Creating a positive drive

Decarbonisation of New Zealand's transport sector by 2050

thinkstep Australasia

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Document prepared by:

Jeff Vickers (PhD, LCACP)	Technical Director, Australasia
Ben Fisher	Sustainability Engineer
Queenie Hon	Sustainability Engineer

Quality assurance by:

Emily Townsend	Sustainability Engineer

Under the supervision of:

Barbara Nebel (PhD, LCACP)	CEO, Australasia

Contact

thinkstep Ltd

11 Rawhiti Road
Pukerua Bay
Wellington 5026
New Zealand

Web	www.thinkstep-anz.com
Email	anz@thinkstep.com
Twitter	@thinkstepanz
Phone	+64 4 889 2520

Contents

List of acronyms

BEV	Battery Electric Vehicle
EPD	Environmental Product Declaration
EV	Electric Vehicle
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWP100	Global Warming Potential with a 100-year time horizon
HFCV	Hydrogen Fuel Cell Vehicle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MBIE	Ministry of Business, Innovation and Employment
MfE	Ministry for the Environment
MoT	Ministry of Transport
NZ	New Zealand
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
UNFCCC	United Nations Framework Convention on Climate Change

Summary

Transport has a key role to play in New Zealand's low-carbon future

This report presents four future visions for New Zealand in which the carbon footprint of transport is reduced by up to 90% of 2015 levels by 2050 through a combination of new vehicle technologies and behavioural changes. It shows that vehicle technology will likely play the most significant role in decarbonising transport, but that changes in the way we think about mobility will help to drive down carbon emissions even further, while also reducing congestion, promoting healthier lifestyles and increasing security of fuel supply.

The scenarios considered are deliberately optimistic, focusing on a complete transition away from fossil fuels towards renewable electricity, renewable hydrogen and biofuels – all of which can be produced locally. The intention is to understand which changes are likely to lead to the greatest benefits if fully implemented, rather than being overly constrained by today.

The scenarios also consider how we want to travel, factoring in both 'business as usual', in which personal transport is private and individualised, and a different model based much more around the sharing economy. In all cases, the improvement over today is dramatic, indicating that transport has a key role to play in New Zealand's low-carbon future.

Transport is, on average, the leading contributor to the carbon footprint of New Zealanders

While New Zealand's electricity mix is approximately 80% renewable, our total energy mix is only 40% renewable, primarily due to the use of fossil fuels for transport. Transport contributed 19% of all greenhouse gases (GHGs) emitted in New Zealand in 2015. However, when accounting for the emissions embodied in exports (dairy, meat, etc.) and imports (cars, trucks, clothes, etc.), transport jumps to over 40%, making it the single most important area where we as New Zealanders can reduce our national carbon footprint through our own purchasing decisions.

Two complementary courses of action

There are two complementary courses of action: technology (e.g. switching from petrol and diesel vehicles to electric vehicles, biofuels and/or hydrogen fuel cells) and behavioural change (e.g. ride-sharing and public transport). Importantly these two paths are multipliers rather than being mutually exclusive, meaning they can be pursued together to increase the rate and scale of change.

Technological change will be the biggest win, but will take time to roll out

Much of the transition to low-carbon transport can be met through vehicle technology alone. Over the next 30 years, New Zealand will undergo significant technological changes across the vehicle fleet through the introduction of battery-electric vehicles, drop-in (second generation) biofuels, and hydrogen fuel-cell vehicles.

Electric vehicles (EVs) offer the greatest potential for emissions reductions in the New Zealand context, particularly if we can move our electricity grid close to 100% renewable over the next few decades. Biofuels and/or renewable hydrogen are also likely to play an important part in the transport energy mix, particularly for heavy and commercial vehicles where range, refuelling times

and cost may be the deciding factors. For ships and planes, drop-in biofuels seem to be one of the few technologies currently capable of offering equivalent performance to fossil fuels.

This report shows that we could reduce operational GHG emissions by 56% to 95% if we had the ability to replace New Zealand's entire vehicle fleet and fuel mix overnight. At the low end of this spectrum, all vehicles are assumed to run on 100% drop-in biofuels produced in New Zealand from our current electricity grid (approximately 80% renewable). At the high end of this spectrum is full conversion to electric vehicles powered by a 100% renewable electricity mix, with drop-in biofuels for ships and planes. The performance of hydrogen is largely dependent on the renewability of the electricity it is produced from. Assuming hydrogen is used for light commercial and heavy vehicles only, the reductions in operational GHG emissions range from 64% using today's electricity grid to 91% for a fully renewable grid.

Behavioural change will be most effective if it happens now

Behavioural change will be more effective in reducing the carbon footprint of today's fossil fuelled transport fleet than it will be in 2050. This is because behavioural change primarily reduces demand for passenger cars and these cars are already beginning to transition towards electric.

The total effect of all behavioural changes considered in this study is an estimated 29% reduction in the carbon footprint of the transport sector, assuming these changes happened tomorrow. By 2050, the significance of behaviour change reduces to a 10-15% improvement, assuming the electricity mix is 100% renewable by that time. Early carbon savings through quick implementation will buy time and space in the carbon budget for longer-term technology development.

Ride-sharing has the potential to contribute to the greatest overall improvement in carbon footprint from behaviour change, followed by increased uptake of public transport. Importantly, the uptake of ride-sharing can be increased dramatically very quickly with minimal investment while also providing the additional benefits of reducing congestion and helping to recreate a sense of community.

Achieving a transition to low-carbon transport by 2050 is possible, but requires trade-offs

If we look out to 2050 – factoring in growth in population and urbanisation – it is possible to visualise what a low-carbon transport model might look like for New Zealand. Four scenarios for 2050 are presented in Figure 1 to understand the effects of:

- **Technological change (horizontal axis):** The scenarios consider the difference between biofuels versus hydrogen fuels cells for heavy and commercial vehicles. In all cases, EVs are assumed for 100% of the passenger vehicle fleet and biofuels for ships and planes.
- **Behavioural change (vertical axis):** Travel is defined as either 'individual' or 'shared and avoided'. 'Individual' travel is business as usual accounting for growth due to population and urbanisation. It results in the number of passenger cars and light commercial vehicles on the road increasing linearly. 'Shared and avoided' travel considers reductions in passenger journeys through increased uptake of public transport, car sharing, teleworking and home deliveries from online shopping. It results in fewer cars on the road, but greater use of light commercial vehicles to deliver goods to people's homes.

Each scenario in Figure 1 presents a possible future where the domestic GHG emissions from transport are reduced by 80% to 90% of 2015 levels by 2050. Achieving such large improvements comes with trade-offs: electricity generation would need to nearly double, or 5% of all agricultural land in New Zealand would need to be converted to biofuel production. It is also likely that these scenarios would take the full 30 years to be realised, given the scale of renewable energy that would need to be produced and that some of the required technology is not yet fully commercialised.

Time for government and business to act

What is clear from Figure 1 is that no matter which scenario you consider, the improvement from today is dramatic, indicating that New Zealand has significant potential to reduce the carbon footprint of our transport fleet, and of our country as a whole.

A reduction in transport emissions by 90% would reduce New Zealand's total gross GHG emissions by 17%, assuming that the share of emissions from transport remains constant in the future. The good news is that many of the solutions to rapidly decarbonise New Zealand's transport sector already exist.

The role of government and business, as we see it, is to make these low-carbon choices easy and convenient. Encouraging uptake of ride-sharing through widespread use of carpool lanes and other incentives offers the potential for a quick-win, alongside creating a pricing model for electric vehicles that makes them attractive to New Zealand consumers. Investment in biofuels and renewable hydrogen, together with continued investment in renewable electricity generation, seem like logical next steps beyond this.

