engineer, KiwiRail, pers comm, 25 March 2010.

b) Kiani et al (2008).

It is difficult to understand the underlying reasons for this disparity, as the basis for the speed of construction in the UK study is unknown. This could be attributed to the differences in construction practices used in New Zealand and the UK, but that was not investigated in this study. The actual construction activity includes site establishment and disestablishment, which can be highly time-consuming. In the UK, where train speeds are generally higher than in New Zealand, the hand-back standards are much higher than in New Zealand. The expectation in the UK is that trains should be able to return to line speed much sooner than those in New Zealand, where a temporary speed restriction until the track settles is acceptable in most cases.[24] This may partially explain the disparity between the UK and New Zealand values.

The New Zealand values shown in table 5.10 include only the machinery used for the prescribed activity. As construction speed was used in this study to estimate the fuel use for construction activity, the actual machine use as indicated by KiwiRail was used. In addition, the track machinery and rail wagons used for construction and maintenance (table 5.9) were included in the lifetime resource use for rail infrastructure. The machinery and wagons are expected to last 60 years, and were allocated accordingly.

5.2.2 Resource use for rail tracks

5.2.2.1 Initial construction resource use for rail tracks

Initial construction resource use by the construction of rail tracks was estimated based on the data shown in table 5.11.

Table 5.11 Details for the rail track construction used in this study, based on New Zealand practices

Type of data	Relevant data	Data source
Rails	Materials: two steel rails weighing 50kg/m each Transport: Manufacturing plant to port: rail; distance: 1900km China to New Zealand: shipping; distance: 9525km Port of origin: Guangzhou, China Port of discharge: Auckland, New Zealand Auckland port to welding depot: 40t truck; distance: 15km, return trip empty Yard to site: rail; distance: 25km (transport between welding depot and local rail yard using rail is not included) Machinery use: [a]rail-laying machine 8hr/km of track; diesel use 5l/hr	Manson 8 February and 7 April 2010, pers comm a) Helm 29 March 2010, pers comm
Sleepers	Number of sleepers: 1538 per track km at an average spacing of 650mm Materials (per sleeper):[b] Concrete (50MPa) 214.96kg (including 39.6kg of cement) Steel reinforcement 6.504kg (sourced from China) Pandrol cast steel rail fixing shoulders 3.536kg (sourced from Australia) Transport (mode/distance): Materials to sleeper manufacturing plant: • *Concrete*: 28t truck; 5km, return trip empty • *Steel reinforcement:* – Factory to Guangzhou, China: rail; distance 1900km – China to New Zealand: shipping; distance:10,150km – Port of origin: Guangzhou, China – Port of discharge: Lyttelton, New Zealand – Lyttelton port to manufacturing plant: 40t truck; distance: 13km, return trip empty • *Steel rail fixing shoulder:* – Manufacturing plant to Adelaide port: 40t truck; 9km, return trip empty	b) White 15 January and 26 April 2010, pers comm a) Helm 29 March 2010, pers comm

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[24] New Zealand now uses Dynamic Track Stabilising machines to reduce the need for temporary speed restrictions.

Type of data	Relevant data	Data source
	– Australia to New Zealand: shipping; distance: 3500km – Port of origin: Adelaide, Australia – Port of discharge: Lyttelton, New Zealand – Lyttelton port to manufacturing plant: 40t truck; distance: 13km, return trip empty Sleeper-manufacturing plant is located within the rail yard) Machinery use: [a] sleeper-laying machine 8hr/km of track; diesel use 5l/hr Packaging material use: for fixing shoulders is not included	
Sleeper fastenings	Materials (per sleeper): Four steel Pandrol e-clips each weighing 0.77kg Two HDPE pads each weighing 0.15kg Four nylon spacers (insulators) each weighing 0.06kg Transport: Factory to Sydney port: 40t truck; distance: 50km Australia to New Zealand (Auckland): shipping; distance: 2400km Yard to site: rail; distance: 25km Exclusions: Transport between port and yard Packaging material use for fastenings	Manson 29 March 2010, pers comm
Ballast track bed (single track)	Materials: Volume of ballast aggregate is 1.62m^3/m Density of aggregate is 1569kg/m^3 Transport (mode/distance): Quarry to yard: • 28t truck, distance: average 25km, max 100km • Yard to site: rail; distance: 25km Machinery use[a]: Ballast-spreading machine 1hr/km; diesel use 10l/hr	Estimated based on TranzRail (2001) a) Helm 29 March 2010, pers comm

5.2.2.2 Maintenance resource use of rail tracks

Maintenance of rail mainly involves routine inspections of the rail and ballast tamping. Because of the difficult terrain in New Zealand, 36% of the existing network is in curves. As rails on curves wear out faster than on straights, these rails need to be replaced every 20 years. Rails are removed by lifting them in or out with the boom of an excavator. During rail transposing, sleepers are left intact. If sleepers are replaced[25], those in reasonable condition are reused in the yards, while timber sleepers in poor condition are generally sold for landscaping purposes. The removed rails are often used in the sections of the network with less traffic. Sleeper fastenings in reasonable condition are also reused in yards or lightly used lines. Fastenings that are not reusable are recycled.

Maintenance resource use for rail infrastructure was estimated based on the data shown in table 5.12.

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[25] The number replaced during transposing was considered to be negligible and was disregarded.

Table 5.12 Details of the rail track maintenance practices used in this study, based on New Zealand practices

Type of data	Relevant data	Data source
Routine maintenance	Inspections: rail distance 50km/year	Manson 30 July 2010, pers comm
Ballast maintenance	Frequency: Tamping: once a year on primary lines (75%) and once every six years on secondary lines (25%) Cleaning: 20-year intervals. Materials: Ballast aggregate: 5% and 30% replacement material during tamping and cleaning, respectively Transport (mode/distance): Ballast aggregate to rail maintenance yard: • Quarry to yard: 28t truck; distance: 25km • Yard to site: rail; distance: 25km • Waste materials (weeds and fines) to landfill: 28t truck; distance: 25km Machinery use: Changing machine 12hr/km; diesel use 15l/hr Tamping machine 2hr/km; diesel use 15l/hr Cleaning machine 12hr/km; diesel use 15l/hr	Manson 29 March and 22 October 2010, pers comm
Replace sleeper fastenings	Replace pads and spacers with new after 20 years	
Transposing rails (on curves only)	Remove existing fastenings and replace with new Remove rails and re-lay Machinery use: requirements for removal are same as for initial construction (excavator use to remove rails) Waste transport (distance and mode) Rail pads/spacers: to landfill	

5.3 Road and rail infrastructure life cycle externalities

The life cycle inventories identified in sections 5.1 and 5.2 above were used to estimate the lifetime externalities of cumulative energy use (in terms of primary energy), CO_2e GHG emissions, and total contaminant load.

The results discussed in this section are for road and rail infrastructure that are constructed today and maintained according to current practices used in the industry. Unless indicated otherwise, the results for road and rail infrastructure are for one lane-kilometre of road and one single-track kilometre of rail, respectively. Earth-moving to facilitate the construction of infrastructure varies from site to site and therefore two extreme cases have been considered. Australian data was used to estimate the likely externalities of bridges in New Zealand road and rail networks, because of the lack of construction and maintenance details for these structures.

5.3.1 Life cycle externalities of earthworks

Cumulative energy use and GHG emissions for earthworks in difficult (hilly) and easy (flat) terrains are shown in table 5.13. If the average useful life of a pavement is assumed to be 40 years, earth-moving on flat sites annually adds 16GJ/lane-km to the cumulative energy use and releases 1.1tCO_2e/lane-km GHG emissions. On difficult sites, for a pavement with a 40-year useful life, the impact is larger, with an annual addition of 127GJ/lane-km for cumulative energy use and 9tCO_2e/lane-km as GHG emissions.

Table 5.13 Comparison of energy use and emissions due to earth-moving in difficult and easy terrain conditions

Terrain condition	Energy use (GJ/lane-km)	GHG emissions (tCO_2e/lane-km)
Easy (flat)	646	44
Difficult (hilly)	5062	348

5.3.2 Life cycle externalities of bridges

A comparison of carbon emissions factors for New Zealand building materials (Alcorn 2003), fuels and electricity (Barber 2009) and factors used for the Australian study (Maguire 2010) is shown in table 5.14. Australian emissions factors are for CO_2 equivalents. While New Zealand fuel and electricity emissions factors by Barber (2009) are also CO_2 equivalents, building material embodied emissions factors for New Zealand by Alcorn (Alcorn 2003) are only CO_2 emissions. The Australian embodied emissions factors for building materials are from various sources dating from 2003 to 2005.

If electricity and fuel emissions are considered, diesel emissions are similar in both countries, while electricity emissions in Australia are six and a half times those in New Zealand. This could be expected as in 2007, the base year for electricity emissions, 66% of New Zealand electricity was generated from hydro and other renewable sources (MED 2007).

Table 5.14 Comparison of New Zealand and Australian carbon emissions factors for road construction materials, fuels and electricity

Item	CO_2 equivalent emissions		Units	Ratio (Australia/NZ)
	Australia[a]	NZ[b, c]		
Aggregate	0.008	0.0031	tCO_2e/t	2.58
Asphalt	0.01	0.015	tCO_2e/t	0.67
Bitumen	0.05	0.171	tCO_2e/t	0.29
Cement	0.67	0.994	tCO_2e/t	0.67
Concrete	0.258	0.189	tCO_2e/t	1.37
Steel, virgin	2.65	1.242	tCO_2e/t	2.13
Steel, recycled	1.14	0.352	tCO_2e/t	3.24
Electricity	1.31	0.2019	kgCO_2e/kWh	6.49
Diesel	2.9	3.108	kgCO_2e/l	0.93
LPG	1.7	3.357	kgCO_2e/l	0.51

a) A Maguire, Construction Manager, Regional Rail Link Division, Department of Transport, Victoria, Australia, pers comm, January 2010 (Mickleham Road GHG calculations Final 070308.xls).

b) Alcorn (2003).

c) Barber (2009).

The embodied emissions for steel in Australia are two to three times those in New Zealand, depending on whether it is virgin or recycled steel. Steel manufacture is an energy-intensive process, and the difference in emissions is explained by average electricity emissions in Australia, which are 6.5 times those of emissions in New Zealand, and natural gas emissions in Australia, which are 25% higher (Nebel et al 2009, p18) than those in New Zealand.[26] Emissions due to use of Australian natural gas are 53g CO_2e/MJ and those due to use of New Zealand natural gas are73gCO_2e/MJ. Embodied emissions of Australian aggregates are two and a half times those of New Zealand aggregates. This could be attributed to the high reliance on river-sourced aggregate in New Zealand.

The main materials used for bridge construction are aggregates, concrete and steel. Therefore the analysis above suggests that the emissions from concrete bridge construction in New Zealand, using New Zealand materials, are likely to be half those in Australia – ie 0.75t CO_2e/m^2 of bridge deck. Emissions due to bridge construction in New Zealand calculated on this basis are shown in table 5.15.

Table 5.15 Emissions from bridge construction in New Zealand

Category	Sub-category	Bridge length (m)	Deck width (m)	Deck area (m^2)	Emissions (tCO_2e)
State highway bridges		**127,651**	**9**	**1,148,859**	**861,644**
	single-lane	12,648	5	63,240	47,430
	speed-restricted	682	5	3410	2558
	weight-restricted	324	5	1620	1215
	timber	843	5	4215	3161
Local urban road bridges		**61,525**	**9**	**553,725**	**415,294**
	single-lane	140,882	5	704,410	528,308
	speed-restricted	4489	5	22,445	16,834
	weight-restricted	13,577	5	67,885	50,914
	timber	11,786	5	58,930	44,198
Local special-purpose road bridges		**800**	**9**	**7200**	**5400**
	single-lane	2597	5	12,985	9739
	speed-restricted				
	weight-restricted	26	5	130	98
	timber	305	5	1525	1144

On this basis, the total emissions due to bridges on state highways are 916Mt CO_2e, while bridges on urban local roads and special-purpose local roads emit 1056Mt CO_2e and 16Mt CO_2e, respectively. Since bridges are assumed to have an 80-year useful life, contributions by the bridges to state highways, urban local roads and special-purpose local roads are 0.51, 0.38 and 0.20t CO_2e/lane-km/annum respectively.

5.3.3 Life cycle externalities of pavements

5.3.3.1 Unbound granular pavement

Initial construction resource use of unbound granular pavement

Pavement base layers are constructed to last the life of the pavement, and therefore the lifetime resource use is the same as the construction resource use. The wearing course, however, needs to be maintained depending on the traffic. Cumulative energy use and GHG emissions estimates for the construction of one kilometre length of 9m wide road (ie two-lane state highway) with varying foundation thicknesses is shown in table 5.16.

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[26] The composition of gas in New Zealand is different from that in Australia.

Table 5.16 Comparison of energy use and emissions due to initial construction of 9000m^2 of unbound granular pavement with different foundation thicknesses

Foundation thickness (mm)	Pavement structure	Energy use (GJ/9,000m^2)	GHG emissions (t/9,000m^2)
850	Subgrade improvement layer	74 (1%)	21 (5%)
	Base course (200mm) and sub-base (650mm) layers	5819 (96%)	352 (92%)
	Wearing course	145 (2%)	9 (2%)
	TOTAL	**6038**	**382**
675	Subgrade improvement layer	74 (2%)	21 (7%)
	Base course (175mm) and sub-base (500mm) layers	4626 (95%)	280 (90%)
	Wearing course	145 (3%)	9 (3%)
	TOTAL	**4845**	**310**
400	Subgrade improvement layer	74 (3%)	21 (12%)
	Base course (150mm) and sub-base (250mm) layers	2332 (91%)	141 (82%)
	Wearing course	145 (6%)	9 (5%)
	TOTAL	**2551**	**171**

Fuel use for transporting the materials to the site contributes the most to the cumulative energy use (58–60%) and GHG emissions released (59–60%). Contribution from materials to cumulative energy use and GHG emissions is moderate at 19–20% and 20–26% respectively. On-site machinery and its fuel use contribute up to 7% each to cumulative energy and emissions, while the balance comes from transport vehicles.

The majority of cumulative energy use and GHG emissions released as a result of pavement construction is due to foundation (base course and sub-base) layers. Increasing the foundation thickness from 400mm to 850mm (113%) and 675mm (68%) increase the cumulative energy use and emissions by 150% and 98%, respectively. Seventy-seven percent of the cumulative energy use and 78% of emissions for base course and sub-base layers is due to transport. Contribution from materials is moderate at 19% for energy use and 16% for the emissions. The balance is due to on-site machinery use.

For the wearing course, however, transport and materials are the major contributors to cumulative energy (43% and 42% respectively) and emissions (42% and 44% respectively). On-site machinery use contributes 15% to the energy use and 14% to the emissions attributable to the wearing course construction.

The majority of energy use for the subgrade improvement layer is due to on-site machinery use (48%), with a further 28% contribution from materials. Emissions are mainly due to lime (84%), while the contribution of transport is negligible at 5%.

Maintenance resource use for unbound granular pavement

Energy and emissions due to maintenance of the unbound granular pavement over 40 years with different resealing practices (see table 5.2) is shown in table 5.17.

Table 5.17 Comparison of energy use and emissions due to maintenance of 9000m^2 of unbound granular pavement for different levels of traffic over 40 years

Traffic level (vehicles/day)	Maintenance activity	Energy use (GJ/9000m^2)	GHG emissions (t/9000m^2)
10,000	Routine maintenance	526 (31%)	34 (31%)
	Resealing	1182 (69%)	75 (69%)
	TOTAL[a]	**1708**	**109**
5000	Routine maintenance	560 (38%)	36 (38%)
	Resealing	919 (62%)	59 (62%)
	TOTAL[a]	**1479**	**94**
500	Routine maintenance	560 (38%)	36 (38%)
	Resealing	919 (62%)	59 (62%)
	TOTAL[a]	**1479**	**94**

a) Contributory components may not add up, owing to rounding off.

Fuel use for transport contributes the most to the cumulative energy use (53–56%) and GHG emissions released (57–60%). The contribution from materials to cumulative energy use and GHG emissions is moderate at 29–32% and 30–33%, respectively. On-site machinery and their fuel use contribute up to 3–4% to cumulative energy and 3% to emissions. Transport vehicles contribute 11–12% and 7% respectively to energy and emissions due to maintenance.

As pothole-fixing material is assumed to be negligible and is therefore disregarded, routine maintenance energy and emissions are due to transport (ie 28t tray truck use for inspections, and transporting material and machinery).

While 49% of energy use and 47% of emissions due to resealing are attributable to transport, materials contribute 46% to energy and 48% to emissions. The contribution from on-site machinery use to the total resealing energy use and emissions is negligible at 5% each.

5.3.3.2 Structural asphaltic concrete pavement

Initial construction resource use of structural asphaltic concrete pavement

Construction of one kilometre length of 9m wide road with two lanes (ie 2-lane motorway) uses 8027GJ of primary energy and releases 522tCO_2e GHG emissions (see table 5.18).

Table 5.18 Energy and emissions due to construction of 9000m^2 of structural asphaltic concrete pavement for motorway

Pavement structure	Energy use		GHG emissions	
	GJ/9000m^2	%	tCO_2e/9000m^2	%
Subgrade improvement layer	74	1%	21	4%
Base course and sub-base layers	5459	68%	339	65%
Structural asphalt layer	2071	26%	135	26%
Open graded asphalt wearing course	423	5%	28	5%
TOTAL[a]	**8027**		**522**	

a) Contributory components may not add up, owing to rounding off.

Sixty-eight percent of total energy and 65% of total emissions are from the base layers, while the structural asphalt layer and OGPA wearing course contribute 26% and 5% each, respectively, to the total energy use and emissions. Subgrade improvement with lime contributes the balance of 1% to the total energy use and 4% to the total emissions.