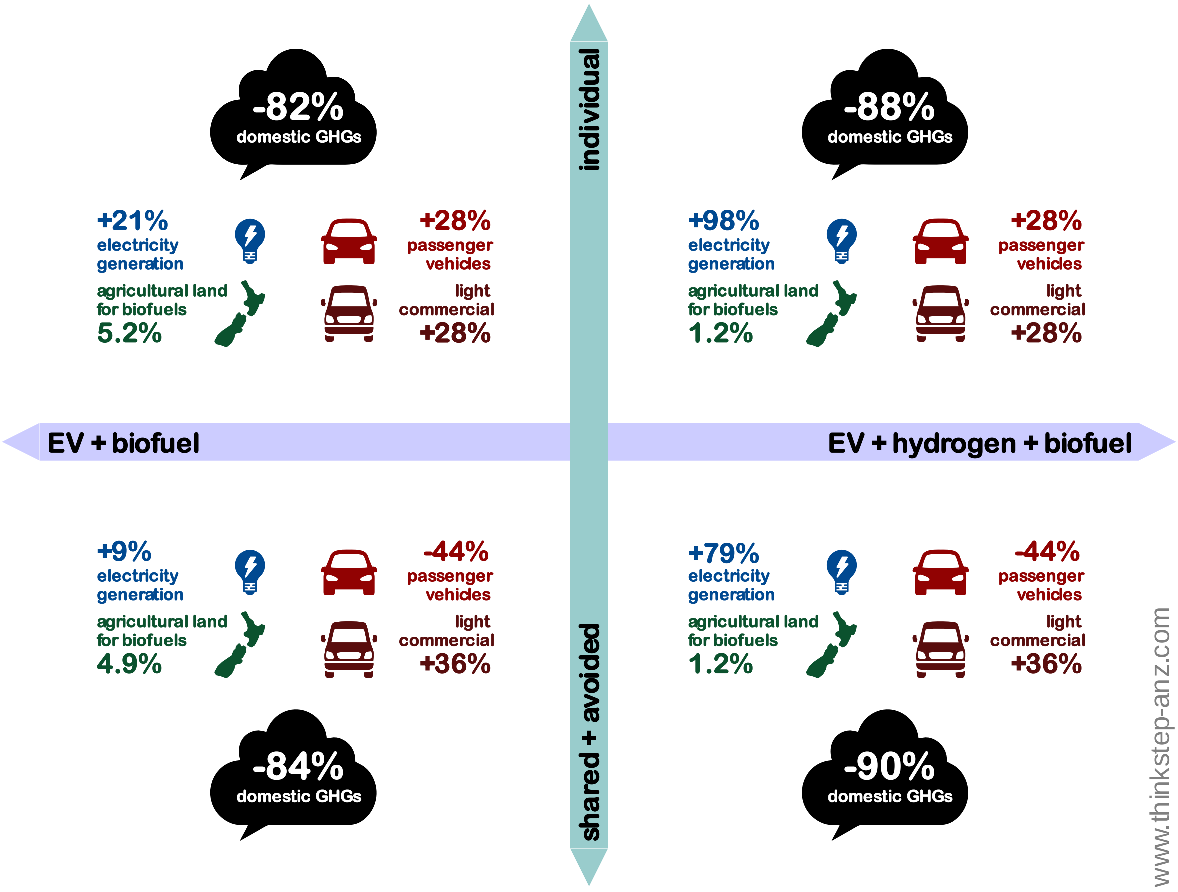

Figure 1: Transport scenarios for 2050 relative to 2015 (savings include domestic GHG emissions only)

1. Introduction

1.1. Background

New Zealand's electricity mix is approximately 80% renewable; however, our total energy mix is only approximately 40% renewable when we consider fossil fuels for transport (petrol, diesel, etc.) and stationary combustion (natural gas, LPG, etc.) alongside renewables (MBIE, 2018).

Our current reliance on fossil fuelled vehicles means that transport contributed 19% to New Zealand's total carbon footprint in 2015 (MfE, 2017). While similar to the global average (Sims, et al., 2014), the use of percentages masks the fact that our renewable electricity is effectively being cancelled out by our large share of agricultural emissions – the highest in the OECD per capita (Productivity Commission, 2018) – much of which are for products which are then exported.

The IPCC's recent special report on limiting global temperature rise to 1.5°C (Allen, et al., 2018) argued that:

> Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*).

Action is therefore needed now if we are to come close to the 1.5°C global warming target.

1.2. What is a carbon footprint?

When applied to a product, a carbon footprint is the "sum of greenhouse gas emissions and greenhouse gas removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change" (ISO, 2018, section 3.1.1.1).

A carbon footprint of a nation state is the same except the 'product system' becomes a national boundary. In this report, we focus on 'gross' greenhouse gas (GHG) emissions, i.e. we exclude removals of carbon dioxide from the atmosphere, primarily due to growth of trees. This is done simply because we are interested in sources of emissions, not sinks for them. When carbon dioxide stored in forests is included, this is referred to as 'net' GHG emissions or a 'net' carbon footprint.

The unit *kilograms of carbon dioxide equivalents* (kg CO_2e) is used to represent the potential of GHGs to contribute to climate change via global warming. To convert from emissions of individual GHGs to a potential impact upon the climate, each GHG has a characterisation factor applied. This report applies the characterisation factors for GWP100 (Global Warming Potential with a 100-year time horizon) from the Intergovernmental Panel on Climate Change's Fourth Assessment Report (Forster, et al., 2007) to align it with *New Zealand's National Greenhouse Gas Inventory*.

GWP100 following IPCC AR4 applies the following characterisation factors:

- Carbon dioxide (CO_2): 1 kg CO_2e
- Methane (CH_4): 25 kg CO_2e
- Nitrous oxide (N_2O): 298 kg CO_2e

According to ISO 14067:2018, a carbon footprint study must have both a goal and a scope, as described in the next section. While this study is much higher-level than a conventional product carbon footprint, the same structure (goal, scope, inventory, impact assessment and interpretation) applies to all life-cycle approaches within the ISO framework following ISO 14040:2006 (ISO, 2006).

1.3. Goal of this study

The goal of this study is to understand which of the various pathways towards a low-carbon transport sector are likely to be most effective within the New Zealand context. It considers both technological change, such as electric vehicles, and behavioural change, such as ride-sharing. The scenarios considered are deliberately optimistic, focusing on a complete transition away from fossil fuels towards renewable electricity, renewable hydrogen and biofuels. This report aims to understand what good would look like. That is, which strategies – if fully implemented – would have the greatest impact on reducing carbon footprint, irrespective of their economics today?

This study is aimed at businesses, policy-makers and individuals who are interested in tackling climate change in the New Zealand context.

1.4. Scope of this study

This study applies to New Zealand in the year 2015 (baseline/reference year) and the year 2050 (for future scenarios). A 2015 reference year has been chosen to align with *New Zealand's Greenhouse Gas Inventory 2017* (MfE, 2017), which was also used in a previous report by thinkstep on the carbon footprint of the built environment (Vickers, et al., 2018). In 2015, New Zealand's electricity was 81% renewable and our total energy mix was 40% renewable (MBIE, 2016).

This study considers all major vehicle types (passenger cars, motorcycles, light commercial vehicles, heavy trucks, buses, trains, ships and planes), as well as active transport (walking and cycling). While this study is oriented towards the future, it focuses on conventional vehicles rather than nascent technologies such as flying taxis (Air NZ, 2018) and drone deliveries (Ryan, 2016). Although these new technologies certainly have the potential to disrupt the current technology mix, it is likely they will rely on similar propulsion technologies to current vehicles and therefore can be driven towards a low-carbon path in a similar way to conventional vehicles.

This study also considers a range of behavioural changes that have the potential to significantly reduce the carbon footprint of transport. The behavioural changes considered include increased uptake of public transport, ridesharing (carpooling), teleworking (working from home or other offsite location), increased uptake of active transport (walking and cycling), online shopping with home delivery and delivery of prepared meals.