For the subgrade improvement, lime contributes 28% to the cumulative energy use and 84% to the emissions. Transport energy use is 24%, with transport emissions being only 5%. On-site machinery use to spread lime and mill, mix and compact the subgrade contributes 48% to the total energy use, but only 11% to the total emissions.

Because of the need to transport large volumes of aggregate, transport is a significant contributor to the energy use (77%) and emissions (79%) of the construction of base layers (sub-base and base course). However, as aggregate production is low in process requirements, aggregate contributes only 18% and 15%, respectively, to the total energy use and emissions from base layers. On-site machinery use is marginal, contributing 5% and 6% respectively to the cumulative energy use and emissions due to the construction of base layers.

For both the structural asphalt layer and the OGPA wearing course, construction materials are a significant contributor to energy use and emissions. Materials contribute 65% and 67% respectively to the total energy and emissions as a result of the construction of the structural asphalt layer, while materials also contribute 64% and 66% respectively to the total energy and emissions from construction of the OGPA wearing course. Seven litres of fuel (diesel) is required to mix the ingredients of a tonne of asphalt. Fuel use contributes over 41% and 39% to the total energy and emissions for structural asphalt and OGPA layers, respectively. The contribution from transport is significant, at roughly a third of the total energy and emissions from both structural asphalt layer and OGPA wearing course construction. On-site machinery uses for both of these layers are marginal, at 3% each (structural asphalt) and 5% each (OGPA) for energy and emissions.

Maintenance resource use of structural asphaltic concrete pavement

Energy and emissions due to maintenance of structural asphalt pavement over 50 years are as shown in table 5.19.

Table 5.19 Energy and emissions due to maintenance of 9000m^2 of structural asphaltic concrete pavement over 50 years

Maintenance activity	**Energy use**		**GHG emissions**	
	GJ/9000m^2	**%**	**tCO$_2$e/9000m^2**	**%**
Routine maintenance	423	14%	27	13%
Milling and replacing wearing course	2660	86%	174	87%
TOTAL	**3083**		**201**	

The wearing course is milled and replaced with new materials at intervals of eight years. This contributes 86% to the energy use and 87% to the emissions due to maintenance.

If milling and replacing the OGPA wearing course is considered, the contribution by materials and transport to the total energy use is significant, at 61% and 29% respectively. In terms of total emissions, the contributions are 63% (materials) and 28% (transport). The contribution of on-site machinery use is moderate at 10% and 9%, respectively, to the total energy and emissions attributable to milling and replacing the OGPA layer.

The contribution by the materials to the total energy use and emissions due to maintenance is 53% and 55% respectively, while transport contributes 39% to energy use and 37% to emissions.

Lifetime resource use of structural asphaltic concrete pavement

Lifetime resource use by the structural asphalt pavement is shown in table 5.20. Lifetime resource use is more dependent on the initial construction than on the maintenance of the pavement. If structural asphaltic concrete pavement is assumed to last 50 years, the annual energy and emissions due to 9000m^2 area of pavement are 222.2GJ/year and 14.5tCO_2e/year, respectively.

Table 5.20 Lifetime energy and emissions due to 9000m^2 of structural asphalt pavement, based on life stage

Construction stage	Lifetime energy		Lifetime emissions	
	GJ/9000m^2	**%**	**tCO_2e/9000m^2**	**%**
Initial construction	8027	72%	522	72%
Maintenance	3083	28%	201	28%
TOTAL[a]	**11,109**		**723**	

a) Contributory components may not add up, owing to rounding off.

Over 90% of the lifetime energy use and emissions due to structural asphalt pavement are attributable to materials and transport (see table 5.21).

Table 5.21 Lifetime energy and emissions due to 9000m^2 of structural asphalt pavement based on resource use category

Resource use	Lifetime energy		Lifetime emissions	
	GJ/9000m^2	**%**	**tCO_2e/9000m^2**	**%**
Materials	4251	38%	287	40%
Transport	6248	56%	395	55%
On-site machinery	610	5%	41	5%
TOTAL	**11,109**		**723**	

5.3.3.3 Pavements with unsealed wearing course

As shown in table 2.2, some pavements in the network use unsealed wearing courses. This construction includes a 50mm layer of loose aggregate wearing course built on an unbound granular pavement suitable for low traffic. Because of erosion as a result of vehicle traffic and weathering, a 15mm thick layer of wearing course needs to be replaced annually, in addition to reshaping and smoothing the surface four times a year. On this basis, the annualised energy and emissions for a 9000m^2 area of an unbound granular pavement with an unsealed wearing course would be 1211.7GJ/year and 74.9tCO_2e/year over the 40-year lifetime.

Table 5.22 Lifetime energy and emissions due to 9000m^2 of unbound granular pavement with an unsealed wearing course over 40 years

Pavement structure	Energy use		GHG emissions	
	GJ/9000m^2	%	tCO$_2$e/9000m^2	%
Subgrade improvement layer	74	0.2%	21	0.7%
Base course and sub-base layers	2332	5%	141	4%
Unsealed wearing course	160	0.3%	10	0.3%
Total for initial construction	2566	5%	172	5%
Maintenance	45,904	95%	2825	90%
TOTAL for lifetime[a]	**48,470**		**2,996**	

a) Contributory components may not add up, owing to rounding off.

5.4 Lifetime resource use by the road network

Pavement and wearing course construction types and the lane widths of the existing road network are assumed as shown in table 5.23.

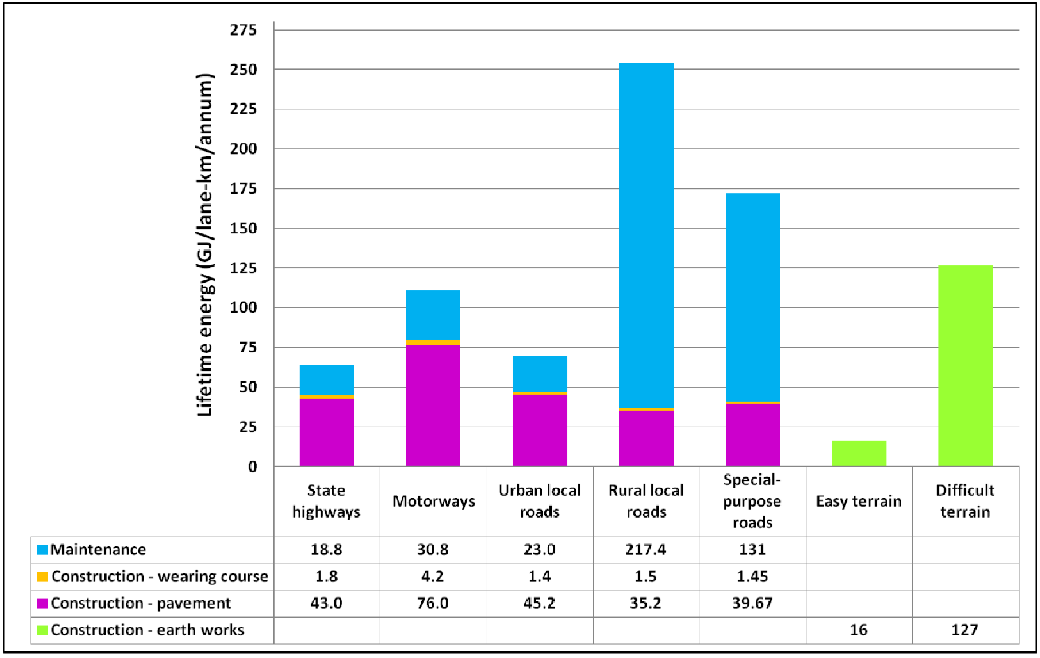
Table 5.23 Road network statistics used for resource use estimates

Road category	Lane length (km)	Pavement construction type	Wearing course type	Notes
State highways	22,645	Flexible unbound granular	Chipseal (100%)	Lane width 3.5m with 1.0m shoulder 99.5% of length is sealed; modelled as 100% sealed
Motorways	431	Structural asphaltic	Asphalt	Lane width 3.5m with 1.0m shoulder
Local urban roads	34,639	Flexible unbound granular	Chipseal (98% of length)	Lane width 3.5m, no shoulders
Local rural roads	117,914		Chipseal (53% of length)	
Special-purpose roads	1001		Chipseal (73% of length)	

5.4.1 Lifetime energy use of existing road network in New Zealand

A comparison of lifetime energy use estimated on this basis for a single lane-kilometre of different road categories per annum is shown in figure 5.3. Bridges and earthworks have not been included in these because of insufficient data.

Figure 5.3 Comparison of lifetime energy use by different road categories (GJ per lane-km per annum)



	State highways	Motorways	Urban local roads	Rural local roads	Special-purpose roads	Easy terrain	Difficult terrain
🟦 Maintenance	18.8	30.8	23.0	217.4	131		
🟨 Construction - wearing course	1.8	4.2	1.4	1.5	1.45		
🟪 Construction - pavement	43.0	76.0	45.2	35.2	39.67		
🟩 Construction - earth works						16	127

Lifetime energy use from the construction and maintenance of the pavement structures is dwarfed by the energy use for earth-moving, especially in difficult terrains. In easy terrains (flat sections), earthworks contribute 20% and 13% respectively to the lifetime energy use of state highways and motorways, and 19%, 6% and 9% to urban local, rural local and special-purpose roads respectively. Energy use for earth-moving in difficult terrain is twice as much as the lifetime energy use of a motorway. In difficult terrain (hilly sections), earthworks contribute 67%, 53% and 65% to the lifetime energy use of state highways, motorways and urban local roads respectively. For rural local roads and special-purpose roads in hilly conditions, earthworks contribute 33% and 42% respectively.

Both state highways and motorways use 4.5m wide lanes (including shoulders), with unbound granular construction and structural asphalt construction, respectively. Lifetime energy use (excluding the earthworks) for structural asphalt construction is 75% higher than that for unbound granular construction. Local urban, local rural and special-purpose roads use 3.5m wide lanes. However, lifetime energy use for a local urban road is only 10% lower than that for a state highway, while local rural and special-purpose roads are 299% and 171%, respectively, higher than the value for a state highway. While maintenance contributes 33% to the lifetime energy use of local urban roads, contributions by maintenance to the total for rural local and special-purpose roads are 86% and 76%, respectively.

Local urban, local rural and special-purpose roads have the same lane width. Lifetime energy use is significantly higher for local rural and special-purpose roads because of the higher use of unsealed surfaces with higher maintenance requirements. Lifetime energy use for different road categories is shown in table 5.24.

Table 5.24 Lifetime energy use for different road categories for a single lane-kilometre per annum – excluding earthworks and bridges (GJ per lane-km per annum)

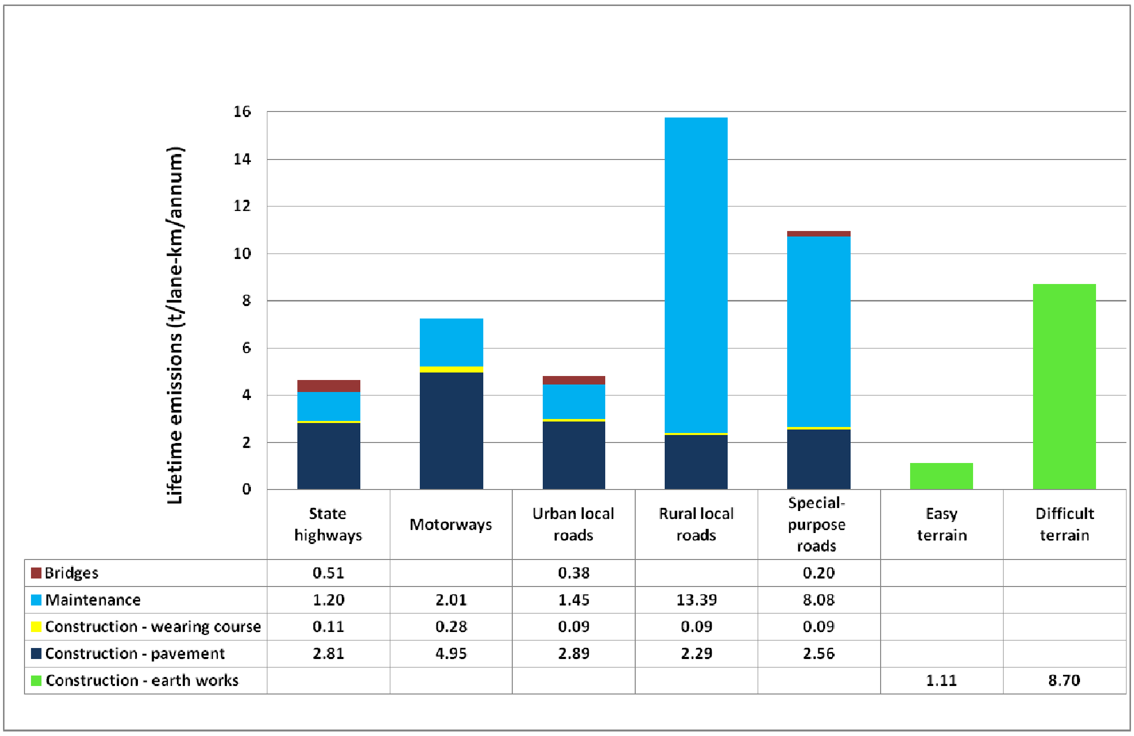
Item	State highways	Motorways	Urban local roads	Rural local roads	Special-purpose roads
Construction, pavement	43.0	76.0	45.3	35.2	39.67
Construction, wearing course	1.8	4.2	1.4	1.5	1.45
Maintenance	18.8	30.8	23.0	217.4	131.0
TOTAL[a]	**63.6**	**111.1**	**69.7**	**254.1**	**172.1**

a) Contributory components may not add up, owing to rounding off.

5.4.2 Lifetime GHG emissions of the existing road network in New Zealand

A comparison of lifetime GHG emissions established based on the road network statistics (see table 5.25) is shown in figure 5.4. As shown in table 5.15, bridges on state highways, urban local roads and special-purpose roads are 1.2×10^6, 1.4×10^6 and 21,840 m^2, respectively. These have been included in the estimates although, because of uncertainty of original terrain conditions, earthworks have not been included.

Figure 5.4 Comparison of lifetime emissions by different road categories (tCO_2e per lane-km per annum)



	State highways	Motorways	Urban local roads	Rural local roads	Special-purpose roads	Easy terrain	Difficult terrain
🟥 Bridges	0.51		0.38		0.20		
🟦 Maintenance	1.20	2.01	1.45	13.39	8.08		
🟨 Construction - wearing course	0.11	0.28	0.09	0.09	0.09		
■ Construction - pavement	2.81	4.95	2.89	2.29	2.56		
🟩 Construction - earth works						1.11	8.70

GHG emissions follow a pattern similar to that of energy use. When constructed in difficult terrain, the construction type has limited impact on the lifetime emissions of all roads other than rural local roads and special-purpose roads.

Bridges contribute 11% to the lifetime emissions of state highways and 8% to lifetime emissions of urban local roads. The contribution by bridges to the total emissions of special-purpose roads is only 2%. Motorways with structural asphaltic construction contribute 56% more emissions than state highways with unbound granular construction. Owing to the increased use of unsealed surfaces, the lifetime emissions are also significantly higher for local rural and special-purpose roads than for local urban roads with the same road width. In comparison with state highways, local rural and special-purpose roads release 241% and 136% (respectively) higher lifetime emissions. Lifetime emissions for different road categories are shown in table 5.25.

Table 5.25 Lifetime emissions due to different road categories for a single lane-kilometre per annum (t CO_2e per lane-km per annum)

Item	State highways	Motorways	Urban local roads	Rural local roads	Special-purpose roads
Construction, pavement	2.81	4.95	2.89	2.29	2.56
Construction, wearing course	0.11	0.28	0.09	0.09	0.09
Maintenance	1.20	2.01	1.45	13.39	8.08
TOTAL[a]	**4.12**	**7.23**	**4.43**	**15.77**	**10.73**

a) Contributory components may not add up, owing to rounding off.

5.4.3 Contaminant delivery due to existing road network

According to Timperley et al (2005), 90g of suspended solids are delivered to water bodies by a square metre of road area in a year. On that basis, suspended solids transported to water bodies by different road categories are calculated and shown in table 5.26.

Table 5.26 Suspended solid transported to water bodies by different road categories for a single lane-kilometre per annum (kg per lane-km per annum)

Road category	Rate of release (kg/lane-km/annum)
State highway	405
Motorway	405
Urban local road	315
Rural local road	315
Special-purpose road	315

The total quantity of suspended solids released by the road network in a year on this basis is 57.7kt/year (327kg/lane-km). Unlike energy and emissions, the impact of contaminants attributable to transport infrastructure depends on the condition of the receiving environment. Therefore contaminants are likely to cause impacts in sensitive sites but not in others.

5.5 Comparison of results with other studies

New Zealand roads use flexible constructions[27] that are low in initial construction requirements but high in maintenance requirements, and because of this, transport becomes a significant contributor to the total energy and emissions from road infrastructure. Transport resource use in the above analyses is modelled based on the fuel use of the transport industry (Bennett 2008). This reflects the actual driving conditions and performance of vehicles in New Zealand.

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[27] Rigid constructions are not appropriate for New Zealand's young soil.

A comparison of fuel usage and fuel factors (energy and emissions per litre of fuel) for European low-sulphur diesel and New Zealand diesel[28] and the impact of these on the lifetime energy and emissions of a unit length of two-lane state highway are shown in table 5.27.

Table 5.27 Lifetime energy and emissions of a kilometre length of two-lane state highway calculated using New Zealand industry data and European data

	Fuel use	Fuel factor (energy and emissions per litre of fuel)		Primary energy	GHG emissions
	l/km	MJ/l	kgCO_2e/l	MJ/lane-km/annum	tCO_2e/lane-km/annum
European fuel, NZ fuel usage – construction machinery, roads and vehicles excluded	0.45–0.55	29.65	2.046	48.74	3.46
NZ fuel, NZ fuel usage – construction machinery, roads and vehicles excluded	0.45–0.55	45.2	3.108	56.79	4.01
European fuel, European fuel usage – construction machinery, roads and vehicles included	0.16–0.37	29.65	2.046	119.26	7.46
NZ fuel, European fuel usage – construction machinery, roads and vehicles included	0.16–0.37	45.2	3.108	131.60	8.30
NZ fuel, NZ fuel usage – construction machinery, roads and vehicles included	0.45–0.55	45.2	3.108	197.54	12.57

According to ecoinvent data, New Zealand fuel consumption is higher than the fuel use of similar vehicles in Europe. Further, the EE and GHG emissions of New Zealand diesel are 52% higher than the emissions reported for diesel used in Europe. The fuel consumption of large vehicles used in New Zealand is 33% more than that for similar vehicles in Europe, while for smaller vehicles it is about 64% higher.

The use of New Zealand fuel factors increases lifetime energy and emissions by 17% and 16% respectively compared with European fuel factors, if construction machinery, vehicles to transport materials and machinery during construction and maintenance, and roads on which these vehicles travel, are excluded.[29] Once all these are included, the impact of fuel factors reduces to 10% and 11% respectively, for lifetime energy and emissions. Contribution to the total due to variation in fuel use is much larger, at 50% and 51% respectively, for lifetime energy and emissions.

Treloar et al (2004, p47) estimated the construction energy use of various road construction types used in rural locations in Australia, using hybrid[30] LCA. Granular construction used in Treloar et al's study is similar to the unbound granular construction discussed here. Treloar et al estimated 4220GJ/lane-km for the initial construction energy of granular construction.

Based on data shown in table 5.24, the initial construction energy for a kilometre length of New Zealand roads ranges from 1460GJ for rural local roads to 1790GJ for state highway (lane-km). (The construction energy of the motorway using structural asphaltic construction is 4010GJ.) Hence, compared with Treloar et al's 2004 estimate, the New Zealand estimates in this study seem low. However, as discussed earlier (see section 5.3.2), Australian EE and emissions of road construction materials are twice those in

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[28] It is assumed that 1 litre of European and New Zealand diesel weighs 0.536kg.

[29] Only material and on-site fuel use by machinery is considered.

[30] Combination of process analysis and economic input–output analysis.

New Zealand. In addition, Treloar et al used a hybrid assessment that is a combination of process analysis and economic input–output (EIO) analysis. EIO-based LCA captures wider economic activities that are not included in the process-based assessment that was used in this study. Using the EIO assessment, however, can lead to unreliable estimates for New Zealand, as New Zealand input–output tables use a higher level of aggregation.

In their hybrid LCA of US roads, Chester and Horvath (2009) estimated the initial construction energy and emissions for a lane-kilometre as 2500GJ and 200t CO_2e, respectively. Based on data shown earlier in table 5.25, the initial construction emissions for a kilometre length of New Zealand roads ranges from 95t CO_2e per lane-km for rural local roads to 260t CO_2e for motorways.

Based on Santero and Horvath's information (2009a), the life cycle emissions of roads range from 80–498t CO_2e/lane-km (see table 2.3). Life cycle emissions for a kilometre length of New Zealand roads range from 165t CO_2e for state highways to 631t CO_2e for rural local roads (see table 5.25). The life cycle emissions of rural local roads (631t CO_2e) are higher than emissions estimated in international studies, owing to the use of unsealed surfaces that require high levels of maintenance.

Embodied resources of machinery contribute 1% to the lifetime energy use and 2% to the lifetime emissions of motorway construction. This is in agreement with Browne's (2008) estimate of 1.6% of construction energy for the projects she considered.

The average energy use and emissions due to a kilometre length of road in New Zealand, established based on the existing network characteristics, are shown in table 5.28. The average energy use of the road network is 193GJ/lane-km/annum, while the average GHG emissions are 12t CO_2e/lane-km/annum. At the time of this research, 32% of the total length of pavements (in terms of lane length) was unsealed. If the total network were to be sealed, average energy use and GHG emissions could be reduced to 126GJ/lane-km/annum and 8t CO_2e/lane-km/annum, respectively. This could further reduce the energy use and emissions associated with pavements, as traffic delays[31] through wearing course maintenance would be avoided.

Table 5.28 Average EE and GHG emissions of a unit length of New Zealand road – earthworks excluded

Road type	Lane length (km)	Pavement construction type	Wearing course type	EE (GJ/yr)	GHG (tCO_2e/yr)
State highways	22,645	Flexible unbound granular	Chipseal (100%)	1,440,659	104,727
Motorways	431	Structural asphalt	Asphalt	47,882	3116
Local urban roads	34,639	Flexible unbound granular	Chipseal (98% of length)	2,413,509	166,722
Local rural roads	117,914		Chipseal (53% of length)	29,957,640	1,859,739
Special-purpose roads	1001		Chipseal (73% of length)	172,217	10,739
Total for all types of roads[a]				34,031,908	2,145,044
Total for a unit length (km) per annum				192.67GJ/km/yr	12.14tCO_2e/km/yr

a) Contributory components may not add up, owing to rounding off.

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[31] Traffic delays have not been included in the above estimates.

5.6 Sensitivity of results to the assumptions used

The thickness of unbound granular pavement foundation (base course and sub-base layers) can range from 400–850mm, depending on the site conditions. For this research, the base case used (on expert advice) a combination of thicknesses for state highway construction (see table 5.1). Two extreme scenarios, where the state highway is constructed of either 850mm or 400mm foundation, were considered in order to test the sensitivity of this assumption.

As aggregate is the single largest volume of material used in unbound granular road construction in New Zealand, the aggregate's transport distance can influence the liabilities. Maximum (100km) and minimum (0km) aggregate transport distances were therefore considered.

Depending on the location of the construction site, the transport distance for bitumen can also range from 30–200km. As a consequence, the minimum (0km) and maximum (200km) bitumen transport distances were considered.

Table 5.29 EE and GHG emissions due to a single lane-kilometre of New Zealand road under different scenarios over 40 years of useful life – earthworks excluded

Scenario	Embodied energy		Embodied GHG emissions	
	GJ	GJ/annum	tCO_2e	tCO_2e/annum
Base case	7710	192.7	486	12.14
State highway constructed with 850mm thick foundation	7880	197	499	12.40
State highway constructed with 400mm thick foundation	7642	188.4	484	12.04
Aggregate transport distance 100km	28,399	710	1761	44.01
Aggregate source besides the construction site (transport 0km)	813	20.3	61	1.52
Bitumen transport distance 200km	7786	194.6	491	12.26
Bitumen source besides the construction site (transport 0km)	7696	192.3	485	12.12

Note: Annualised values may be different, owing to rounding of total energy and emissions.

While the state highway foundation thickness and bitumen transport distance impact the results marginally, aggregate transport significantly impacts the liabilities.

5.7 Rail infrastructure life cycle externalities

5.7.1 Rail tracks

5.7.1.1 Rails

Steel rails for tracks are produced in China. As energy use and emissions attributable to Chinese steel imported to New Zealand are not published, these had to be derived. Price et al (2001) studied steel manufacturing in China based on 1996 industry practices. Although actual production processes could have changed since then, leading to improvements in energy efficiency and a reduction in emissions attributable to the Chinese steel-manufacturing processes, this study uses their figures in the absence of better-quality data.

According to Price et al (ibid), the average energy use for steel produced in China is 36.7GJ/tonne. The theoretical energy use (based on the production technology used in China) for the production of recycled steel is 40% that of virgin steel. The majority of scrap steel used in recycled steel production comes to China from the US. Therefore, the transport of scrap steel using sea freight (from New York to Shanghai; 19,250km) has been added. Ships are assumed to carry other goods on the return journey to US. Inland transport of steel scrap in both the US[32] (scrap yard to port) and in China (port to manufacturing plant; 2700km), using rail, is also included.

Emissions are calculated using the Chinese energy mix for steel production (coal 75%, fuel oil 7%, gas 8% and electricity 10%); transport of scrap from the US to China (sea freight) and land transport of scrap in both the US and China (by rail) are included.

As the average transport distance of scrap steel within the US is not published, the impact of scrap transport over different distances within the US on the energy and emissions embodied in recycled steel produced in China was investigated, and is shown in table 5.30. Since rail is the transport mode, the variation in distance has only a marginal impact on the energy and emissions of recycled steel.

Table 5.30 Energy and emissions embodied in recycled steel produced in China, with varying scrap transport distances within the US

Transport distance (km)	Embodied energy (MJ/kg)	Embodied emissions (kgCO$_2$e/kg)
100	19.57	2.08
500	19.88	2.10
1000	20.26	2.13

Once it is produced, recycled steel has to be formed into rails. According to ecoinvent data, the manufacturing process for metal products uses, on average, 0.99 times the energy of the steel-manufacturing process and releases 1.12 times the emissions. This includes the loss of steel during processing and use of average processing machinery.

Welding rails to form longer lengths is not included, owing to lack of data.

5.7.1.2 Sleepers

Sleepers are manufactured in Christchurch and Hamilton, New Zealand. Resource use is assumed to be similar for sleepers produced in both locations, and calculations are based on the manufacturing practices used at the Christchurch facility.

Transport of concrete from Allied Concrete Ltd to the manufacturing plant (over 5km by 28t truck) is included. Reinforcing steel is sourced from Asia (assumed to be recycled Chinese steel). Shipping of steel from Guangzhou, China, to Lyttelton, New Zealand, and 40t truck transport from the New Zealand port to manufacturing plant, is included. Land transport within China by rail is also included.

Energy and emissions due to manufacture of sleepers are assumed to be similar to that of precast double-tee beams. The energy required to handle and mix precast concrete and to vibrate forms in New Zealand is reported as 0.071MJ/kg (Jacques 2001). Emissions due to the manufacturing process are estimated based on the energy mix (electricity 0.039MJ/kg and diesel 0.032MJ/kg) used.

Fixing shoulders are imported from South Australia. The finished product is shipped from Adelaide to Lyttelton, New Zealand. Transport from factory to port in Australia (9km) and from Lyttelton port to manufacturing plant (13km), using a 40t truck, is also included. In addition to steel used to manufacture

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[32] Owing to lack of data, a distance of 500km is assumed.

fixing shoulders, manufacturing process requirements and steel losses during the process are also included.

Sleeper fastenings are imported to New Zealand from New South Wales in Australia. In addition to steel and plastic used for fastenings, manufacturing requirements and material losses are included.

In the North Island, the maximum distance for transporting concrete sleepers from their point of manufacture to where they are used is approximately 300km, although the distance is much shorter in many cases. The average distance sleepers are transported from the rail yard to the construction site, using a rail wagon, is considered to be 200km.[33]

The requirement for ballast material is estimated based on a flat, straight track.

Initial construction resource use for rail tracks

Resource use for the initial construction of rail tracks, on this basis, is shown in table 5.31.

Table 5.31 Energy and emissions due to construction of 1km length of single rail track

Item	EE (GJ)	%	GHG emissions (tCO_2e)	%
Rails				
Two steel rails (2000m length)	3437.97	91%	406.62	95%
Transport, factory in China to rail depot in Auckland	319.93	8%	18.63	4%
Transport from NZ depot to construction site	5.41		0.54	
Rail-laying machinery – fuel use	1.81		0.12	
TOTAL for rails	**3765**		**426**	
Sleepers				
Sleepers (#1538) at manufacturing plant	1147.17	88%	101.45	87%
Transport from plant to construction site	149.84	12%	14.81	13%
Sleeper-laying machinery – fuel use	1.80		0.12	
TOTAL for sleepers	**1299**		**116**	
Sleeper fastenings				
Steel Pandrol e-clips (#6152)	358.21	79%	11.45	69%
HDPE pads (#3076)	49.01	11%	1.48	9%
Nylon spacer (#6152)	44.88	10%	3.40	21%
Transport, Australian factory to Auckland rail depot	3.83		0.24	
Transport from NZ rail depot to site	0.3		0.03	
TOTAL for sleeper fastenings	**456**		**17**	
Ballast				
Aggregate, (2542t) delivered to rail depot	152.51	16%	7.88	13%
Transport from quarry to yard	648.69	69%	41.28	66%
Transport from yard to site	137.57	15%	13.6	22%
Ballast-spreading machinery fuel use	0.45		0.03	
TOTAL for ballast forming	**939**		**63**	

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[33] This is based on average rail distances from Middleton to Picton, and Ngakawau and Invercargill.

Item	**EE (GJ)**	**%**	**GHG emissions (tCO_2e)**	**%**
Rails	3765	58%	426	69%
Sleepers	1299	20%	116	19%
Sleeper fasteners	457	7%	17	3%
Ballast	939	15%	63	10%
Total for initial construction[a]	**6460**		**622**	
Materials	5190	80%	532	86%
Transport	1266	20%	89	14%
Machinery and fuel use	4		0.28	
Total[a]	**6460**		**622**	

a) Contributory components may not add up, owing to rounding off.

The construction of one kilometre length of single track uses 6460GJ of primary energy and releases 622tCO_2e. Fifty-eight percent of the total energy use is due to rails, while sleepers and fastenings together are responsible for 27% of total energy use. Ballast is responsible for the remaining 15% of the energy use. Emissions follow a pattern similar to that for energy use, with rails contributing 69% to the total, sleepers and fastenings together contributing 22%, and ballast construction contributing only 10%.

The majority of energy use and emissions attributable to rail track components are due to materials used for track components. However, transporting track components from the Auckland rail depot to a local yard, by rail, is not included as it is likely to be negligible. For ballast construction, which involves transporting large volumes of aggregate, energy use and emissions due to materials are modest, at 16% and 13% respectively, while transport is the most significant contributor, at 84% and 88% respectively. Track-construction machinery and fuel use is negligible.

Maintenance resource use of rail tracks

Maintenance requirements depend on whether the track is primary rail or secondary rail (see table 5.12). It is assumed that primary rail tracks are renewed once during their 40-year life, while secondary tracks are renewed twice during their 60-year life. In addition, secondary track sleepers are replaced 50 years after construction.

Maintenance of one kilometre length of the primary rail single track uses 2421GJ of primary energy and releases 158tCO_2e GHG emissions (see table 5.32).

Table 5.32 Energy and emissions due to maintenance of 1km length of primary rail single track

Item	**EE (GJ)**	**EE (%)**	**GHG (tCO_2e)**	**GHG (%)**
Ballast tamping	1922	79%	129	81%
Ballast cleaning	298	12%	20	13%
Replacing rail pads	49	2%	2	1%
Rail transposing	148	6%	6	3%
Maintenance of wagons and track machinery	4		3	2%
TOTAL for maintenance[a]	**2421**		**158**	
Material	545	23%	25	16%
Transport	1810	75%	126	80%
Track machinery, maintenance of wagons, and fuel use	66	3%	7	4%
TOTAL for maintenance[a]	**2421**		**158**	

a) Contributory components may not add up, owing to rounding off.

Seventy-nine percent of the maintenance energy use and 81% of emissions are due to ballast tamping and replenishing ballast aggregate, while ballast cleaning (once during the 40-year life) contributes 12% and 13% respectively to energy use and emissions. Transposing rail in the curved sections (36% of the length), where left and right rails are swapped over, contributes 6% and 3% respectively to energy use and emissions.

Transport is the most significant contributor to maintenance energy and emissions, with 75% and 80% contribution, respectively.

Maintenance of one kilometre length of secondary rail single track uses 2745GJ of primary energy and releases 203tCO_2e GHG emissions (see table 5.33).

Table 5.33 Energy and emissions due to maintenance of 1km length of secondary rail single track

Item	**EE (GJ)**	**EE (%)**	**GHG (tCO_2e)**	**GHG (%)**
Ballast tamping	467	17%	31	15%
Ballast cleaning	580	21%	39	19%
Replacing rail pads	99	4%	3	1%
Replacing sleepers	1301	47%	117	57%
Rail transposing	296	11%	11	5%
Maintenance of wagons and track machinery	4		3	1%
TOTAL for maintenance[a]	**2745**		**203**	
Material	1696	62%	123	16%
Transport	979	36%	73	80%
Track machinery, maintenance of wagons, and fuel use	70	2%	7	4%
TOTAL for maintenance[a]	**2745**		**203**	

a) Contributory components may not add up, owing to rounding off.

Forty-seven percent of the maintenance energy use and 57% of emissions are due to sleeper replacement. However, the sleepers still have 40 years of residual life left at the end of the useful life of secondary rail track. Ballast cleaning twice during the 60-year life contributes 21% and 19% respectively to maintenance energy use and emissions, while ballast tamping also contributes 17% and 15%, respectively. Transposing rail in the curved sections (36% of the length) contributes 11% and 5% respectively to energy use and emissions. Replacing rail pads and machinery use for maintenance are negligible.

According to McGimpsey et al (2009, p31) pollution of water and land attributable to the rail network and its operations is low. The current track construction with ballast is similar to a continuous swale, and therefore contaminant delivery to water bodies by the rail network is disregarded.

5.7.1.3 Lifetime resource use for rail tracks

Lifetime resource use for primary and secondary rail single track is shown in table 5.34.[34] The residual life of concrete sleepers has been deducted in this estimate and therefore represents the actual resource use, rather than locked resources. Lifetime resource use is heavily dependent on initial construction, which contributes over 70% to the lifetime energy use and emissions of rail tracks. Similarly, materials make a significant contribution (over 65%) to both lifetime energy use and emissions. Contribution by on-site machinery use is negligible, at 1% each to lifetime energy and emissions.