The 2050 scenarios also consider expected growth in population and urbanisation, which affect the potential number of journeys taken and the amount of goods transported.

1.5. Structure of this report

This report starts by addressing the question: **Why focus on transport?**

The section titled **Approach** presents the calculation method through which the transport sector was disaggregated and analysed.

It then considers the two complementary courses of action to decarbonise transport:

1. **Technological change**, e.g. switching from petrol and diesel vehicles to electric vehicles, biofuels and/or hydrogen fuel cells; and
2. **Behavioural change**, e.g. ride-sharing and public transport.

Scenarios for 2050 then adds a time dimension, factoring in changes in population and urbanisation, to understand the potential significance of both technology and behavioural change to New Zealand's future.

The report ends with **Conclusions**, which present the key findings of the study.

2. Why focus on transport?

2.1. Understanding the hotspots in New Zealand's carbon footprint

Figure 2a presents the classic production-oriented view of New Zealand's carbon footprint as used in (RSNZ, 2016), (Vivid Economics, 2017) and (Productivity Commission, 2018). This view derives from *New Zealand's GHG Inventory* and splits emissions into 'energy', 'industry', 'agriculture', 'land use, land-use change and forestry' and 'waste'. 'Energy' is often further divided into 'transport', 'electricity' and 'heat'. Emissions are allocated in the sectors where they occur, e.g. methane from cows falls under 'agriculture' and combustion of fossil fuels falls under 'energy'.

Use of production perspective is entirely appropriate in the context of reducing our national carbon footprint. It is the reporting format used within the United Nations Framework Convention on Climate Change (UNFCCC) and subsequent amendments through the Kyoto Protocol and Paris Agreement. As a nation, we are responsible for everything that happens within our own geographic boundary.

However, a production-oriented view does not help us to understand the demand that ultimately drives production. Furthermore, if used alone, this production perspective can allow nations to shift primary industry offshore to meet their national targets. Given that climate change is a shared problem, shifting the burden will not help us to tackle it; instead, we must take responsibility for the emissions we create through our decisions.

Figure 2b and Figure 2c flip the perspective from production to consumption. International trade is excluded from Figure 2b but included in Figure 2c. By accounting for the carbon footprint embodied in our exports (dairy, meat, etc.) and our imports (cars, trucks, clothes, etc.), transport jumps up to 44% of our national carbon footprint (Figure 2c), the single-largest hotspot.

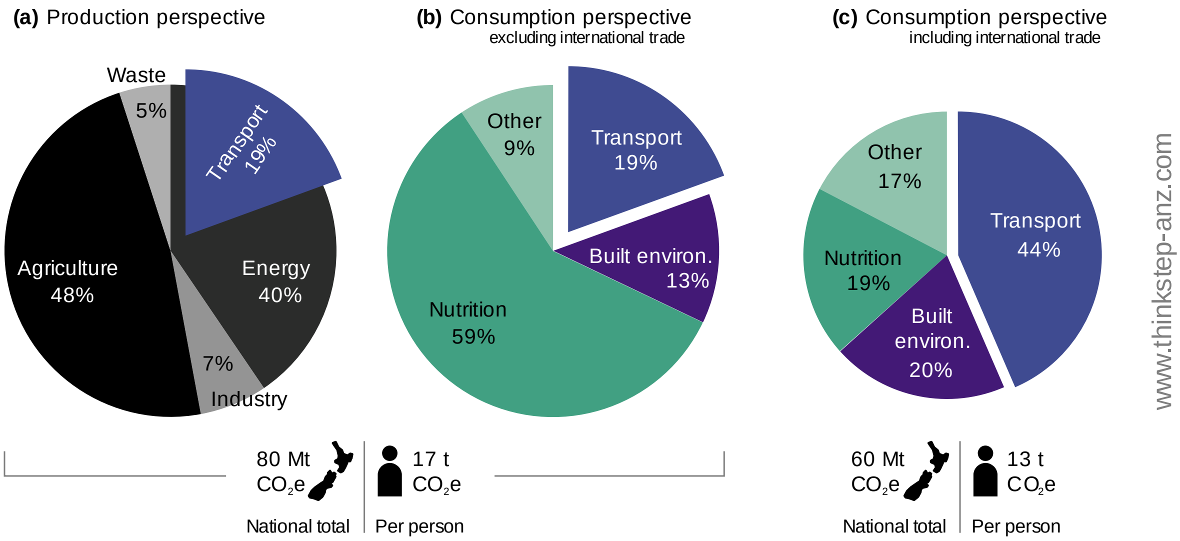

Figure 2: A breakdown of New Zealand's carbon footprint in 2015 from (a) a production perspective, (b) a consumption perspective excluding trade, and (c) consumption perspective including trade

2.2. A consumption-oriented approach

In carbon footprint terms, *New Zealand's GHG Inventory* covers Scope 1 and Scope 2. Three 'scopes' are used when calculating the carbon footprint of an organisation (GHG Protocol, 2015):

- Scope 1 is direct emissions, e.g. combustion of fossil fuels on-site.
- Scope 2 is indirect emissions, notably consumption of electricity.
- Scope 3 is upstream and downstream emissions, e.g. production of raw materials.

Scope 1 and Scope 2 emissions must always be reported under our national greenhouse accounts. However, Scope 3 is excluded if parts of the value chain occur overseas. The use of life cycle thinking to account for Scope 3 emissions is vital to prevent burden-shifting. To understand why, consider this example:

> How do we meet our national target of reducing New Zealand's carbon footprint by 30% from 2005 levels by 2030?
>
> One simple though controversial answer would be to wind down our domestic dairy and meat industries, import dairy and meat products instead, and substitute lost export earnings with tourism. This 'solution' works because enteric fermentation from livestock is the single biggest GHG hotspot in our national inventory, contributing 35% of total gross carbon footprint in 2015, while there are no emissions from international travel because they occur over international waters (emissions are calculated, but they are reported as standalone values) (MfE, 2017).
>
> While this might meet our international climate obligations, this approach would likely lead to an increase in carbon footprint at a global level unless all New Zealanders became vegetarians overnight. This is because long-haul flights (to support our tourism industry) would increase, global demand for meat and dairy would remain the same, additional production capacity for meat and dairy would emerge somewhere else (with potentially higher GHG emissions per unit production), and these products would now need to be shipped to New Zealand rather than produced domestically.

Climate change is a global problem. GHG emissions released in New Zealand have essentially the same impact as those produced anywhere else in the world. We therefore need to find solutions that reduce our domestic carbon footprint while also reducing global emissions. Put another way, we need to understand both the production and consumption perspectives. This report presents results from both the production and consumption perspectives. If not otherwise stated, the production perspective has been applied.

2.3. Analysing an intermediate level of the economy

While less common that the production-oriented view, there are existing analyses of New Zealand's carbon footprint from a consumption viewpoint, notably Romanos and colleagues (2014) and Chandrakumar and colleagues (2018). The main difference between this report and past work is the unit of analysis. Romanos and Chandrakumar use a technique called economic input-output life cycle assessment (EIO-LCA) to relate carbon footprint to categories of household expenditure. Using this approach, it is only possible to split out impacts of the private and public transport, as the impacts of the freight are divided up into the various categories of household expenditure. For example, the carbon footprint of getting your hair cut would include the transport of haircare products to the hair dresser, emissions from heating your hair dresser's building, their electricity consumption, disposal of their waste, and all other components of their carbon footprint.