Table 5.34 Lifetime energy and emissions due to rail track construction and maintenance

	Lifetime energy		Lifetime emissions	
Primary rail				
Initial construction	6200	72%	598	79%
Maintenance	2421	28%	158	21%
TOTAL for 40 years[a]	**8620**	**GJ/km**	**756**	**t/km**
Material	5505	64%	537	71%
Transport	3045	35%	212	28%
On-site machinery	70	1%	7	1%
TOTAL	**8620**	**GJ/km**	**756**	**t/km**
Externalities per annum	**215.51**	**GJ/km/yr**	**18.91**	**t/km/yr**
Secondary rail				
Initial construction	6459	79%	622	85%
Maintenance	1704	21%	110	15%
TOTAL for 60 years	**8164**	**GJ/km**	**732**	**t/km**
Material	5968	75%	575	79%
Transport	2124	24%	150	20%
On-site machinery	72	1%	7	1%
TOTAL[a]	**8164**	**GJ/km**	**732**	**t/km**
Externalities per annum	**136.06**	**GJ/km/yr**	**12.19**	**t/km/yr**

a) Contributory components may not add up, owing to rounding off.

5.7.2 Rail bridges and tunnels

Mainly because of the lack of data, secondary sources were used to estimate resource uses of rail bridges and tunnels. In a study of high-speed rail in Europe, Tuchschmid (2009) evaluated carbon emissions from

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[34] This is rail track only, without rail bridges and tunnels.

rail track, tunnels and bridges. According to his estimates, in terms of carbon-equivalent life cycle emissions, road bridges are similar to rail tunnels and approximately equal to one-third of rail bridges.[35] This relationship was used to derive the emissions from rail bridges and tunnels.

In New Zealand, emissions from road bridges are $0.75tCO_2e/m^2$ (see section 5.3.2). On this basis, a one-metre length of single-track rail tunnel ($1.067m^2$) and a one-metre length of single-track rail bridge release $0.8tCO_2e/m$, and $2.4tCO_2e/m$, respectively.

Similar data was not available to establish the lifetime energy use of rail bridges and tunnels.

If the lifetime GHG emissions from bridges and tunnels established in section 5.7.2 are included, emissions from primary and secondary rail tracks increase to $20.28tCO_2e$/km/annum and $13.15tCO_2e$/km/annum, respectively. The contribution to the total GHG emissions of a kilometre length of track by bridges (5%) and tunnels (2%) is 7%.

Seventy-five percent of the existing New Zealand rail network is considered to be primary track, with the balance being secondary track. The total length of the network is 4190km of single track (with a 241km section that is double tracked). On this basis, the EE of the rail track (without the energy use by bridges and tunnels) is 195.65GJ/km/annum, while embodied GHG emissions are $18.49tCO_2e$/km/annum (including the emissions from bridges and tunnels).

5.7.3 Sensitivity of results to the assumptions used for rail tracks

The transport distance for scrap steel within the US is not published. The base case used a 500km distance. The impact of scrap steel transport was evaluated using two scenarios where distance was reduced to 100km or increased to 1000km.

Steel rails are dispatched either from Guangzhou or from Shenzhen ports in China (see section 5.2.1.1). The discharge port selection impacts on the distance rails need to be transported (by Chinese rail and transoceanic shipping). The base case used Guangzhou as the discharge port, so the sensitivity of results to the discharge port selection was tested.

The steel energy and emissions factors used in the base case are based on the industry average reported by Price et al (2001). However, these factors are based on the production practices and fuel mix that were used in 1996. Price and others reported that the use of best practice in production could reduce the energy and emissions intensity by 45% of the average (op cit, pp21, 24). The impact of purchasing steel from a factory with the best practice in steel production was tested.

Ballast replacement makes a significant contribution to the maintenance requirements. The transport distance of ballast aggregate can influence the liabilities. Therefore, the maximum (100km) and minimum (0km) ballast aggregate transport distances were considered.

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[35] The GHG emissions reported by Tuchschmid (2009) are as follows: road bridges 69.21kg/m/annum, tunnels 78.79kg/m/annum, rail bridges 186.09kg/m/annum. Bridges and tunnels are assumed to last 100 years.

Table 5.35 Energy use and emissions due to a single track-kilometre of New Zealand rail under different scenarios – bridges and tunnels excluded

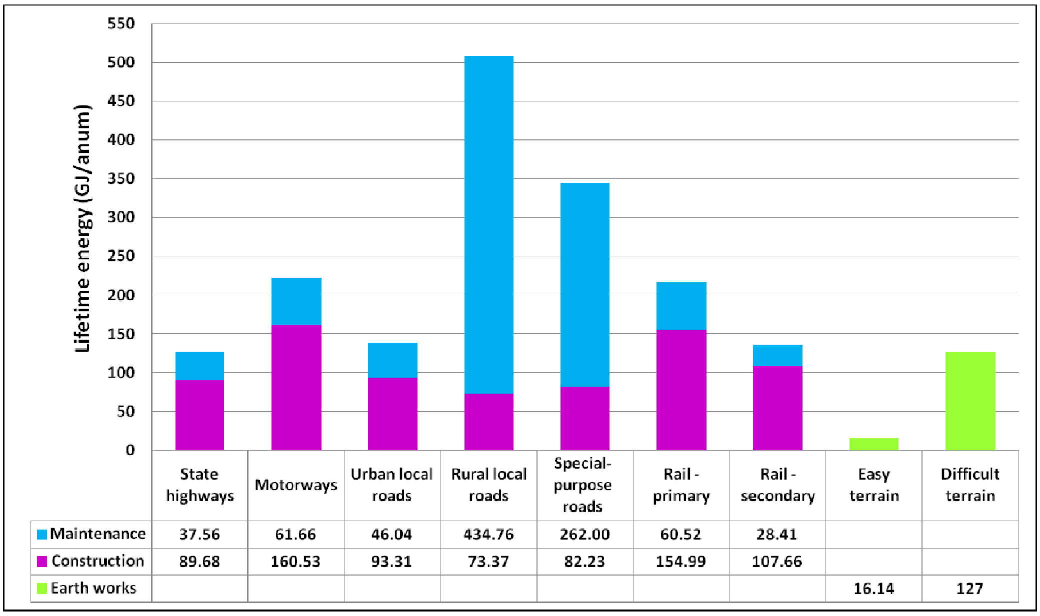
Scenario	Embodied energy		Embodied GHG emissions	
	GJ	GJ/annum	tCO_2e	tCO_2e/annum
Base case	8506	195.65	806	18.49
Scrap steel transported 1000km	8548	196.60	808	18.56
Scrap steel transported 100km	8473	194.88	803	18.44
Steel rails shipped from Shenzhen	8505	195.62	805	18.49
Steel production using best practice	7531	173.36	702	15.57
Aggregate transport distance 100km	14,320	332.68	1175	27.21
Aggregate source beside the rail yard	6568	149.97	682	15.59

The source of scrap steel for recycled steel manufacture and the dispatch port in China have only marginal impact on the EE and emissions for rail infrastructure. Selecting a production facility that uses the best practice has a moderate effect, with 11% and 13% reduction in energy use and emissions of rail infrastructure, respectively. However, the source of aggregate can increase the EE and emissions by 68% and 45% respectively.

5.7.4 Comparison of roads and rail

While two lanes are needed for vehicle transport on the roads, rails mostly operate with a single track – only 6% of the total length is double tracked.[36] A comparison of lifetime energy use by roads and rail on this basis (ie two-lane roads vs single rail track) is shown in figure 5.5.

Figure 5.5 Comparison of lifetime energy use for roads and rail in terms of fixed infrastructure (GJ/annum)



The life cycle energy use for rail is 35% and 26% higher than that for state highways and urban local roads, respectively. However, compared with motorways, rural local roads and special-purpose roads, rail is 14%,

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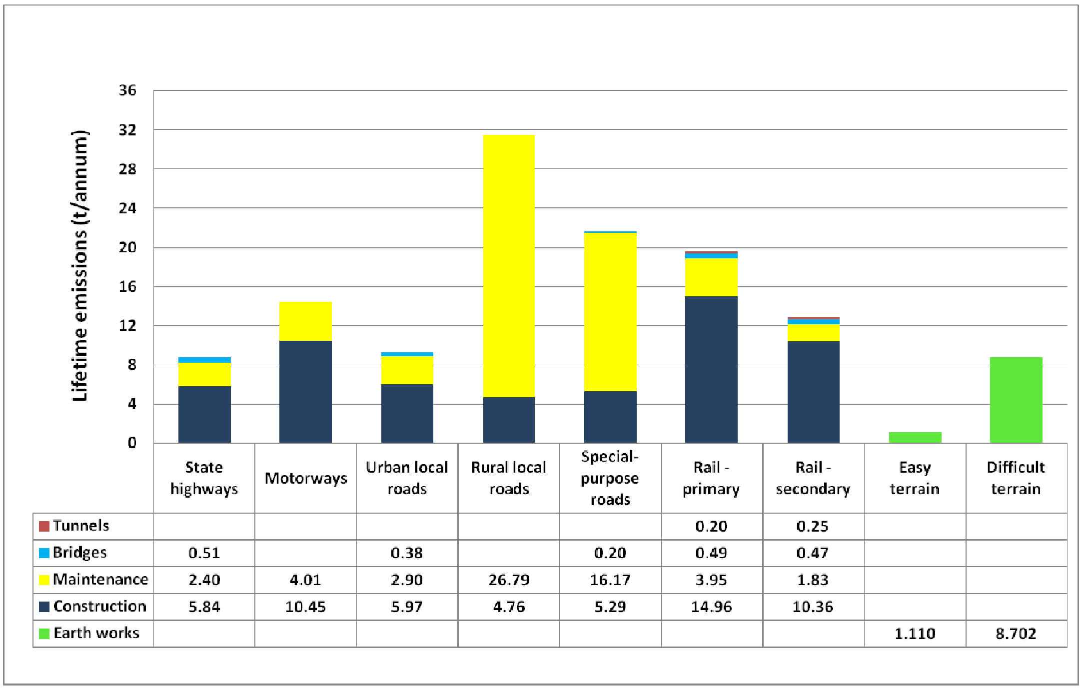
[36] Double-tracked length of suburban service is, however, higher at 61% of the total.

160% and 76% lower in life cycle energy use. This is mainly due to the high maintenance requirements of the unsealed wearing course that is used for these roads.

A comparison of lifetime emissions for roads and rail on the same basis is shown in figure 5.6. Life cycle GHG emissions for rail are 19%, 51% and 48% higher than motorways, state highways and urban local roads, respectively. Rural local roads and special-purpose roads are 76% and 21% higher respectively in lifetime emissions (embodied emissions) than rail.

Figure 5.6 Comparison of lifetime emissions for roads and rail in terms of fixed infrastructure (tCO_2e/annum)



	State highways	Motorways	Urban local roads	Rural local roads	Special-purpose roads	Rail - primary	Rail - secondary	Easy terrain	Difficult terrain
🟥 Tunnels						0.20	0.25		
🟦 Bridges	0.51		0.38		0.20	0.49	0.47		
🟨 Maintenance	2.40	4.01	2.90	26.79	16.17	3.95	1.83		
⬛ Construction	5.84	10.45	5.97	4.76	5.29	14.96	10.36		
🟩 Earth works								1.110	8.702

However, the above analysis disregards the capacity differences between road and rail infrastructure in terms of providing transport services, and the comparison of roads and rails has to be on the basis of actual maximum capacity. Data on the actual maximum road capacity in New Zealand was not available for a comparison.[37] Although it is possible to establish the theoretical maximum capacity of transport infrastructure in New Zealand using the current vehicle fleet and rolling stock data, it is of limited value, as infrastructure is never used to its theoretical maximum capacity. Smith (2003) suggests that passenger transport on roads using cars and buses can move 200 and 1500 persons per metre width of road per hour respectively, while rail can move 9000 persons per hour. On this basis, rail capacity would be twice that of New Zealand roads, which are, on average, 3.5m wide.

International studies show that the majority of roading impacts come from the operation and EE of the vehicles, so the two forms of transport need to be compared as systems, rather than merely in terms of their infrastructure. The next section considers the EE of vehicles and rolling stock used in New Zealand.

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[37] Data is available for motorways, which comprise only 0.2% of the total lane length of the existing road network.

6 Road and rail transport service lifetime liabilities

The estimates in this study were based on the current road vehicle fleet[38] and rolling stock used in New Zealand. The vehicles and rolling stock used in New Zealand are imported from overseas either as new or used imports.

6.1 Road vehicles

Road vehicles in New Zealand come under several categories: passenger and freight vehicles, and light and medium/heavy vehicles.

6.1.1 Light vehicles

More than 90% of the New Zealand vehicle fleet comes into the light-vehicle category (MoT 2009). Light vehicles for passenger and freight include cars, vans, utility vehicles, four-wheel drives and sports utility vehicles (SUVs), and buses and motor caravans with a gross vehicle mass under 3.5 tonnes.

In a 2008 hybrid (EIO and process analysis-based) LCA study of passenger transport in the US, Chester reported the tare weight of three different light passenger vehicles (LPVs) (based on the median weight of vehicles in 2005); sedan 3200lbs (1452kg), SUV 4600lbs (2087kg) and pickup 5200lbs (2359kg). Fels (1975) estimated the tare weight of a motorcar in the US as 3600lbs (1600kg).

The mass of different light-vehicle types, the number in the New Zealand vehicle fleet, and the percentage of the total in the class that are diesel vehicles, according to MoT (2010), are shown in table 6.1.

Table 6.1 Mass, number and percentage of diesel vehicles in the New Zealand light-vehicle fleet in 2008 (MoT 2010, and accompanying data spreadsheet (version 1.0, February 2010) 1.1, 1.2, 1.1 extra)

Vehicle category	Motor vehicle register (MVR) vehicle type	Mass[a] (t)	Total (no.)	Diesel vehicles	Average age (years)
Light passenger	Passenger car/van	Up to 3.5	2,584,337	8.5%	12.22
Light commercial	Goods van/truck/utility Motor caravan Light bus	Up to 3.5	377,014	64%	11.56
Motorcycle[b]	Motorcycle/moped		111,566	–	10.87

a) Laden weight (gross vehicle mass).

b) Motorcycles are assumed to be powered by petrol.

6.1.2 Medium/heavy vehicles

Medium goods vehicles have a gross vehicle mass from 3.5–7.5t, and heavy vehicles are over 7.5t[39] (Tate et al 2004, p23). The number of medium/heavy vehicles in different mass categories, and the percentage of the total in the class that are diesel vehicles, are shown in table 6.2.

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[38] 2008 vehicle fleet data is used for the base case.

[39] There are a further 15,126 vehicles in the fleet that are not included in road vehicles (ie mobile machines, other trucks and tractors).

Table 6.2 Mass, number and percentage of diesel vehicles in the New Zealand heavy vehicles fleet in 2008 (MoT 2009, and accompanying data spreadsheets (version 5.0, August 2009) 2.9)

Vehicle type	Weight range[a] (t)	Total (no.)	Diesel vehicles	Average age (years)
Truck	<5	20,774	98%	13.95
	5-7.5	28,434		
	7.5-10	14,790		
	10-12	6363		
	12-15	6215		
	15-20	6575		
	20-25	15,146		
	25-30	10,275		
	>30	6624		
Bus	<7	1758	96.5%	15.86
	7-12	2180		
	>12	4588		

a) Laden weight (gross vehicle mass).

6.1.3 Origin of road vehicles

Seventy-six percent of the light vehicles (passenger and commercial) and 99% of the motorcycles entered the fleet between 2000 and 2008 (MoT 2010). The origin of all vehicles that entered the fleet in 2008 is shown in table 6.3.

Table 6.3 Origin of vehicles that entered the New Zealand vehicle fleet in 2008 (MoT 2010, and accompanying data spreadsheets (version 1.0, February 2010) 6.9)

Vehicle type	Europe	Asia	Australia	NZ
Light vehicles (passenger and commercial)	19%	75%	6%	0%
Motorcycles	26%	68%	0%	4%
Buses	25%	66%	2%	7%
Trucks	20%	73%	7%	0%

6.1.4 Useful life of road vehicles

The average useful life of road vehicles can be represented either by the number of years of use or by the total distance travelled before the vehicle is scrapped.

Davis and Diegal (2006), cited by Chester (2008), reported the useful life of different LPVs used in the US as follows: sedan 16.9 years; SUVs and pickups 15.5 years. The annual travel distance is estimated to be 11,000 miles (17,700km). This indicates a useful life of 300,000km for sedans and 275,000km for SUVs and pickups. Based on the Federal Transport Authority (FTA 2006) data, a 12-year useful life was reported for a US urban bus that travels 42,000 miles (67,600km) in a year (op cit). Fels (1975, p303) estimated the useful life of an automobile and a bus as 10 years at 10,000miles/year (160,000vkm) and 100,000 miles/year (1,600,000vkm), respectively. The useful life of a motorcycle was estimated at 50,000 miles

(80,500vkm). Lenzen (1999, p280) estimated the useful life of Australian cars to be 20 years, with 320,000km of travel during the life. Anecdotal evidence suggests that the useful life of Australian cars used at the time of this research was 12 years.

However, as the New Zealand vehicle fleet has been imported predominantly from Europe and Asia, the above estimates may have limited relevance. Useful life estimates of road vehicles according to various sources are shown in table 6.4.

Table 6.4 Useful life estimates for road vehicles in New Zealand

Vehicle type	Useful life	
	Years	Kms
Car	15–16.9[a]	150,000[b]–250,000[c]
Sedan	16.9[a]	300,000[a]
SUV	15.5[a]	275,000[a]
Pickup	15.5[a]	275,000[a]
Light commercial[f]	17.6[d]	235,000[b]
Bus[g]	30	1,000,000[b]–1,800,000[c]
Motorcycle	10.8–18[d]	100,000[e]–200,000[e]
Truck	18.3–23.9[d]	540,000[b]

a) Chester (2008)
b) Spielmann et al (2007)
c) Carbon Neutral (2008)
d) MoT (2010)
e) Kawasaki Motorcyle Forum (2007)
f) Based on van
g) Chester (2008, p52) estimated the useful life of urban buses in the US to be 800,000km.

The average age at which light vehicles in New Zealand are scrapped varies depending on whether the vehicle is New Zealand-new or a used import (49% of the total), at 18.7 and 16.7 years respectively. The average life at which New Zealand-new buses are scrapped is about 30 years (MoT 2009). The total distance travelled before the vehicle is scrapped depends on the type of use (private or commercial), fuel type (diesel or petrol), and whether the vehicle is New Zealand-new or a used import. The total distance travelled by the vehicles that left the fleet in 2008 is shown in table 6.5.

Table 6.5 Odometer reading of vehicles that left the light-vehicle fleet in 2008, and percentage composition in the fleet (MoT 2010, and accompanying data spreadsheets (version 1.0, February 2010) 7.3abc; 8.1a,b,c)

Vehicle type		Distance (km)	Light passenger vehicle (%)	Light commercial vehicle (%)
Fuel type	Diesel	219,744	8.5%	64%
	Petrol	191,624	91.5%	36%
Use type	Private	191,219	100%	–
	Commercial	228,150	–	100%
Origin	NZ-new	206,920	47%	75%
	Used import	185,696	53%	25%

This suggests that in New Zealand, light vehicles are discarded before the end of useful life, which leads to inefficient use of embodied resources.

6.1.5 Road travel

The total vehicle-kilometres travelled on New Zealand roads in 2008 was dominated by LPVs, which contributed 78% to the total, with LCVs and other vehicles (motorcycles, heavy trucks and buses) contributing 14% and 8%, respectively (MoT 2010, p5).

Travel by diesel vehicles is 10% and 73% of the total travel for LPVs and LCVs, respectively (MoT 2009 – New Zealand vehicle-fleet data spreadsheet). Travel by the New Zealand vehicle fleet in the year 2008 is shown in table 6.6.

Table 6.6 Total travel by vehicle category in New Zealand in 2008 (MoT 2010, and accompanying data spreadsheets (version 1.0, February 2010) 1.4 to 1.7, 8.0a,b; 8.2a,b)

Vehicle category	MVR vehicle type	Total travel (billion km)	% by diesel vehicles
Light passenger	Passenger car/van	30.91	10%
Light commercial	Goods van/truck/utility Motor caravan Light bus	5.75	73%
Motorcycles	Motorcycle/moped	0.31	–
Trucks	<5t to >12t	2.62	–
Buses	<7t to >12t	0.23	–

6.2 Rolling stock

The rolling stock operated by KiwiRail, as of June 2009, includes:

- 149 mainline locomotives[40]
- 4200 freight wagons (see section 6.2.3)
- 57 carriages
- 141 metro passenger units (KiwiRail 2009, pp3, 23).

6.2.1 Useful life of rolling stock

Rolling stock could theoretically last up to 100 years (Fels 1975), although over time, the maintenance demand increases and the use decreases. Heavy diesel locomotives and carriages used in the US are estimated to last 26–30 years (Chester 2008, pp67, 79). The average useful life of rolling stock according to various sources is shown in table 6.7.

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[40] According to KiwiRail rolling stock monitoring software, there were 159 locomotives.

Table 6.7 Useful life of rolling stock (Spielmann et al 2007)

Type	Useful life	
	Years	km
Locomotive	40	9.6 million
Freight wagon		850,000
Carriage[a]		6 million
Suburban service units		6 million

a) Chester (2008, pp67–68) estimated the useful life of heavy and light trains used in the US to be 30 and 27 years, respectively.

However, based on the existing KiwiRail coal wagon fleet, the useful life suggested for freight wagons seems low. In the year 2008, part of the coal wagon fleet travelled 136,000km. On this basis, the total travel since their manufacture in 1987 (over 23 years) is over three million kilometres (Manson 24 March 2011, pers comm).

The age of locomotives in the New Zealand fleet (excluding the six new DL class locomotives (Anon 2010, p23)) ranges from 20 to 40 years (average 30 years), while the age of freight wagons ranges from 10 to 28 years, with an average of 25 years (KiwiRail 2008, pp13, 24; NIU 2010, p16).

6.2.2 Locomotives

Details of the locomotives in the current fleet, and their type and weight, are shown in table 6.8.

Table 6.8 Details of the mainline locomotives in the KiwiRail fleet (excluding locomotives used for Auckland suburban services) in 2008 (Manson 24 March 2011, pers comm)

Locomotive class	Total in service (no.)	Type	Weight[a] (tonnes)	Country of origin	Year of manufacture/ refurbishment
EF	17	Electric	108	UK	1988 (manufacture)
DXR	2	Diesel-electric	104	US	1993/2006 (refurbishment)
DX/DXB/DXC/DXH	46	Diesel-electric	98/100/103[b]	US	2002–2008 (refurbishment)
DFM/DFB	12	Diesel-electric	87	Canada	1998 (refurbishment)
DFT	18	Diesel-electric	87	Canada	1992–1997 (refurbishment)
DQ	4	Diesel-electric	87	Australia	1997 (refurbishment)
DC/DCP	54	Diesel-electric	82	Canada	1978–1983 (refurbishment)
DBR	6	Diesel-electric	68	Canada	1980–1982 (refurbishment)

a) Wikipedia 2010.

b) Modelled as 100 tonnes.

The electric locomotives were imported from Loughborough in the UK, while diesel-electric locomotives were from either Pennsylvania in the US, Ontario in Canada, or Queensland in Australia. The new DL class were built in China.[41]

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[41] DL class is not included in the locomotive fleet shown in table 6.8, which shows the fleet in year 2008.

6.2.3 Freight wagons

The existing fleet of freight wagons includes a range of types. The size of the serviceable freight wagon fleet can vary widely, owing to:

- withdrawal pending major repairs or scrapping
- reintroduction after a period of being out of service
- new commissioning.

Different wagon classes are designed for different maximum axle loads. Older wagons generally operate at a maximum axle load of 14t. Wagon classes have been progressively introduced to operate at axle loads of 16.3t and 18t (giving maximum gross weights of 65 and 72t respectively). While some wagon classes that are capable of operating at maximum gross weights of 80 or 90t have been introduced, these are currently restricted to operating at 72t. As maximum permitted axle loads are raised on particular routes (generally by upgrading bridges), the wagon payload will be able to be increased on certain wagon types, which will result in efficiency gains.

Freight wagons predominantly use steel for their body construction (or steel frame with fibreglass), and aluminium, stainless steel or composite materials for the body. The composition of the freight wagon fleet, the average weight of wagons of various types, and their goods-carrying capacity is shown in table 6.9.

Table 6.9 Composition of the freight wagon fleet on 1 July 2007 (Manson 19 October 2010, pers comm)

Wagon type	Type of construction	Approx fleet size	Average tare weight (t)	Average payload (t)
Container flat wagon	Steel	2132	14.09	45.40[a]
Box	Steel (19%), steel under-frame and top with curtain sides (34%), or steel under-frame with fibreglass body (47%)	484	19.65	57.21
Log	Steel	366	14.81	53.86
Coal	Steel (13%), or steel under-frame with aluminium body (87%)	303	18.21	70.41
Milk tanker	Steel under-frame with stainless-steel body	66	13.00	72.00
Flat general	Steel	62	13.20	54.08
4-wheeler		145	8.46	24.47
Canopy (eg steel)	Steel under-frame with synthetic canopy	143	13.44	17.50
Reefer	Steel under-frame with composite body	35	25.00	72.00
Grain/fertiliser	Steel under-frame with aluminium body	41	15.7	72
Auto	Steel (71%), or steel under-frame with stainless-steel body	21	28.24	45.55

a) 100 wagons with a gross weight of 80t operate only at 72t, owing to current track limitations.

6.2.4 Carriages

At the time of this research, there were 57 carriages in the fleet. Small-window carriages (class A), which are based at Otahuhu, Auckland, are used for charter trains in the North Island. Business-car carriages (class AD) are typically used for charter trains; if the demand warrants these can be used as an additional carriage on passenger rail services. The RM class (Silver Fern) two-car diesel-electric multiple units, which are now used for charter train services, were leased to Auckland Regional Transport Authority (ARTA) for use on Auckland metro services between Pukekohe and Auckland until mid-2009, and are therefore included in table 6.13.[42] Class S carriages are used exclusively on the weekday morning commuter service from Palmerston North to Wellington (see table 6.12), returning in the evening. The details of the carriage fleet and its composition are shown in table 6.10.

Table 6.10 Composition of carriage fleet (Manson 25 Mar 2010, pers comm)

Class	No.[a]	Description	Empty weight (t)	Seating capacity[b]
A	7	Small-window charter-fleet carriages	25 approx	50 approx
AD	2	Business-car carriage	30	24
AG	11	Former guards vans converted for use as generator vans, luggage vans and open-air viewing platforms	30	Nil
AO	19	Big-window cars	25 approx	50
ASO	7	Big-window servery cars	25 approx	26

a) Number of carriages currently in service.

b) Excluding standing.

6.3 Passenger and suburban train services

6.3.1 Passenger services

The four main passenger services in New Zealand are as follows:

- Overlander, between Auckland and Wellington
- Coastal Pacific service between Picton and Christchurch
- TranzAlpine service between Christchurch and Greymouth
- Capital Connection, between Palmerston North and Wellington.

According to Manson (25 February 2010 pers comm), about half of those using the Overlander service travel the total trip length, three-quarters of users travel the total trip length of the Coastal Pacific and TranzAlpine services, while only a small percentage (assumed to be 25%) travel the total trip length of the Capital Connection service. The operational details of the services, including the composition of rolling stock used, are shown in table 6.11.

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[42] These were only counted in the Auckland suburban service units, not in the main carriage fleet.

Table 6.11 Train composition and operational details for passenger services

Service	Carriage composition	Capacity (in millions)			
		Passenger km/year		Gross tonne km/year[a]	
		Max[b]	Ave[c]	Max[b]	Ave[c]
Overlander	2×(3AO+ASO+ AG)	56.42	24.04	45.34	43.23
Coastal Pacific	3AO+ASO+2AG	43.48	20.75	42.35	40.88
TranzAlpine	9AO+2ASO+2AG	84.19	40.35	61.66	58.81
Capital Connection	7S+AG	26.59	20.47	19.95	19.55

a) Based on gross weight of train excluding locomotives.

b) Based on the same train composition and number of trips.

c) Based on 2007/2008 passenger travel.

Except for the Capital Connection, which is a commuter service, the existing maximum capacity of each service is greater than the average use. The feasible maximum capacity is even greater, as carriages may be added to the existing composition without additional locomotive power.

6.3.2 Suburban passenger services

There are two suburban passenger services in operation: the Tranz Metro service in Wellington and Maxx in Auckland. Details of the metro passenger units/locomotives used for services in Wellington are shown in table 6.12. All Wellington passenger services are fuelled by electricity, except those between Masterton and Wellington, and Palmerston North and Wellington, which are fuelled by diesel. The average Tranz Metro passenger trip length is different during the peak period compared with the off-peak period (GWRC 2009).

Table 6.12 Details of metro service units used in Wellington (Manson 25 March 2010, pers comm)

Class	Total (no.)[a]	Description	Empty weight (t)	Seating capacity[b]	Typical usage
EM/ET	44 2-car sets	2-car electric multiple unit (built by Ganz Mavag)	EM: 37.6 ET: 34.5	148 per 2-car set	Daily services between: - Wellington and Paraparaumu (and peak services to Porirua and Plimmerton) - Wellington and Melling - Wellington and Upper Hutt (may include peak services to Taita)
DM/D	9 2-car sets	2-car electric multiple unit (built by English Electric), mainly used on Johnsonville Line	DM: 42.5 D: 27.2	DM: 54 per car D: 70 per car	Daily services between Wellington and Johnsonville May also be used between Wellington and Melling
D/DM/D	5 3-car sets	3-car electric multiple unit (built by English Electric), mainly used on peak services	3-car set: 99.5	3-car set: 194	Peak services between: - Wellington and Taita - Wellington and Upper Hutt

Class	Total (no.)[a]	Description	Empty weight (t)	Seating capacity[b]	Typical usage
EO-hauled SE set	1 set	5- or 6-carriage train hauled by an EO-class electric locomotive on each end	5 cars × 34 + 2 locos × 55 = 280	Approx 300	Peak services between: – Upper Hutt and Wellington (one service each way on weekdays) – Plimmerton and Wellington (1service each way on weekdays)
DC-hauled SW set	3 sets using 18 carriages	3 train sets using 5–7 carriages, depending on the popularity of an individual service	6 cars × 34 + 1 loco × 82 = 286	Approx 350	Exclusively on services between Masterton and Wellington
DX-hauled S set	1 set	7/8 carriage train, typically hauled by a DX class diesel locomotive (but may be hauled by a DFT or 2 DCs)	7 cars × 34 + 1 loco × 98 = 336	391 (or 451 if using 8 cars)	Exclusively on weekday-morning commuter service from Palmerston North to Wellington, returning in the evening (counted as part of KiwiRail's Tranz Scenic fleet)

a) In service.

b) Excluding standing.

Note: Table 6.12 includes neither the new Korean Matangi units being introduced into service in 2011, nor the extension of service to Waikanae, which opened early in 2011.

The total passenger service provided by Tranz Metro in 2007/08 was 3.2 million train-km, and the total number of trips travelled during 2007/2008 was 11.6 million trips (Manson 11 June 2010, pers comm). The average passenger trip length varied from 23.5km during the peak period to 21.9km during the off-peak period. The total passenger service during the year 2008 was 264.9 million pkm, with 67.3% of the total travel during the peak period (Farrell 2010, pers comm). On this basis, the average passenger trip length during the year 2007/2008 was 23km.

Details of the metro passenger units/locomotives used in Auckland are shown in table 6.13.

Table 6.13 Details of metro service units used in Auckland in 2008 (Manson 30 March 2011, pers comm; Wikipedia 2010)

Class	Total (no.)	Description	Empty weight (t)	Seating capacity
ADK/ADB	9	3-car diesel multiple units	78.72[a]	134
ADL/ADC	10	3-car diesel multiple units	ADL: 42.97 ADC: 35.75	128
RM (Silver Fern)	3	2-car diesel-electric multiple unit	2-car unit: 107	2-car unit: 96
DBR (locomotive)	2	2 DBR locomotives operated in top-and-tail mode with one 5-car SX carriage set	DBR locomotive: 68 SX carriage: 23.7[b]	SX: 56[b]
DC[c]/DCP (locomotive)	17	Operating in push–pull mode with 12 sets (2 more on order) of 2–4 (generally 3) SA cars and an SD driving car	DC/DCP locomotive:82 SA/SD carriage: 33[d]	SA: 60 SD: 64[e]

a) Assumed to be the same as ADL/ADC.

b) ZigZag Railway (2010).

c) DC-hauled SA/SD sets will be supplemented with longer SA/SD sets hauled by more powerful DFT locomotives.

d) SA/SD carriages are rebuilt from ex-British Mark 2 coaches, for which the weight is available at *http://wapedia.mobi/en/Brake_Standard_Open, 29 July 2009.*

e) Paling and Rutherford (2006, p10).

The total passenger service provided by the Auckland suburban service in 2007/08 was 2.2 million train-km (Veolia Transport website (2009), with:

- 6.79 million total passenger trips
- 111.69 million total pkm (ARTA 2010, p34).

In 2008/09, the Auckland suburban service provided 124.71 million pkm passenger transport (ibid), with 3.12 million train-km (Veolia Transport website 2011) – the average rail occupancy declined from 50 passengers/train in 2007/08 to 40 passengers/train in 2008/09.

6.4 Road vehicle and rolling stock lifetime liabilities

The inventory of road vehicle and rolling stock established in sections 6.1 and 6.2 above is used to estimate the lifetime externalities in terms of cumulative energy use (primary energy), CO_2-e GHG emissions, and total contaminant load. Primary energy use and carbon emissions due to the manufacturing process, maintenance and disposal are based on ecoinvent data for European practices. Transport from the country of origin to New Zealand using shipping has been included for road vehicles, while for rolling stock, land transport from the manufacturing plant to the overseas port has been included, in addition to shipping. European data was used for vehicle/rolling stock maintenance and end-of-life disposal owing to the lack of New Zealand data.

6.4.1 Road vehicles

6.4.1.1 Embodied resource use

According to Lenzen (1999, p281), the energy embodied in an Australian passenger car is 152GJ/vehicle, while embodied emissions are 14.6tCO_2/vehicle. A further 236GJ (23.8tCO_2e) is added during the 20-year vehicle life[43] for maintenance, parking, crash repairs and licensing. However, the contribution to the total from manufacture (10%) and maintenance (15%) is moderate, compared with the 75% contribution from fuel (op cit). According to Carbon Neutral (2008, p14), Australian automobile manufacture and maintenance, on average, requires 113.6MJ of energy per kg of vehicle, while manufacture and maintenance releases 17.5kg CO_2e per kg of vehicle.

Lenzen (1999) cited two earlier studies that estimated the EE of Japanese cars (Nishimura et al 1996) and US cars (Fels 1975). The EE of Japanese cars with a 1200kg weight has been estimated at 200GJ/vehicle (180MJ/kg), while an American car with a 1600kg weight embodies 140GJ/vehicle (op cit). A more recent study of US passenger transport (Chester 2008) using hybrid LCA (EIO coupled with process analysis) based on 1997 economic tables, estimated the EE of three types of LPVs: sedan (119GJ/vehicle), SUV (167GJ/vehicle) and pickup (117GJ/vehicle).[44] The emissions embodied in the vehicles are reported as 10, 13 and 10tCO_2e/vehicle, for sedan, SUV and pickup respectively.

The New Zealand vehicle fleet is predominantly imported from Europe and Asia. The origin of vehicles was assumed, based on the percentage of new entrants to the fleet in 2008 (see table 6.3). Japan and the UK are used as the origin of imports from Asia and Europe, respectively. In this study, the embodied resource use of both petrol and diesel light vehicles was assumed to be the same (which could underestimate the embodied resource use of diesel vehicles). Light-vehicle embodied resource use was based on data for an average car (based on the Golf A4). Motorcycles (based on the Honda CB750) were assumed to have an average weight of 223kg. The above Australian data (Carbon Neutral 2008, p85) was used to estimate the embodied resource use of motorcycles, and the useful life of light vehicles (vkm) was calculated based on the odometer readings shown in table 6.5. The EE and embodied GHG emissions estimates for different road vehicles thus estimated are shown in table 6.14.