The purpose of this report is to present transport in its entirety, not split across multiple categories. As such, rather than focus on consumption by households (final consumers), we focus on consumption at an intermediate level of the economy. Alongside ‘transport’, we split out ‘nutrition’, ‘built environment’ and ‘other’. (‘Other’ includes sanitation, clothing and other emissions not easily included elsewhere.) While nutrition and the built environment are not the focus of this report, these three categories are the main hotspots from the perspective of final consumption in both New Zealand (Romanos, et al., 2014) and the European Union (Tukker, et al., 2006).

2.4. A life cycle perspective

The aim of this report is to look at transport in its entirety, not just emissions during operation. By applying life cycle thinking to transport, we must consider manufacture of vehicles, shipping of vehicles to New Zealand, production of the energy needed to operate the vehicles, emissions during operation, vehicle maintenance, and vehicle disposal at end-of-life.

‘Life cycle thinking’ is used here as a general term to describe the various life cycle approaches standardised at an international level: ISO 14040 and ISO 14044 for life cycle assessment (LCA) of products and services (ISO, 2006), ISO/TS 14072 for LCA of organisations (ISO, 2014) and related standards such as ISO 14067 on the carbon footprint of products (ISO, 2018).

The core of life cycling thinking is its holistic approach – an approach designed to help prevent burden-shifting when making comparisons. This burden-shifting can occur in many ways: from one region to another, from one time to another, from one medium to another (e.g. exchanging soil emissions for water emissions), from one environmental impact to another (e.g. exchanging carbon emissions for acidifying emissions), etc. Unlike a full LCA, a carbon footprint only considers one environmental indicator (climate change); however, the approach is otherwise the same.

This report considers the full lifecycle of the transport category from ‘cradle to grave’ to the extent possible with the national data available. Given that the aim is to capture transport in its entirety, transport of building products and food (and their associated waste products) are included in ‘transport’ rather than ‘built environment’ or ‘nutrition’. Our goal has been to include those things that either make up or are required to deliver the final product/service. This approach broadly follows the Greenhouse Gas Protocol’s distinction between ‘attributable’ and ‘non-attributable’ processes, where material and energy flows that do not become part of the final product can be considered ‘non-attributable’ and are optional within the carbon footprint (GHG Protocol, 2013, pp. 35-36). An overview of what is included within each category is provided in Table 1. For detailed calculations and results, please see (Vickers, et al., 2018).

Table 1: Categories included within each intermediate consumption category

Category	Includes	Excludes
Transport	• Manufacture of vehicles (cars, trucks, etc.) • Use of vehicles (e.g. transport of people & goods). • Production of energy / fuels	• Disposal of vehicles (as hard to separate and low emissions).
Nutrition	• Production of food and beverages for domestic consumption, including on-site emissions and food manufacturing. • Treatment of food waste in landfill and in residential wastewater.	• Transport of food and beverages (included under Transport). • Residential cooking (included under Built Environment). • Production of food for export.
Built Environment	• Construction and maintenance of residential buildings, commercial buildings and infrastructure (roads, railways, bridges, wastewater treatment networks, etc.). • Operation of buildings. • Disposal of building waste and garden waste.	• Transport of building materials to site (included under Transport). • Operation of transport networks (included under Transport). • Production of building products for export.

3. Approach

The approach taken to calculate the transport emissions for each scenario was to deconstruct the total GHG emissions of the New Zealand transport fleet and then to vary each influencing factor based on possible future scenarios, following a similar approach to that outlined in the "Transport" chapter of the *IPCC's Fifth Assessment Report* (Sims, et al., 2014) and as shown in Figure 3.

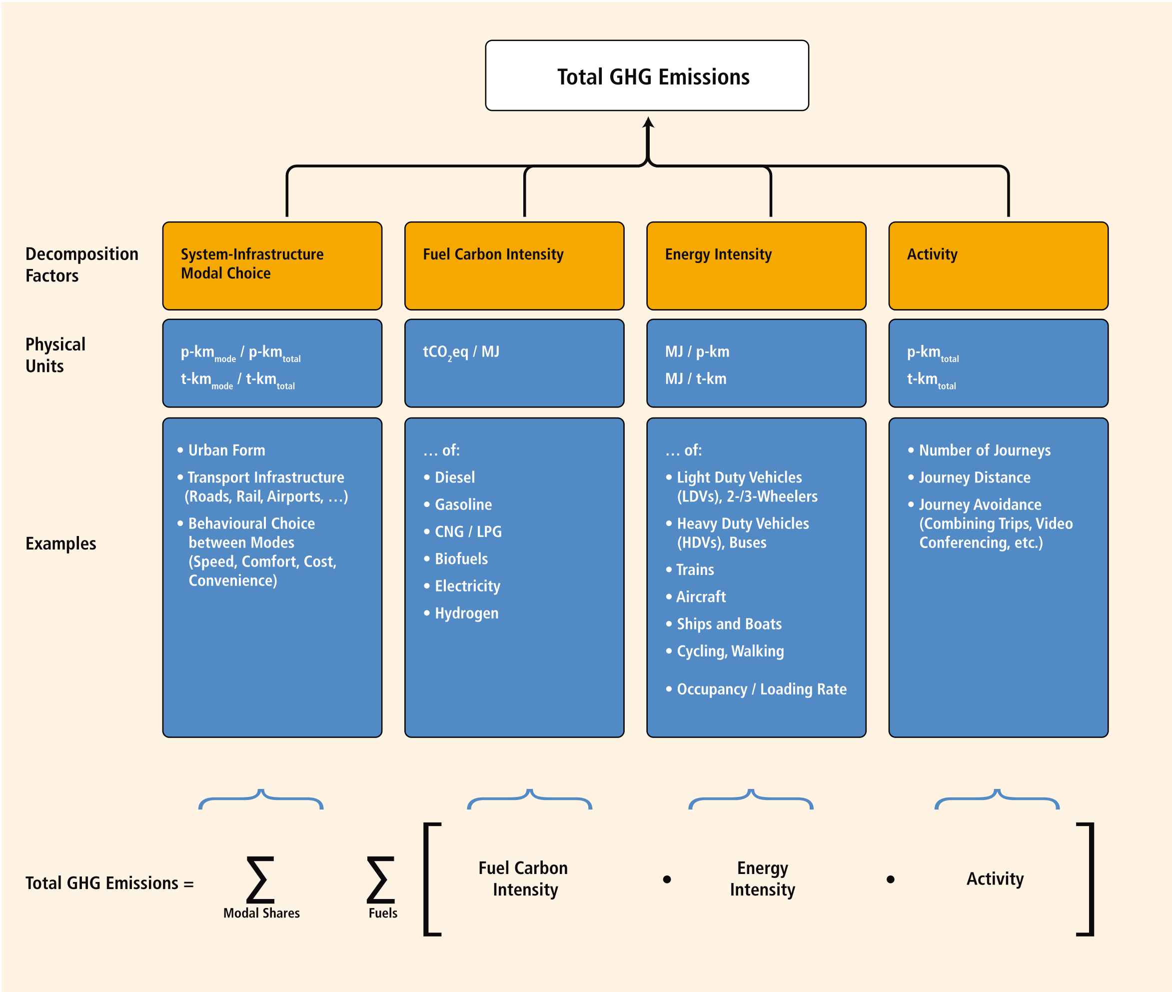

Figure 3: Calculation of direct GHG emissions from transport, reproduced from (Sims, et al., 2014)

The following equation relates each influencing transport factor to the emissions of the total transport sector. The value applied to each factor was identified from literature research and calculations for the current fleet, then adjusted to reflect technological or behavioural changes in each of the other scenarios presented within this report.

$$\sum_{Fuel\ type} \sum_{Transport\ mode} \binom{Fuel\ emission}{factor} \times \binom{Fuel}{economy} \times \binom{Number\ of}{journeys} \times \binom{Average\ journey}{distance} \times \binom{Correction}{Factor}$$

Each factor is explained in further detail below.