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[43] Industry experts suggest that the average useful life of a passenger car is currently 12 years.

[44] Sedans, SUVs and pickups weigh 1450kg, 2100kg and 2400kg, respectively. As cited by Chester and Harvath (2009), Carnegie Mellon University (2008) used an EIO-based life cycle assessment and calculated the energy required to manufacture a light motor vehicle in the US as ranging from 103–146GJ/vehicle – sedans 121GJ, SUVs 103GJ, and pickups 146GJ. Total GHG emissions due to light motor-vehicle manufacture vary from 9–12t CO_2e/vehicle – sedans 10tCO_2e, SUVs 12tCO_2e, and pickups 12tCO_2e.

Table 6.14 EE and GHG emissions estimates for different road vehicles in the New Zealand vehicle fleet (manufacture, maintenance and disposal)

Vehicle type	Embodied energy		Embodied GHG emissions (CO_2e)	
	GJ/vehicle	MJ/vkm[a]	t/vehicle	kg/vkm[a]
LPV	115.04	0.593[b]	5.64	0.029[b]
LCV	115.04	0.504[c]	5.64	0.025
Motorcycle	25.93	0.259[d]	3.95	0.040[d]
Truck <5t to 7.5t	246.25	0.456	14.06	0.026
Truck, 7.5t to15t	627.97	1.163	31.32	0.058
Truck 15t to 30t	966.05	1.789	44.14	0.082
Truck >30t	1403.82	2.600	61.93	0.115
Bus	1602.63	1.603	58.69	0.059

a) Based on New Zealand vehicle fleet data (table 6.5).

b) Based on an average vehicle (8.5% of the fleet is diesel vehicles with a life of 219,744vkm, while the balance is petrol vehicles with a life of 191,624vkm).

c) Based on MoT (2009) data, average vehicle life is 228,150vkm.

d) Based on a life of 100,000vkm; based on a life of 1 million vkm.

6.4.1.2 Operating resource use

An earlier study (TERNZ 2005) on New Zealand heavy vehicle efficiency, based on the 2004 fleet performance, estimated the fuel use of trucks to be 50–57l/100km. However, truck fleet composition and performance could have improved since then. Fleet average fuel consumption of similar vehicles currently used in Swiss conditions is 17–41l/100km (Spielmann et al 2007). In New Zealand, the Ministry of Transport's 2005 *National rail strategy* reported the energy use of truck transport as 870Wh/tkm, based on the fleet performance in the year 2003. This is an average energy use that disregards the efficiency gains that may be achieved by using larger trucks. On this basis, the fuel use of New Zealand trucks ranges from 15–85l/100km:

> *The collection of data on freight movements is particularly significant as there is currently no reliable information available about the energy costs and other environmental externalities associated with different transport modes* (McGimpsey et al 2009, p22).

Mainly because of the lack of New Zealand data, for this study the fuel consumption of diesel vehicles used on New Zealand roads was estimated based on ecoinvent data for European conditions (Swiss data). The fuel use of LCVs was estimated based on a van (<3.5t). However, the petrol use for LPVs and motorcycles was based on the average New Zealand fleet petrol use, which is 9.9l/100km and 6l/100km, respectively (MoT 2009). Truck travel using petrol (2% of total travel) was disregarded and considered as diesel travel.

Table 6.15 is a comparison of the published New Zealand fuel emissions factors with varying system boundary conditions. LCA-based emission factors included by Barber (2009) include the energy and emissions associated with producing fuel, in addition to its combustion. This study used Barber's (2009) data, which included upstream resource uses, to estimate energy and emissions due to fuel use.

Table 6.15 Comparison of published data on New Zealand fuel emissions factors (MoT 2009, p59; MfE 2009; Barber 2009)

Fuel type	Combustion-based emissions factor (gCO_2e/litre)		LCA-based emissions factor (gCO_2e/litre)
	MoT (2009)	MfE (2009)	Barber (2009)
Diesel	2605	2690	3108
Petrol (regular unleaded)	2296[a]	2330	2735

a) Based on regular/premium petrol mix used in New Zealand.

Operating energy use and emissions due to road vehicles used in New Zealand estimated on this basis are shown in table 6.16.

Table 6.16 Operating energy and GHG emissions estimates for different road vehicles in the New Zealand vehicle fleet

Vehicle type	Fuel type	Fuel use (l/100km)	Energy (MJ/vkm)	GHG Emissions ($kgCO_2e$/vkm)
LPV	Petrol	9.9[a]	4.118	0.271
	Diesel	7.2	3.275	0.225
LCV (van)	Petrol	12.7	5.262	0.346
	Diesel	8.3	3.740	0.257
Motorcycle	Petrol	6.0[a]	2.496	0.164
Truck <5t–7.5t	Diesel	17.0	7.715	0.530
Truck >7.5t–15t		26.2	11.845	0.814
Truck >15t–30t		25.1	11.353	0.781
Truck >30t		34.6	15.622	1.074
Bus	Diesel	41.4	18.689	1.285

a) Based on MoT (2009).

Metal loads delivered to water bodies due to vehicle operation

Road vehicles are also responsible for dissolved and suspended metals (eg zinc, copper and lead) that are transported to water bodies. While vehicle tyres and brake pads mainly release zinc and copper, historically petrol was responsible for lead. Timperley et al (2005) estimated the total metal attributable to road runoff as: zinc 0.368mg/vkm (51% dissolved), copper 0.055mg/vkm (25% dissolved), and lead 0.047mg/vkm (2% dissolved). This, however, disregards the vehicle type (motorcar, truck etc), which can influence the metal load. Owing to the lack of better data, for this study the metal loads due to road transport were estimated based on Timperley et al’s 2005 data (see section 6.5.1).

6.4.2 Rolling stock

6.4.2.1 Embodied resource use of locomotives

The resource use for the manufacturing and maintenance of electric, diesel-electric and diesel locomotives were assumed to be the same. Total cumulative energy use and GHG emissions were estimated based on the weight of the locomotive, using ecoinvent data for European manufacturing and maintenance practices. Transport of locomotives to the overseas port by truck and shipping to New Zealand was also included. Trucks were assumed to be empty on the return journey, while ships would be carrying other goods. Cumulative energy use and GHG emissions estimates for the locomotive fleet is shown in table 6.17.

Table 6.17 Comparison of EE and emissions of locomotives in the KiwiRail fleet[a]

Locomotive class	Total number	Type	Weight (tonnes)	Embodied energy[b] (GJ/locomotive)	GHG emissions[b] (tCO_2e/locomotive)
EF	17	Electric	108	11,635	655
DXR	2	Diesel-electric	104	11,721	626
DX/DXB/DXC/DXH	46	Diesel-electric	100	10,686	601
DFB/DFM	12	Diesel-electric	87	9336	526
DFT	18	Diesel-electric	87	9336	526
DQ	4	Diesel-electric	87	9100	511
DC/DCP	54	Diesel-electric	82	8799	495
DBR	6	Diesel-electric	68	7297	411
Total for locomotives				1.55PJ	87.09ktCO_2e
Average per locomotive				9737GJ/locomotive	548tCO_2e/locomotive
Average per locomotive-km				1.014MJ/km	0.057kgCO_2e/km

a) Based on fleet composition in 2008.

b) Per locomotive.

6.4.2.2 Embodied resource use of freight wagons

Freight wagons use a combination of designs and constructions. The implications of different construction types and materials on various types of freight wagons were not considered in the estimates, which were based on the average weight. Cumulative energy use and GHG emissions for the manufacture and maintenance of the freight wagon fleet was estimated using ecoinvent data for material consumption by European wagons, with a fleet consisting of 65% closed wagons and 35% open wagons. The transport of wagons to New Zealand was not included, owing to lack of data. Cumulative energy use and GHG emissions estimates for the freight wagon fleet are shown in table 6.18.

Table 6.18 Comparison of EE and emissions due to freight wagons in the fleet[a]

Wagon type	No.	Tare weight[b] (t)	Description	Embodied energy (GJ/wagon)	GHG emissions (tCO_2e/wagon)
Container flat	2132	14.09	Steel construction	4165	56
Box	484	19.65	Three types of construction: steel; steel under-frame and top with curtain sides; and steel under-frame with fibreglass body	5810	78
Logs	366	14.81	Steel construction	4380	59
Coal	303	18.21	Two types of construction: steel; and steel under-frame with aluminium body	5382	72
Milk tanker	66	13.00	Steel under-frame with stainless-steel body	3843	52
Flat general	62	13.20	Steel	3902	52

Wagon type	No.	Tare weight[b] (t)	Description	Embodied energy (GJ/wagon)	GHG emissions (tCO_2e/wagon)
4-wheeler	145	8.46	Steel	2500	34
Canopy (eg steel)	143	13.44	Steel under-frame with synthetic canopy	3974	53
Reefer	35	25	Steel under-frame with composite body	7391	99
Grain/ fertiliser	41	15.7	Steel under-frame with aluminium body	4641	62
Auto	21	28.24	Two types of construction: steel; and steel under-frame with stainless-steel body	8348	112
Total for freight wagons				16.98PJ	227.98ktCO_2e
Average for a freight wagon				4469GJ/wagon	60tCO_2e/wagon
Average per freight wagon-km				5.284MJ/km	0.071kgCO_2e/km

a) Based on fleet composition in 2008.

b) This is only the average tare weight of the undercarriage for the wagon type, and does not include the weight of tanks and containers used for certain freight – eg milk tankers, coal hoppers, etc.

6.4.2.3 Embodied resource use for carriages

Total cumulative energy use and GHG emissions were estimated based on the weight of the carriage, using ecoinvent data for the manufacture and maintenance of a regional European train. Cumulative energy use and GHG emissions thus estimated for carriages in the fleet are as shown in table 6.19.

Table 6.19 Comparison of EE and emissions due to the Tranz Scenic carriage fleet[a]

Carriage class	No.	Weight (tonnes)	Description	Embodied energy (GJ/P)	GHG emissions (tCO_2e/P)
A	7	25	Small-window charter fleet carriage	1365	52
AD	2	30	Business-car carriage	1639	62
AG	11	30	Former guards' van converted for use as a generator van to supply power to passenger trains, but also for use as a luggage van and open-air viewing platform	1639	62
AO	19	25	Big-window car for Tranz Scenic services	1365	52
ASO	7	25	Big-window servery cars for Tranz Scenic services	1365	52
Total for carriages[b]				66,363GJ	2526tCO_2
Average per carriage				1443GJ/carriage	55tCO_2/carriage
Average per carriage-km				0.240MJ/km	0.009kgCO_2/km

a) Based on fleet composition in 2008.

b) Contributory components may not add up, owing to rounding off.

6.4.2.4 Embodied resource use for suburban service (Tranz Metro and Maxx) units

The cumulative energy use and GHG emissions for Wellington suburban service units and Auckland suburban service units, established on the same basis as the carriages, are shown in tables 6.20 and 6.21 respectively.

Table 6.20 Comparison of EE and emissions due to Tranz Metro service units[a]

Unit class	No.	Weight (tonnes)	Description	Embodied energy (GJ/unit)	GHG emissions (tCO_2e/unit)
EM/ET (2-car set)	44	72.1	Two-car electric multiple unit	3938	150
DM/D (2-car set)	9	69.7	Two-car electric multiple unit	3807	145
D/DM/D (3-car set)	5	99.5	Three-car electric multiple unit	5435	207
EO-hauled SE set	1	170[b]	5- or 6-carriage loco-hauled train hauled by an EO-class electric locomotive on each end	9285	353
DC-hauled SW set	3	204[b]	3 train sets using 5–7 carriages	11,142	424
DX-hauled S set	1	238[b]	7- or 8-carriage train, typically hauled by a DX-class diesel locomotive	13,000	495
Total for service units (excluding locomotives)[c]				290,425GJ	11,054tCO_2e
Total for locomotives				60,352GJ	3399tCO_2e
Average per service unit (including locomotives)				5568GJ/unit	229tCO_2e/unit
Average per service unit-km (excluding locomotives)				0.928MJ/km	0.038$kgCO_2e$/km

a) Based on fleet composition in 2008.

b) May not add up due to rounding off.

c) Excluding the weight of locomotive(s).

Table 6.21 Comparison of EE and emissions due to Auckland suburban service units[a]

Unit class	No.	Weight (tonnes)	Description	Embodied energy (GJ/unit)	GHG emissions ($kgCO_2e$/unit)
ADK/ADB	9	78.72	2-car diesel multiple unit	4300	164
ADL/ADC	10	78.72	2-car diesel multiple unit	4300	164
RM (Silver Fern)	3	107	2-car diesel–electric multiple unit	5844	222
DBR/SX	2	91.7	Two DBR locomotives operated in top-and-tail mode with one 5-car SX carriage set	5009	191
DC/DCP/SA/SD	17	148	Operating in push–pull mode with 12 sets (2 more on order) of 2–4 (generally 3) SA cars and an SD driving car	8084	308
Total for service units[b]				246,668GJ	9,389tCO_2e
Average per service unit				6016GJ/unit	229tCO_2e/unit
Average per service-km				1.003MJ/km	0.038$kgCO_2e$/km

a) Based on fleet composition in 2008.

b) May not add up, owing to rounding off.

6.5 Road and rail transport services life cycle externalities

Transport services require infrastructure (construction and maintenance)[45] and vehicles (manufacture, maintenance, operation and disposal), and road and rail infrastructure both support passenger and freight transport services. Infrastructure therefore has to be allocated to the passenger and freight services provided. Since infrastructure renewal depends on the damage caused as a result of the vehicles, weight mass allocation based on the Gtkm was used, with the following assumptions:

- Average private passenger vehicle occupancy is 1.6 passengers (MoT 2009) and the weight of an average passenger is 65kg.
- The net weight of heavy vehicles is 50% of the licence weight, and payload is 55% of the actual capacity; the weight of driver (65kg) is disregarded for heavy vehicles. On this basis, a 16t lorry has a net vehicle weight of 8t, a payload of 4.4t, and a gross vehicle weight of 12.4t.

The percentage of the road infrastructure attributable to different vehicle categories (providing transport services), based on their travel in 2007/2008, is shown in table 6.22.

Table 6.22 Road infrastructure attributable to road transport services, based on travel on New Zealand roads in 2007/2008

Road vehicle type	Ave payload (t)	Gross vehicle weight (t)	Million Gtkm/yr	% use of road
Light passenger car/van	1.6 occupants (0.104)	2.104	65,035	55%
LCV	0.96	2.71	15,597	13.2%
Motorcycle	1 occupant (0.065)	0.29	89	0.1%
Truck, <5-7.5t	0.96	5.81	6505	5.5%
Truck, 7.5-15t	4	12	7718	6.5%
Truck, >15-30t	7.7	21.7	15,791	13.4%
Truck, >30t	11	31	4670	4%
Bus	14 passengers (0.975)	11.975	2750	2.3%

6.5.1 Passenger and freight transport by road

6.5.1.1 Passenger transport by road

Externalities of passenger transport were estimated per pkm. In 2007/2008 there were 2,584,337 LPVs, with an average occupancy of 1.6 passengers who travelled 30.91 billion kilometres.

Therefore, the total passenger transport service provided = average occupancy of a vehicle (p/v) x total distance travelled by all LPVs (vkm) = 1.6 × 30,910,000,000 = 49.456 × 10^9pkm.

Road construction and maintenance attributable to LPV travel = 55% (see table 6.21).

From the analysis of road construction and maintenance, total annual energy use for road construction and maintenance = 34,031,908GJ/annum (see table 5.28).

Energy for road construction and maintenance attributable to the light-vehicle travel = 34,031,908 × 55% = 18,717,549GJ/annum.

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[45] But the operation of roads (eg street lighting, traffic control) is outside the boundary of the study.

Road construction and maintenance attributable to passenger transport = 18,730,925(GJ/annum)/49.456 × 10^9(pkm/annum) = 0.378MJ/pkm.

Light-vehicle EE use = 0.593MJ/vkm (see table 6.14) = 0.593/1.6 = 0.371MJ/pkm.

In 2007/2008, 90% of the travel was by petrol vehicles, and the remaining 10% was by diesel vehicles.

Light-vehicle operating energy use = 4.118 × 90% + 3.275 × 10%MJ/vkm (see table 6.16) = (4.118 × 90% + 3.275 × 10%) ÷ 1.6 = 2.521MJ/pkm.

Therefore the total energy use for passenger transport using LPVs in 2007/2008 = 0.378 + 0.371 + 2.521 = 3.270MJ/pkm.

Road construction and maintenance contributed 12% to the total energy use; vehicle manufacture and maintenance contributed 11%; while operation of vehicles contributed 77%.

Cumulative energy use and GHG emissions of passenger transport by road

Cumulative energy use and GHG emissions for road passenger services, established on this basis, are shown in table 6.23. The LPV 2008 fleet estimate was based on the data in table 6.14, the average fuel use of petrol vehicles (9.9l/100km) reported by MoT (2009), and the average occupancy of 1.6 passengers. Owing to the lack of New Zealand data on LPV diesel fuel use, ecoinvent data for similar Swiss vehicles was used. LPV low and high estimates were based on the useful life estimates shown in table 6.14, and the minimum (9.8l/100km) and maximum (10.1l/100km) LPV petrol use reported by MoT (ibid) and ecoinvent data for diesel use in similar Swiss vehicles.

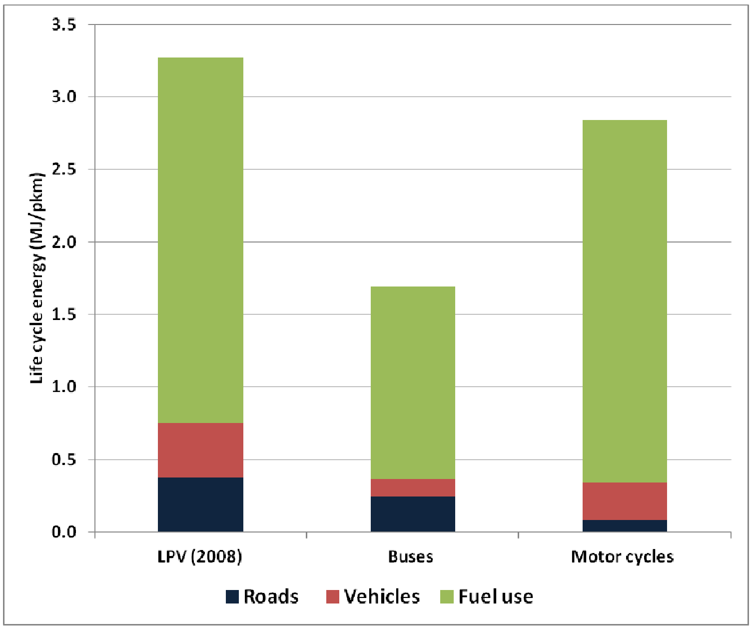
Table 6.23 Cumulative energy use and GHG emissions for road passenger services in 2007/2008

	Energy (MJ/pkm)[a]	GHG emissions ($kgCO_2e/pkm$)[a]
LPV, based on 2008 fleet		
Road construction and maintenance	0.378 (12%)	0.024 (12%)
Vehicle manufacture and maintenance	0.371 (11%)	0.018 (9%)
Vehicle operation	2.521 (77%)	0.166 (80%)
TOTAL	**3.270**	**0.208**
Motorcycle (useful life 100,000km/vehicle)		
Road construction and maintenance	0.083 (3%)	0.005 (3%)
Vehicle manufacture and maintenance	0.259 (9%)	0.040 (19%)
Vehicle operation	2.496 (88%)	0.164 (79%)
TOTAL	**2.838**	**0.209**
Bus (useful life 1 million km/vehicle)		
Road construction and maintenance	0.246 (15%)	0.016 (14%)
Vehicle manufacture and maintenance	0.114 (7%)	0.004 (4%)
Vehicle operation	1.335 (79%)	0.092 (82%)
TOTAL	**1.696**	**0.112**

a) Percentages may not add up to 100%, owing to rounding off.

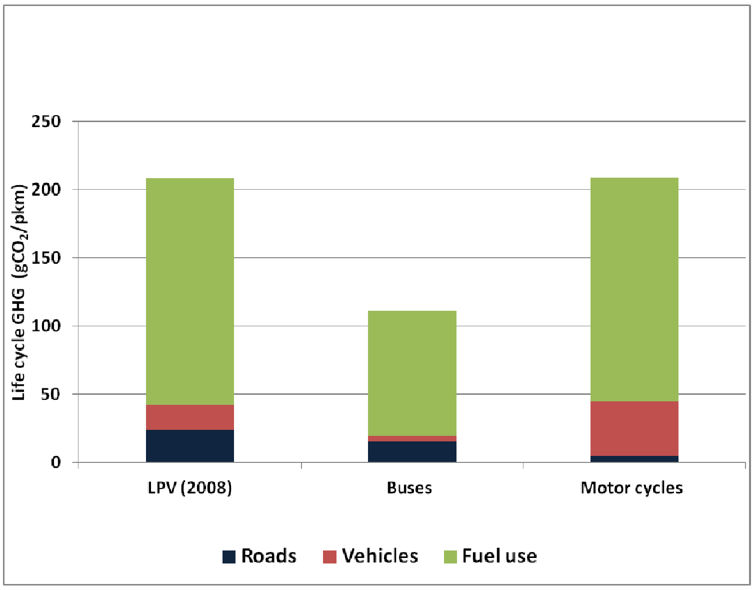
These results suggest that the contribution to the total energy use by road construction and maintenance (excluding road bridges) is small, ranging from 3–15% of the total for various modes. Vehicle operation is the most significant contributor, with 77–88% contribution to the total energy use, while vehicle manufacture and maintenance make a moderate contribution at 7–11% of the total energy use. In terms of GHG emissions, the contribution by the road construction and maintenance (including road bridges) is only 3–14% of the total, with vehicle manufacture and maintenance contributing 4–19%. Vehicle operation contributes 79–82% of the total GHG emissions. Since operational energy use and GHG emissions are significant, increased vehicle occupancy could lead to noticeable reductions in energy and GHG emissions for road passenger transport. However, owing to the lack of data, the useful life of motorcycles and buses used in New Zealand could only be estimated (see section 6.5.4 for the sensitivity of results to the assumptions used). A comparison of life cycle energy use of passenger transport using various on-road modes is shown in figure 6.1.

Figure 6.1 Cumulative energy use of passenger transport using various on-road modes



A bus with high occupancy (14 passengers/vehicle) has the least energy and emissions intensity, followed by a motorcycle with a lower vehicle weight per passenger. As energy and emissions estimates include the production of fuel, these estimates are higher than the direct energy and emissions from fuel use. For all modes other than motorcycle, the contributions from the EE of roads and vehicles are significant. Figure 6.2 is a comparison of life cycle GHG emissions from passenger transport using various on-road modes.

Figure 6.2 Comparison of lifetime emissions from passenger transport by roads



Suspended solids and heavy metals transported to water bodies due to passenger transport by road

Suspended solids and total heavy metals released by passenger road transport services are shown in table 6.24. These estimates are based on Timperley et al's (2005) data, which was based on the number of vehicles without distinguishing between vehicle types.

Table 6.24 Suspended solid and total heavy metals releases to water bodies attributable to passenger transport by road

Vehicle type	Suspended solids (g/pkm)	Zinc (mg/pkm)	Copper (mg/pkm)	Lead (mg/pkm)
LPV	0.642	0.230	0.034	0.029
Motorcycle	0.141	0.368	0.055	0.047
Bus	0.418	0.026	0.004	0.003

6.5.1.2 Freight transport by road

Cumulative energy use and GHG emissions for freight transport by road

Cumulative energy use and GHG emissions for road freight services are shown in table 6.25.

Table 6.25 Cumulative energy use and GHG emissions for road freight services in 2007/2008

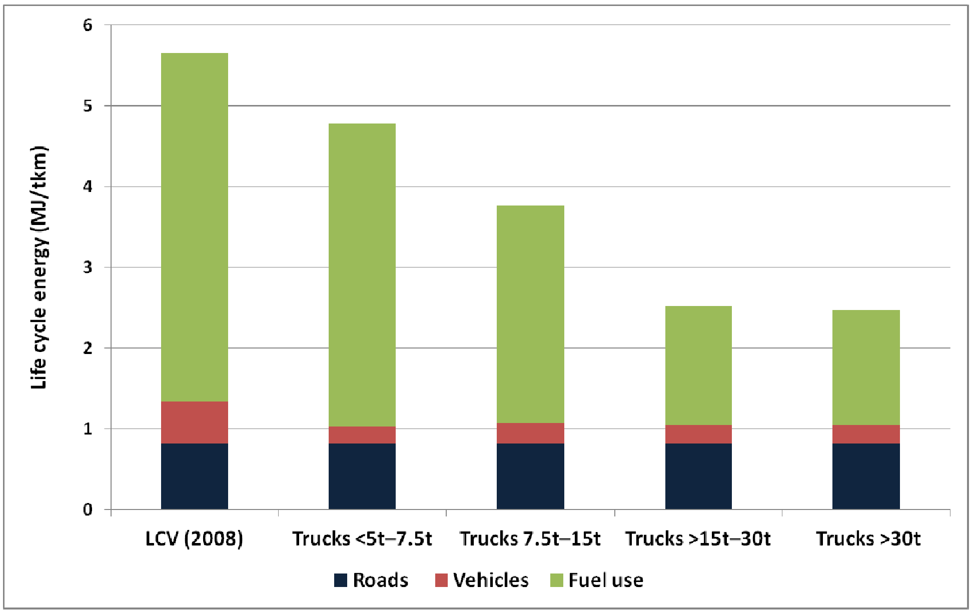
	Energy (MJ/Ntkm)[a]	GHG emissions (kgCO_2/Ntkm)[a]
LCV, based on 2008 fleet		
Road construction and maintenance	0.812 (14%)	0.051 (14%)
Vehicle manufacture and maintenance	0.524 (9%)	0.026 (7%)
Vehicle operation	4.312 (76%)	0.292 (79%)
TOTAL	**5.648**	**0.369**
Truck >5t-7.5t		
Road construction and maintenance	0.812 (17%)	0.051 (16%)
Vehicle manufacture and maintenance	0.221 (5%)	0.013 (4%)
Vehicle operation	3.740 (78%)	0.257 (80%)

	Energy (MJ/Ntkm)[a]	GHG emissions (kgCO$_2$/Ntkm)[a]
LCV, based on 2008 fleet		
TOTAL	**4.773**	**0.321**
Truck >7.5t-15t		
Road construction and maintenance	0.812 (22%)	0.051 (21%)
Vehicle manufacture and maintenance	0.264 (7%)	0.013 (5%)
Vehicle operation	2.692 (71%)	0.185 (74%)
TOTAL	**3.768**	**0.249**
Truck >15t-30t		
Road construction and maintenance	0.812 (32%)	0.051 (31%)
Vehicle manufacture and maintenance	0.232 (9%)	0.011 (7%)
Vehicle operation	1.474 (59%)	0.101 (62%)
TOTAL	**2.518**	**0.163**
Truck >30t		
Road construction and maintenance	0.812 (33%)	0.051 (32%)
Vehicle manufacture and maintenance	0.236 (10%)	0.010 (7%)
Vehicle operation	1.420 (58%)	0.098 (61%)
TOTAL	**2.468**	**0.159**

a) Percentages may not add up to 100%, owing to rounding off.

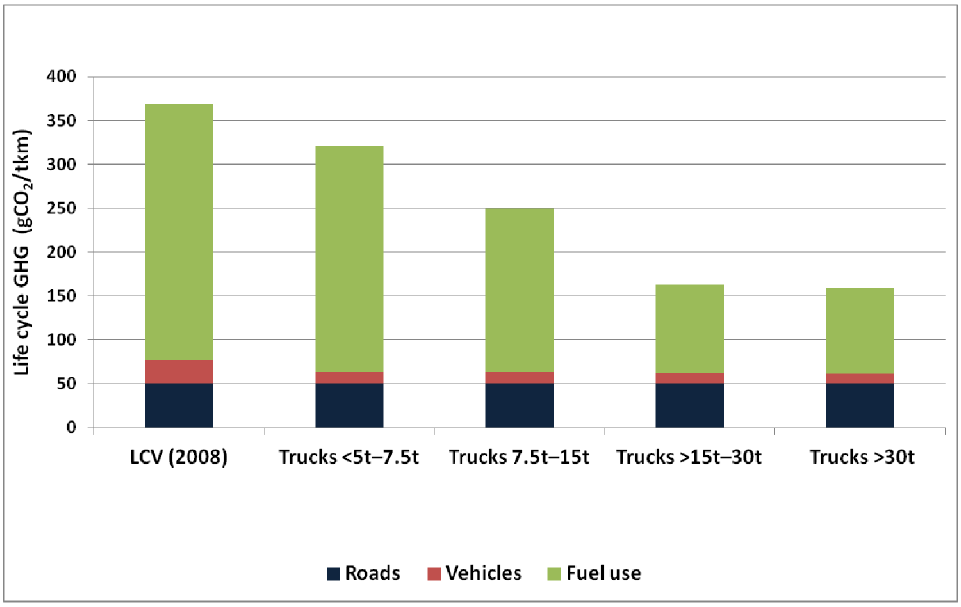
The results suggest that the contribution to the total energy use for freight transport services by road construction and maintenance range from 14–33%. Vehicle operation is the most significant contributor, contributing 58–78%; vehicle manufacture and maintenance make a moderate contribution, at 5–10% of the total. If GHG emissions associated with freight transport services are considered, the contribution to the total GHG emissions by road construction and maintenance ranges from 14–32%, while vehicle manufacture and maintenance contribute 4–7%. The contribution from vehicle operation is significant, ranging from 61–80%. Comparison of life cycle energy use for freight transport using various on-road modes is shown in figure 6.3.

Figure 6.3 Comparison of lifetime energy use for freight transport by on-road modes



The highest energy and emissions intensity is for the LCV, while the energy and emissions intensities of trucks decrease as the size of truck increases. Energy intensity and GHG emissions of LCV use for freight transport are twice those for large trucks. The contribution from road infrastructure and vehicle manufacture and maintenance is significant, with over a third of the total for use of heavy trucks. Figure 6.4 is a comparison of life cycle GHG emissions for freight transport using various on-road modes.

Figure 6.4 Comparison of lifetime emissions for freight transport by roads



Suspended solids and heavy metals transported to water bodies due to freight transport by road

Suspended solids and total heavy metals released by freight road-transport services are shown in table 6.26. These estimates are based on Timperley et al’s (2005) data, which was based on the number of vehicles without distinguishing between vehicle types.

Table 6.26 Suspended solid and total heavy metals releases to water bodies attributable to freight transport by road

Vehicle type	Suspended solids (g/tkm)	Zinc (mg/tkm)	Copper (tkm)	Lead (mg/tkm)
LCV	1.377	0.382	0.057	0.049
Truck <5t-7.5t	1.377	0.178	0.027	0.023
Truck >7.5t-15t	1.377	0.084	0.013	0.011
Truck >15t-30t	1.377	0.048	0.007	0.006
Truck >30t	1.377	0.033	0.005	0.004

6.5.2 Comparison of results with other studies

6.5.2.1 Passenger transport by roads

In an EIO-based LCA study of Australian transport with a base date of 1994/1995, Lenzen (1999) reported 4.4, 4.8 and 4.8MJ/pkm for petrol, diesel and LPG passenger cars, respectively. The contribution to the total energy intensity for infrastructure (eg roads, street lighting, etc) ranged from 13%–14% of the total, while fuel contributed 68–71% of the total. GHG emissions were reported as 0.34, 0.38 and 0.35kgCO_2e/pkm respectively, for petrol, diesel and LPG passenger cars. The energy intensity (GHG emissions) for the urban bus service was reported to range from 1.8–4.9MJ/pkm (0.15–0.39kgCO_2e/pkm), depending on the service operator. Fels (1975) reported an energy intensity of 2.3MJ/pkm for urban buses at an average occupancy of 10 passengers. However, she excluded embodied resource uses, such as fuel production, maintenance, street lighting and administration, which could explain her value being lower than Lenzen's.

In a study of passenger transport in the US, Chester's findings (2008, p62) were similar to Lenzen's: total energy use for sedan, SUV and pickup vehicles at 2.9, 4.1 and 4.9MJ/pkm, respectively. Total GHG emissions were 0.24, 0.28 and 0.39kgCO_2e/pkm for sedan, SUV and pickup, respectively.

There could be several reasons for this research's somewhat lower estimates for passenger cars, compared with those of Lenzen. Firstly, EIO-based LCA captures wider economic activities that were not included in the process-based assessment used in the current study. However, New Zealand input–output tables use a higher level of aggregation, leading to unreliable EIO assessments.

Secondly, although the power and weight of vehicles have increased, engine technologies have improved significantly, leading to a 1.5% annual reduction in fuel consumption for all vehicles (BTRE 2002).

Thirdly, road construction and maintenance practices in New Zealand are dissimilar to those used in Australia. Street lighting, traffic management, roadside barriers, embankments, etc, were excluded from the system boundary in this study.

6.5.2.2 Freight transport by roads

Lenzen (1999) reported an energy intensity of 48.8MJ/Ntkm for Australian freight transport that used LCVs. The energy intensity of articulated trucks and rigid trucks was estimated as 1.7MJ/Ntkm and 4.6MJ/Ntkm, respectively. On this basis, the energy intensity of truck use for freight transport is a tenth that of LCV use. Lenzen's (ibid) emissions estimate for articulated trucks (0.13kgCO_2e/Ntkm) is similar to the emissions estimate for >30t trucks in this study, while Marheineke et al (1998, cited by Lenzen) reported 0.1kgCO_2e/Ntkm for 40t truck use in Germany. In terms of emissions breakdown, Lenzen reported 78% and 7% respectively for fuel use and roads. The contribution from roads is much higher in this study (33%) than Lenzen's estimate, which was a result of weight-mass allocation used, rather than the distance travelled.

The life cycle energy use comparison of freight transport using various on-road modes, shown in figure 6.3, is in agreement with direct operational energy use (65–74% of the total) reported by Chester and Horvath (2009) for US road transport services.

6.5.3 Sensitivity of results to the assumptions used

The useful life of motorcycles and buses was estimated, owing to the lack of New Zealand data. The base case used a 100,000vkm and 1 million vkm as the useful life of a motorcycle and bus, respectively. The impact of this assumption was evaluated using a 200,000vkm useful life for a motorcycle and 1.8 million vkm for a bus.

The base case used the odometer readings of light vehicles that left the fleet in 2008 as the useful life of light passenger and freight vehicles used in New Zealand. The impact of this assumption was evaluated, using one scenario where the life of LPVs was increased to 250,000vkm and one scenario where it was reduced to 150,000vkm. For the LCVs, a useful life of 235,000vkm was used. The results of this assessment are shown in table 6.27. Useful life of vehicle has only a marginal effect on the results.