Fuel emission factor (kg CO_2e/MJ)

Emission factors are the amount of GHGs contributing to global warming per megajoule of each fuel combusted and are based on published values from a range of sources. These factors are given in Table 7 for domestic combustion emissions and fuel production emissions which occur within New Zealand and Table 8 for emissions occurring offshore, e.g. solar panel production and offshore fossil fuel production.

Fuel economy (MJ/km or MJ/tkm)

The fuel economy of each vehicle class and fuel type was calculated based on literature sources. Fuel economies are calculated per vehicle-kilometre for passenger vehicles, light commercial vehicles and public transport and per tonne-kilometre for freight vehicles. The chosen values are displayed in Table 6.

Number of journeys

The number of journeys was found from New Zealand transport statistics for each vehicle class. These values are affected by various behavioural aspects and modal shifts between transport types for each of the scenarios. For example, an increase in car sharing results in a decrease in vehicle journeys. This is described further in section 5.

Average journey distance (km)

The average journey distance is taken from average New Zealand transport statistics for each vehicle class. Transport distances are modified for each scenario based on assumptions surrounding infrastructure changes.

Correction factor

The emissions calculated from activity statistics have been compared at a national level to *New Zealand's Greenhouse Gas Inventory* (MfE, 2017). The calculations based on average activity data were generally found to be lower than the emissions data from the GHG Inventory. A correction factor was applied to each vehicle class's emissions to generate the same outcome for the current day scenario. This factor is assumed to account for differences between stated fuel economies of the vehicles and real-world driving conditions, which result in lower fuel economies. The correction factor also accounts for discrepancies in the statistics used for the number of journeys and the average journey distance travelled. The same correction factor for each vehicle class has been applied to all scenarios.

4. Technological change

4.1. Overview

Over the next 30 years, New Zealand will undergo significant technological changes across the vehicle fleet through the introduction of electric vehicles and renewable fuels, while at the same time existing commitments will likely lead to further decarbonisation of our electricity grid. Promising technologies for creating a low-carbon transport fleet include battery-electric vehicles (BEVs), drop-in biofuels, and hydrogen fuel-cell vehicles (HFCVs).

BEVs seem to have already won the technology war for light passenger vehicles, with billions of dollars being invested and more than 200 electric and plug-in model launches already scheduled over the next three years (Frost, 2018).

Although BEVs offer superior efficiency and the lowest life-cycle carbon footprint of these three technologies (Figure 4), drop-in biofuels and HFCVs may be preferable in some cases, particularly for heavy and commercial vehicles – where range, refuelling times and cost may be the deciding factors – and for ships and planes where there are few alternatives to conventional fossil fuels, making drop-in biofuels the most likely replacement (Suckling, et al., 2018).

The effectiveness of BEVs and HFCVs at reducing the carbon footprint of transport depend heavily on the renewability of the electricity grid. For BEVs, this is simply because electricity is used directly to charge the vehicles. For hydrogen, it is because the renewable route for hydrogen production is electrolysis, using electricity to split water into hydrogen and oxygen. This means that it is possible to produce renewable hydrogen, but only if the source of electricity is itself renewable.

The effectiveness of biofuels depends heavily on the technology type selected. Most biofuels on the market today are first generation, meaning that they are derived directly from food crops, either from primary crop (e.g. ethanol produced from corn to substitute for petrol in Brazil and the USA) or from food waste (e.g. used cooking oil or expired vegetable oil for biodiesel production) (Suckling, et al., 2018). These first-generation fuels are not chemically identical to the fuels they replace, meaning that they can typically only be used in blends with fossil fuels in conventional engines (typically between 5% and 20% biofuel), otherwise a flexible-fuel engine may be required. However, there is significant development work going into second generation biofuels which would be chemically identical to current fossil fuels (i.e. a drop-in replacement) and derived from waste products (e.g. wood residues) rather than competing with food crops (Suckling, et al., 2018).

4.2. Scope

The following vehicle groups have been included within this report:

- Passenger cars
- Light commercial vehicles
- Motorcycles
- Trucks
- Buses
- Passenger trains
- Freight trains
- Domestic passenger aircraft
- Domestic ships (coastal shipping)
- Domestic freight aircraft
- International aircraft
- International ships

Ferries are excluded because they are likely to make a very small contribution to the overall GHG emissions of transport and the available data are not good enough to represent them accurately,

While this study is oriented towards the future, it focuses on conventional vehicles rather than nascent technologies such as flying taxis (Air NZ, 2018) and drone deliveries (Ryan, 2016). Although these new technologies certainly have the potential to disrupt the current technology mix, it is likely they will rely on similar propulsion technologies to current vehicles and therefore can be driven towards a low-carbon path in a similar way to conventional vehicles.

Where applicable, the following fuel types have been considered in the current and future scenarios for each of the vehicle types listed above:

- Petrol
- Diesel
- Bioethanol
- Biodiesel
- Electric
- Hydrogen
- Jet A-1 kerosene
- Jet A-1 biofuel
- Heavy fuel oil (HFO)
- Bio-HFO

It is assumed that all electricity, biofuels and hydrogen are produced locally to increase security of fuel supply and minimise fluctuations of fuel price due to external factors such as exchange rates. New Zealand has ample agricultural land to produce biofuels, though it would take time to create a new industry and scale it up to full production (Suckling, et al., 2018).

4.3. Reduction in carbon footprint due to vehicle technology alone

Figure 4 shows the influence of technology alone on the carbon emissions of today's vehicle fleet compared to four hypothetical tomorrows:

- *All biofuels*: Drop-in biofuels for all vehicles;
- *EVs & biofuels*: 100% electric passenger vehicles, with biofuels for all other vehicles;
- *EVs & hydrogen*: 100% electric passenger vehicles, with hydrogen fuel cells for commercial vehicles and biofuels for ships and planes; and
- *Mostly EVs*: All vehicles are electric except ships and planes, which are powered by biofuels.

In all scenarios, the vehicle fleet, fuel mix and sources of electricity generation are replaced overnight, but no other variables (e.g. population) are altered. The results are presented in pairs, with the left bar in each pair showing New Zealand's 2015 electricity mix (81% renewable) and the right bar showing 100% renewable.

As can be seen from this chart:

- All scenarios were found to produce significantly lower GHG emissions than the current fleet. Operational GHG emissions could be reduced by 56% to 95% if we had the ability to replace New Zealand's entire vehicle fleet and fuel mix overnight.
- Converting the fleet to 100% biofuels is the least favourable of the four technology scenarios, resulting in a reduction of 56% using today's grid and 70% for a fully renewable electricity mix.* The effect of electricity on biofuels comes during fuel production rather than in the operation of the vehicle, as it is assumed that all biofuel is manufactured locally.
- The greater the uptake of fully electric vehicles and the more renewable the electricity mix, the greater the improvement. Maximum use of EVs could lead to a reduction in operational GHG emissions of 95% from today. This is simply because EVs offer the greatest efficiency in transforming electricity into motive power, with very low losses involved in storing and releasing electricity from the battery and with the electric motors having very low losses when compared to a conventional internal combustion engine. However, EVs will likely not be practical for larger, heavier vehicles for some decades yet, meaning that biofuels and/or hydrogen fuel cells are likely to be needed as well.
- The performance of hydrogen is largely dependent on the renewability of the electricity it is produced from. Assuming hydrogen is used for light commercial and heavy vehicles only, overall reductions in operational GHG emissions range from 64% using today's electricity grid to 91% for a fully renewable grid.

For detailed results (including a consumption perspective), please see Annex A. For detailed assumptions and emissions factors for technological change, please see Annex B.