Table 6.27 Cumulative energy use and GHG emissions for road transport services under different scenarios

	Energy	GHG emissions
Passenger transport	**MJ/pkm**	**kgCO_2e/pkm**
LPV, base case	3.270	0.208
LPV, useful life 250,000vkm	3.188	0.204
LPV, useful life 150,000vkm	3.379	0.214
Motorcycle, base case (useful life100,000vkm)	2.838	0.209
Motorcycle, useful life200,000vkm	2.709	0.189
Bus, base case (useful life 1million vkm)	1.696	0.112
Bus, useful life 1.8 million vkm	1.645	0.110
Freight transport	**MJ/Ntkm**	**kgCO_2/Ntkm**
LCV, base case	5.648	0.369
LCV, useful life 235,000vkm	5.633	0.368

The above estimates have been based on the assumption that the maximum capacity of the road network in 2008 was similar to the actual use of the network. However, the actual maximum capacity of the road network could be much higher, which could lead to lower energy and emissions intensities for the infrastructure component than the above estimates for all transport services. The impact of the use of roads to the maximum capacity on the energy and emissions intensities of road transport services could not be evaluated, as this information was not readily available. However, its impact would be negligible for passenger transport and marginal for freight transport, considering that the maximum contribution from road construction and maintenance to the total energy and emissions intensities is less than 33% of the total.

6.5.4 Passenger and freight transport by rail

As with roads, rail infrastructure is also shared between passenger (Tranz Scenic, Tranz Metro and Auckland suburban) and freight transport services. In 2007/2008, the existing rail track (4190km[46]) and rolling stock carried 9530 million Gtkm, 92% of which was freight.

Propulsion energy for rail services is mainly provided by diesel, although parts of the network have been electrified. As with fuel production requirements, electricity production and transmission network losses have to be included. The New Zealand electricity mix varies on an annual basis, owing mainly to the higher proportion of hydro-generation, which is affected by rainfall levels. The primary energy content of a unit (kWh) of electricity generation in 2007 was 2.20kWh (7.91MJ/kWh), while CO_2 emissions were 0.202kg CO_2e/kWh (Barber 2009). Because of the elongated nature of the electricity grid, from one island to the other, electricity transmission and distribution losses in New Zealand are estimated to be 11% (Pce 2006). Based on these losses, a unit of electricity used in New Zealand on average embodies 8.78MJ/kWh primary energy and releases 0.224kg CO_2e/kWh. For this study, these values were used to estimate lifetime liabilities of electricity use for rail transport. Cumulative energy use and emissions for different passenger and freight transport services are shown in table 6.28.

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[46] This includes double-tracked length (214km) and sidings (105km).

Table 6.28 Cumulative energy use and GHG emissions for rail services in 2007/2008

Item	Energy (MJ/pkm)[a]	GHG emissions (kgCO_2/pkm)[a]
Freight transport		
Rail infrastructure	0.163 (20%)	0.015 (28%)
Rolling stock – locomotives, freight wagons	0.099 (12%)	0.001 (3%)
Fuel – diesel and electricity	0.562 (69%)	0.036 (68%)
TOTAL	**0.824**	**0.053**
Long-distance passenger transport – Tranz Scenic services		
Rail infrastructure	0.068 (12%)	0.0062 (16%)
Rolling stock – locomotives, carriages	0.011 (2%)	0.0005 (1%)
Fuel – diesel and electricity	0.509 (87%)	0.0322 (83%)
TOTAL	**0.587**	**0.0388**
Urban passenger transport – Tranz Metro services		
Rail infrastructure[b]	0.095 (9%)	0.009 (25%)
Rolling stock – locomotives, service units	0.032 (3%)	0.001 (3%)
Fuel – diesel[c] and electricity	0.906 (88%)	0.026 (72%)
TOTAL	**1.033**	**0.035**
Urban passenger transport – Auckland suburban service		
Rail infrastructure	0.195 (6%)	0.018 (8%)
Rolling stock – locomotives, service units	0.055 (2%)	0.002 (1%)
Fuel – diesel	2.901 (93%)	0.199 (91%)
TOTAL	**3.151**	**0.219**

a) Percentages may not add up to 100%, owing to rounding off.

b) This includes rail tracks, rail bridges and tunnels. Overhead power infrastructure for train control is not included.

c) Diesel is used on the Wairarapa line, which is part of the Tranz Metro service.

The results suggest that for freight transport, rail infrastructure construction and maintenance contribute 20% to the total energy use and 28% to the total emissions.

For passenger services, the contribution from rail infrastructure ranges from 6–12% of the total energy use and 8–25% of the total emissions. Rail operation is the most significant, contributing 71–93% to the total energy use. The contribution from rolling stock manufacture and maintenance is marginal, at 1–3% of the total energy use and GHG emissions. The contribution of rail operation to the total GHG emissions is significant, ranging from 70–91%.

Chester and Horvath (2009, p3) used economic-input–output life cycle assessment (EIO-LCA) in a similar study of passenger rail operations in the US, and reported the contribution of rail infrastructure and rolling stock combined to the lifetime energy use to be twice as much as that of rail operation. As US rail operational energy predominantly comes from fossil fuels, GHG emissions from infrastructure and rolling stock are correlated to energy use, and are reported to be 1.8–2.5 times the operational emissions for the various rail operations considered. However, this could be expected, as the study considered a shorter time span, ranging from 26 to 30 years, compared with the 40-year life used for rolling stock in this research. In addition, Chester and Horvath used EIO-LCA with a wider system boundary that included the rail stations, overhead power structures, signalling, etc.

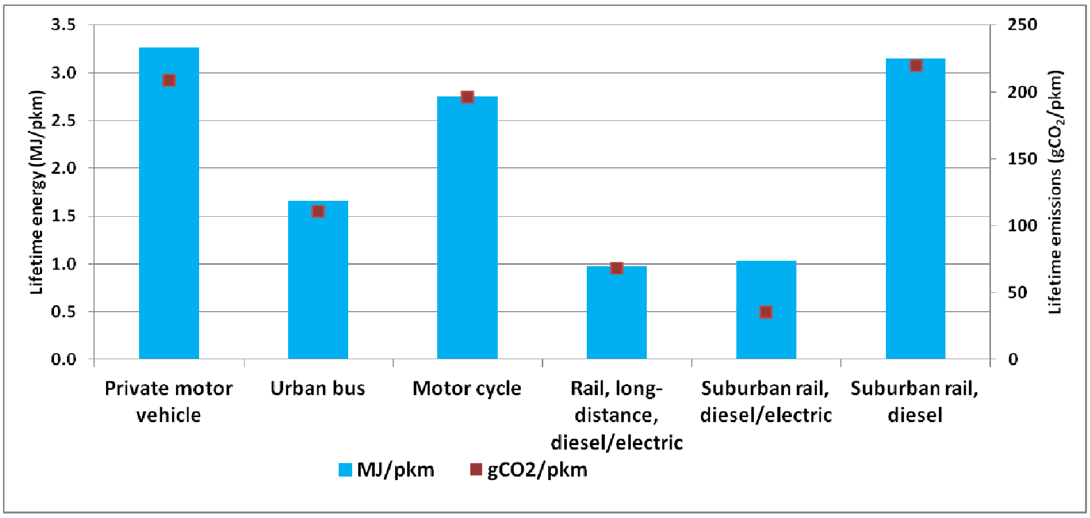
Lenzen's (1999, p235) energy intensity estimate for freight transport using rail in Australia (0.9MJ/Ntkm) is higher compared with the results obtained in this study. In terms of emissions, Lenzen's estimate for Australian rail freight transport (0.08kgCO_2e/Ntkm) is about 50% higher than the estimate for

New Zealand rail freight derived in this study. Energy intensity for Australian urban rail passenger services was reported to range from 2.4 to 4.0MJ/pkm, while emissions ranged from 0.23 to 0.36kgCO_2e/pkm (op cit).

6.5.5 Comparison of passenger and freight transport using roads and rail

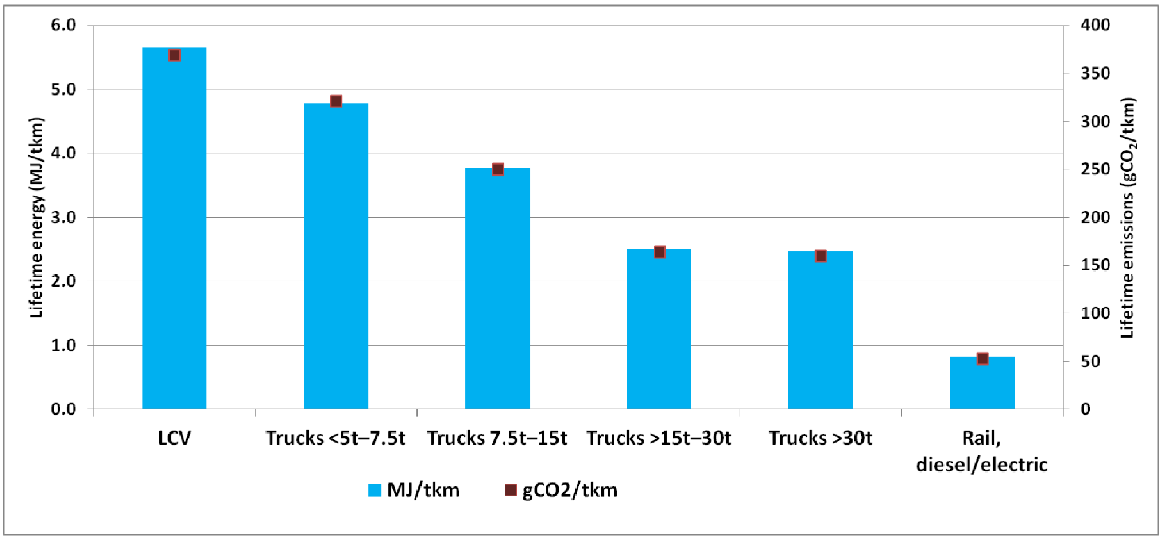
A comparison of lifetime energy use and emissions by passenger transport using roads and rail is shown in figure 6.5.

Figure 6.5 Comparison of lifetime energy and emissions from passenger transport by road and rail



A comparison of lifetime energy use and emissions for freight transport using roads and rail is shown in figure 6.6.

Figure 6.6 Comparison of lifetime energy and emissions from freight transport by road and rail



7 Conclusions

This research was based on a process-based LCA that considers material use, transport requirements, on-site machinery and fuel use. The impact of traffic delays due to construction and maintenance activities was not considered. The findings were as follows:

- The choice of construction type significantly alters the energy use and GHG emissions for the pavement constructions that are commonly used in New Zealand. The unbound granular construction system provides an environmentally friendly pavement solution, provided a sealed wearing course is used.
- At the time of this research, a third of the total network length, especially on rural roads, was unsealed. However, the wearing course construction type has a considerable impact on the energy use and GHG emissions for pavements – because of their high maintenance needs, their energy use and emissions over a 40-year period are four times those of pavements with sealed wearing courses. Sealing the unsealed length of the network could therefore significantly reduce the resource use associated with the existing road infrastructure.
- The contribution from earthworks to the energy and GHG emissions for pavements is moderate on flat terrain, but significant on hilly terrain.
- Steel rails for rail track construction are responsible for nearly half the lifetime GHG emissions and energy use for rail tracks. Currently, steel rails are sourced from China and data on current production practices and the energy mix used in Chinese steel factories are not published. The estimates derived in this study, based on published data, suggest that halving the energy and GHG emissions from steel production by sourcing rails from a best-practice factory in China could only moderately reduce the lifetime emissions and energy use for rail tracks. Therefore, if the environmental impacts of rail track infrastructure are to be reduced, alternative sources of steel rails need to be investigated.
- Rail tracks contribute 50% more GHG emissions than pavements (on a unit-length basis), although they are similar in energy use. However, at the time of this research, the rail infrastructure and many rural and special-purpose roads were being used at below capacity, while motorways were being used at maximum capacity. Any comparison of infrastructure systems needs to be made on the *actual* maximum capacity; however, data on the actual maximum capacity of New Zealand roads was not available for a comparison of roads and rail on that basis.
- Because fuel use is the most influential contributor to the energy and carbon intensity of passenger transport services, using lighter/smaller vehicles and increasing vehicle occupancy can make a significant difference. However, for freight transport services by road, the choice of vehicle and infrastructure is as important as the fuel used.
- The use of rail for passenger and freight transport leads to far greater reductions in energy and carbon emissions, when compared against all modes of road transport. As suburban passenger transport with electrified rail is more environmentally efficient than using diesel rail, the current initiative to electrify the suburban rail network in Auckland will reduce the environmental impact of passenger transport in Auckland.
- The main purpose of this research was to generate New Zealand-specific transport data. The study found the results derived using New Zealand data were drastically different from those derived using European data. It is therefore essential that any attempts to quantify the impact of transport policies and actions should be based on New Zealand data.

8 Recommendations

In order to reduce the environmental impacts of the transport sector, it is recommended that the NZTA should specify the use of:

- sealed wearing course as the standard practice for pavements, to avoid regular maintenance requirements that lead to higher energy use and emissions, in addition to causing traffic delays
- more durable construction types with lower maintenance needs when pavements are constructed on hilly terrains, as construction type has moderate impact on the total environmental impact.

It is recommended that KiwiRail should use locally sourced steel, with lower carbon emissions, for future rail track infrastructure.

In order to improve the reliability of transport data, further research into the following areas is recommended:

- long-distance and suburban bus services in New Zealand
- New Zealand freight movements, including vehicle fleet composition and average fuel use
- the current manufacturing practices and energy mix used in Chinese steel-manufacturing factories
- the quantity of contaminant transported by various vehicle types
- the cost of transport infrastructure construction, maintenance and operation.

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Appendix Energy intensity and emissions factors related to transport infrastructure and operations

Item	Units	Energy intensity (MJ/unit)	Emissions factor (kgCO_2e/unit)	Notes	Data source
Materials					
Aggregate	kg	0.06	0.0031	Sub-base, base course and sealing chips; based on New Zealand data for virgin rock	Alcorn 2003
Bitumen	m^3	2475	176	Chipseal, asphalt; based on New Zealand data for bitumen feedstock	
Cement	kg	6.2	0.994	Pavement stabilisation; New Zealand data	
Lime	kg	0.6	0.5	Subgrade improvement layer	Wells 2001
Rail tracks (single), steel, at rail construction site	m	1881.65	212.90	Based on Chinese steel manufacture (Price et al 2001), using Chinese energy mix for steel manufacture; includes transport of scrap from origin in the US to factory in China, and transport from Chinese factory to site	Calculated value
Sleeper, concrete, at rail construction site	no.	844.48	75.67	Using recycled Chinese steel, 40MPa concrete, Australian steel-fixing shoulders; includes energy uses for manufacture	Calculated value
Sleeper, softwood, treated, at factory	no.	3.94	0.207		Calculated value
Sleeper fastening, steel (Pandrol e-clips), at rail depot	no.	58.76	1.89	Using average Australian steel; includes steel-forming, transport from factory to overseas port, shipping and truck transport from New Zealand port to rail depot in Auckland	Embodied energy – *Your home technical manual*; CO_2 emissions – VicRoads GHG calculator
Sleeper fastenings, HDPE pads, at rail depot	no.	16.04	0.49	Rail pads; includes injection moulding, transport from factory to overseas port, shipping and transport from New Zealand port to rail depot	Calculated value using ecoinvent data for European plastic
Sleeper fastenings, Nylon spacer, at rail depot	no.	7.34	0.56	Material; includes transport from factory to overseas port, shipping and trucking from New Zealand port to depot	Calculated value using ecoinvent data for nylon

Item	Units	Energy intensity (MJ/unit)	Emissions factor (kgCO_2e/unit)	Notes	Data source
Transport					
28t truck & trailer/28t traytruck	tkm	5.104	0.325	Vehicle manufacture and maintenance and road use for transport included Represents New Zealand truck performance (fuel use), based on New Zealand diesel, and includes embodied resource use of diesel	Calculated value using ecoinvent data for 16–32t lorry
15t truck	tkm	4.95	0.305		Calculated value using ecoinvent data for 7.5–16t lorry
10-m^3 tanker	tkm	5.34	0.332		Calculated value using ecoinvent data for 7.5–16t lorry
Utility vehicle	km	22.60	1.481		Calculated value using ecoinvent data for van
Fuel and electricity					
Electricity, New Zealand average, 2007	kWh	8.78	0.2019	Based on Barber 2009; includes network and transmission losses	Calculated value Barber 2009
LPG, New Zealand	kg	55.9	3.357	Includes inputs to manufacture	
Diesel, New Zealand	litre	45.2	3.108		
Petrol, New Zealand	litre	41.6	2.735		
Rolling stock					
Carriage, 2007/08 fleet average	no.	1,733,000	66,000	Includes manufacture and maintenance	Calculated value
Goods wagon, 2007/08 fleet average	no.	4,469,000	60,000		
Locomotive, 2007/08 fleet average	no.	9,706,000	546,000		
Service unit, 2007/08 Tranz Metro fleet average	no.	3,854,000	147,000		

Item	Units	Energy intensity (MJ/unit)	Emissions factor (kgCO_2e/unit)	Notes	Data source
Pavement construction					
Construction, subgrade improvement layer	m^3	40.93	11.49	Includes lime, lime transport over 50km using 28t truck, on-site machinery and fuel for machinery	Calculated value
Construction, sub-base and base-course layers	m^3	753.97	45.52	Includes aggregate, aggregate transport over 25km using 15t truck, on-site machinery and fuel for machinery	
Construction, structural asphalt concrete layer 125mm thick	m^3	1841.21	120.38	Includes materials (bitumen, aggregate, fuel), transport of materials to site, on-site machinery and fuel use for machinery	
Construction, sealed wearing course 25mm thick	m^2	16.07	1.02	Includes bitumen and sealing chips, material transport to site, on-site machinery and fuel use for machinery	Calculated value
Construction, unsealed wearing course	m^2	17.76	1.06	Includes sealing chips, transport of chips to site, on-site machinery and fuel use for machinery	
Construction, OGPA wearing course 25mm thick	m^2	46.98	3.08	Includes materials (bitumen, aggregate, fuel), transport of materials to site, on-site machinery and fuel use for machinery	
Resealing, sealed wearing course	m^2	14.59	0.93	Includes bitumen and sealing chips, material transport to site, on-site machinery and fuel use for machinery	