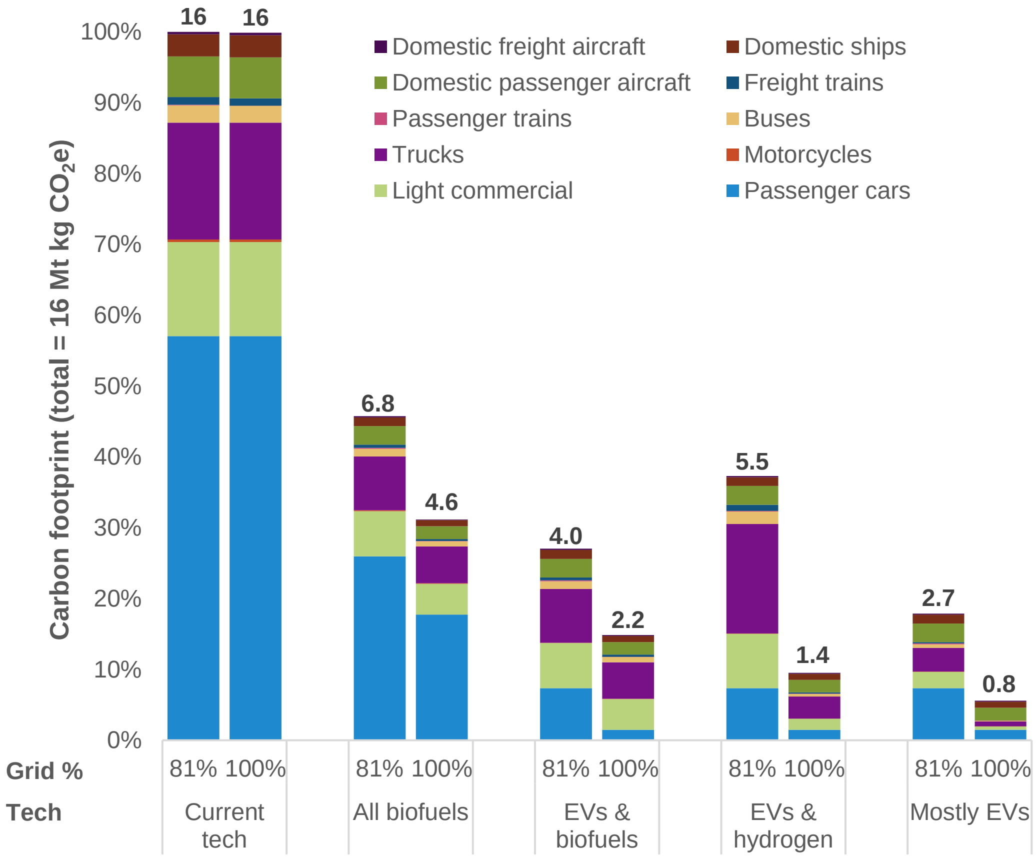

Figure 4: Impacts of technological change on current transport emissions (2015 reference year)

* While biofuels offer the lowest improvement potential, it should be noted that drop-in biofuels are a new technology type and their performance may improve over time. This outcome occurs because the key emissions from biofuel production are due to chemical processes, namely the production of soda. However, there are several different processes for producing second-generation biofuels (Suckling, et al., 2018), which might have differing carbon footprints and it is also possible that the biofuel mix may be made up of a combination of both first and second generation biofuels, which may help to bring down the overall carbon footprint of average biofuel on the market.

5. Behavioural change

5.1. Overview

Behavioural change also has the potential to lead to significant reductions in the carbon footprint of the transport sector. Behavioural changes primarily affect the number of light passenger vehicles on the road but may also increase the number of light commercial vehicles on the road in some cases (e.g. courier deliveries of products ordered online).

5.2. Scope

The types of behaviour change explored within this report include increased uptake of:

- Public transport (bus and train);
- Active transport (cycling and walking);
- Ride-sharing/carpooling (facilitated using smartphone apps);
- Teleworking (working from home or offsite);
- Home deliveries of groceries and durable goods ordered online (e-commerce); and
- Home deliveries of prepared meals.

5.3. Reduction in carbon footprint due to behavioural change alone

Figure 5 shows the influence that behavioural change alone can have on the carbon footprint of the whole transport sector. The results are for a hypothetical tomorrow where the behaviour change is fully rolled out immediately. Each column represents the net change in domestic GHG emissions. For example, for delivered shopping, the decrease in GHG emissions from fewer passenger car trips has been summed together with the increase from greater light commercial van trips.

The results explore the impact of reducing light passenger journeys and the net effect of modal shifts to other fleets (i.e. public transport). The potential for an avoided passenger car journey or a modal shift to public transport has been broken down by the reason for travel, as defined by the New Zealand Household Travel Survey (MoT, 2018). These reasons for travel include commuting to work, personal appointments, shopping trips, social visits, eating out, etc. For example, we assume that there is unlikely to be a modal shift towards public transport for a shopping trip as then the person would need to carry their shopping bags home on the bus or train. The reasons for travel are provided in Table 10 in Annex C. The relationship between the factors influencing the number of light passenger journeys and the assumptions behind the factors are further detailed in Table 12 in Annex C.

As can be seen, the total effect of all changes together is a 29% reduction in the carbon footprint of the transport sector, with the majority due to ride-sharing (12%) and public transport (9%). It is important to note that these two changes are very significant when put in the context of light passenger vehicles only; however, their significance is diminished when considered in the context of the whole transport sector (as is done in Figure 5 to show net savings). It is also important to note that behavioural change will be most effective when implemented early (as illustrated in Figure 5). While there are many other benefits from behavioural change other than carbon footprint (e.g. reduced congestion on the roads), the significance of this strategy from a climate perspective will decrease as the climate impact of passenger vehicles falls through the introduction of EVs and an increasingly renewable electricity grid. More detailed results can be found in Annex A.

Ride-sharing is an important example of a strategy that could be rolled out immediately. There are many ways in which central government, local councils and businesses can help. This could include phased introduction of more T3 and T4 transit lanes, getting engagement around certain ridesharing smartphone apps to create a critical mass of carpoolers, and employers providing incentives to employees if they share rides with their colleagues or with nearby businesses.

Public transport can also make a meaningful reduction to reducing the carbon footprint of transport in the short term by creating a modal shift from passenger cars to buses and trains in those areas where good quality services already exist. Importantly, the increase is based upon full uptake by those people who already use public transport at least once per month, so we can be reasonably confident that these people already have a service accessible to them.

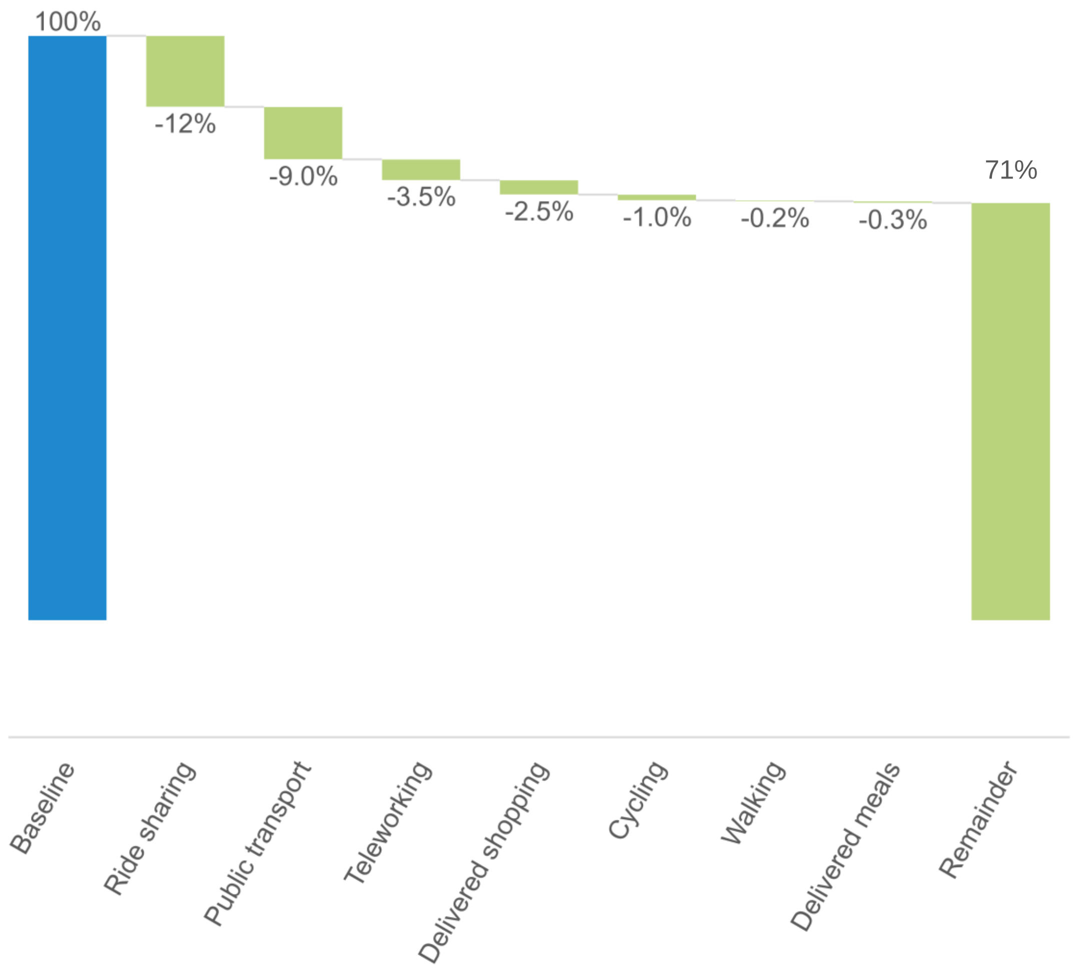

Figure 5: Impacts of behavioural change on current transport emissions (2015 reference year)

6. Scenarios for 2050

6.1. Overview

All results up until this point have compared our baseline year (2015) with the improvement possible if change happened overnight. If we now look out to 2050 – factoring in growth in population and urbanisation – it is possible to visualise what a low-carbon transport model might look like for New Zealand. Four scenarios for 2050 are presented in Figure 6 to understand the effects of:

- **Technological change (horizontal axis):** The scenarios consider the difference between biofuels versus hydrogen fuels cells for heavy and commercial vehicles. In all cases, EVs are assumed for 100% of the passenger vehicle fleet and biofuels for ships and planes.
- **Behavioural change (vertical axis):** Travel is defined as either 'individual' (resistant) or 'shared and avoided' (progressive). 'Individual' travel is business as usual and results in the number of passenger and light commercial vehicles increasing linearly with population and urbanisation. 'Shared and avoided' travel considers reductions in passenger car journeys through increased uptake of public transport, car sharing, teleworking and home deliveries from online shopping. This is the sharing economy in action and it results in fewer cars on the road, but greater use of light commercial vehicles to deliver goods.

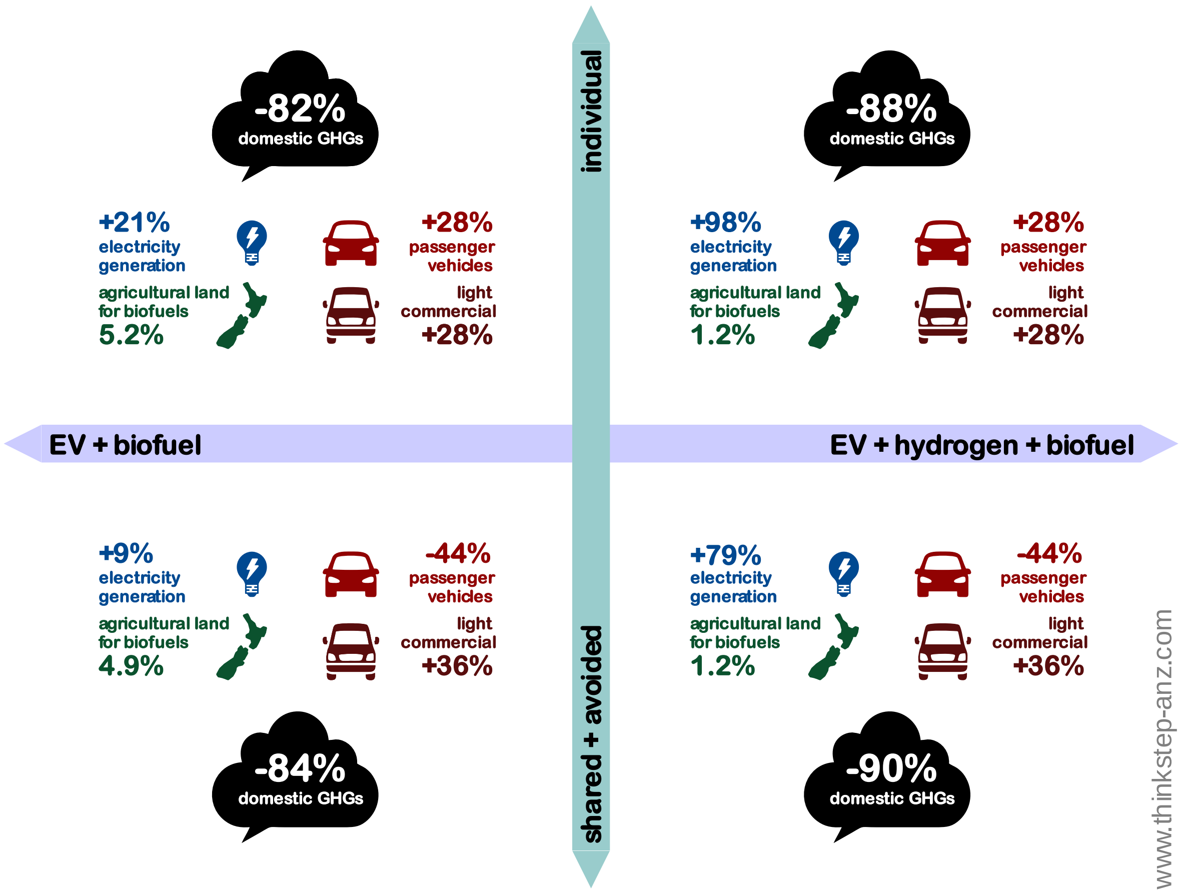

Figure 6: Transport scenarios for 2050 relative to 2015 (savings include *domestic* GHG emissions only)

What these scenarios show is that a reduction of between 82% and 90% in domestic greenhouse gases from the transport sector is achievable by 2050 if the strategies within each scenario are fully implemented. It is important to note that reductions multiply, meaning that the additional benefit of moving from an individualistic model (i.e. business as usual) to a more community-minded, sharing model ("shared + avoided" above) is 11% within an "EV + biofuel" world and 15% in an "EV + hydrogen + biofuel" world (where, for example, the 84% in the bottom-left scenario = 82% + (100%-82%)*11%). These reductions of 11-15% from behaviour change are considerably lower than the 29% in section 5 because the light passenger fleet (which behaviour change affects) has already transitioned to being fully EV under both scenarios and so its impact becomes smaller relative to other forms of transport (such as ships and planes, which rely on biofuel in all scenarios).

Achieving such large improvements comes with trade-offs: electricity generation would need to nearly double in the scenarios involving hydrogen, or 5% of all agricultural land in New Zealand would need to be converted to biofuel production. It is also likely that these scenarios would take the full 30 years to be realised, given the scale of renewable energy that would need to be produced and that some of the required technology is not yet fully commercialised. For example, new plantation forests would need to be planted and mature to feed biorefineries that are not yet built.

6.2. Incorporating off-shore manufacturing

The scenarios presented in the previous section show the GHG reductions from a production perspective only, i.e. including operational GHG emissions. For each of the four scenarios, New Zealand's transport emissions have been calculated using both consumption- and production-based approaches, as shown in Figure 7. This highlights differences between transport emissions accounted under the current GHG inventory framework and all GHG emissions which can be attributed to the use of vehicles within New Zealand, including those which are emitted outside of New Zealand's borders. Inclusions in each approach are shown in Table 2.

Table 2: Inclusions in consumption vs production approach

Production approach inclusions	Additional in consumption approach
Combustion emissions	Production of vehicles and spare parts
Production of fuels within New Zealand	Production of fuels outside of New Zealand
	Recycling of vehicles outside of New Zealand

For the consumption approach, impacts from the manufacturing, importing, maintenance and disposal of vehicles are taken into account along with vehicle use. It is assumed that New Zealand does not produce its own vehicle fleet and that all vehicles and spare parts are imported.

The methodology used to calculate the impacts from manufacturing is as follows:

$$\sum_{Transport\ mode} Distance\ travelled \times Manufacturing\ \&\ maintenance\ emissions\ per\ km$$

GWP impacts for the manufacturing, maintenance and disposal of vehicles are provided in Table 9 in Annex C.

As a check, the total vehicle distance of the light passenger fleet was divided by the average total distance over lifespan of vehicle. This number represents the vehicles consumed and is in-line with the number of light vehicles scrapped. Actual import impacts of light passenger vehicles will be higher than those in our scenarios as New Zealand is a net importer of vehicles, i.e. more vehicles are entering the fleet than are exiting.

International emission factors for fuel production are given in Table 8 in Annex B. These were used as the fuel emission factor to obtain the impacts from the production of fuels offshore, along with emissions due to produce capital goods required for electricity generation (primarily solar panels).

6.3. Detailed results

A comparison of consumption- and production-based emissions in Figure 7 shows:

- Considering offshore emissions results in significantly higher emissions than the production-based approach for all scenarios due to fuel production emissions outside of New Zealand and vehicle manufacture which is assumed to occur completely offshore.
- Vehicle production emissions increase for all the future scenarios compared to the current scenario as low-carbon vehicle technologies have higher production impacts. There is also a larger number of vehicles on the road by 2050 (assuming business as usual) due to increases in population and increased production of heavy and light commercial vehicles.
- The behavioural progressive (community-oriented) scenarios have lower vehicle production impacts compared to the behavioural resistant (individualistic) scenarios due to a decrease in vehicle numbers caused by factors such as ride-sharing and shifts to public transport.
- In the future scenarios, vehicle production accounts for a greater share of the total vehicle impacts as they remain relatively constant but operational emissions decrease significantly.
- No vehicle operation emissions occur for the future scenarios as emissions only occur during the production for each technology type, i.e. no tailpipe emissions. GHG tailpipe emissions for biofuel vehicles are considered to be carbon neutral due to an equal portion of carbon being sequestered during feedstock growth.
- The behavioural progressive, EVs and hydrogen scenario has the lowest GHG emissions of the four future scenarios when looking from a production perspective. However, when looking from a consumption perspective, the lowest emission scenario is the behavioural progressive, EV and biofuel due to lower vehicle manufacture emissions.

A further breakdown of the future scenarios is given in Table 3.

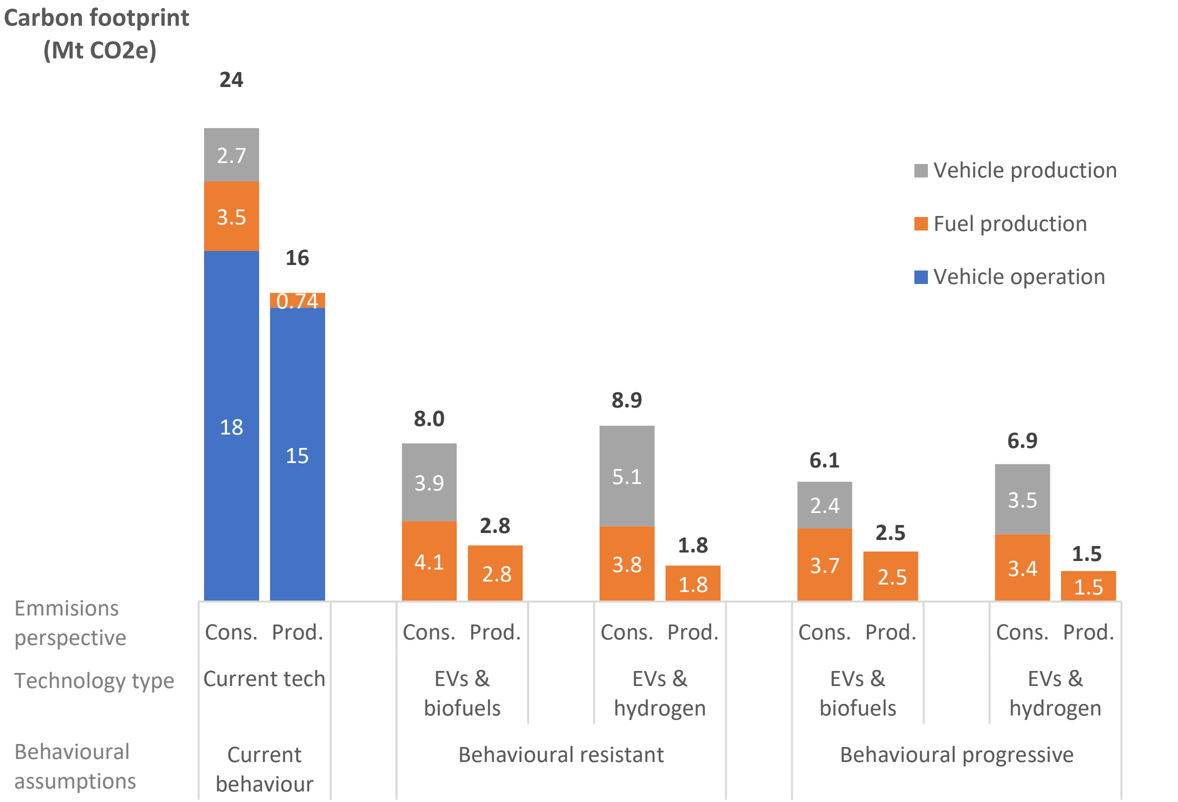

Figure 7: A breakdown of New Zealand's carbon footprint by emission source for 2050 future scenarios

Table 3: Production- and consumption-based emissions for 2050 future scenarios (kt CO_2e)

	Vehicle class	Behavioural resistant		Behavioural progressive	
		EVs & biofuels	**EVs & hydrogen**	**EVs & biofuels**	**EVs & hydrogen**
Production	**Domestic**	**2,831**	**1,816**	**2,525**	**1,548**
	Passenger cars	*290*	*290*	*122*	*122*
	Light commercial	*826*	*297*	*872*	*313*
	Motorcycles	*1*	*1*	*1*	*1*
	Trucks	*985*	*596*	*758*	*458*
	Buses	*142*	*68*	*185*	*89*
	Passenger trains	*5*	*5*	*6*	*6*
	Freight trains	*55*	*33*	*55*	*33*
	Domestic passenger aircraft	*343*	*343*	*343*	*343*
	Domestic ships	*162*	*162*	*162*	*162*
	Domestic freight aircraft	*22*	*22*	*22*	*22*
Consumption	**International**	**1,234**	**1,990**	**1,169**	**1,853**
	International aircraft (total)	*923*	*923*	*923*	*923*
	International ships	*195*	*195*	*195*	*195*
	Imported electricity emissions (solar panel production)	*116*	*871*	*51*	*735*
	Vehicle manufacture, maintenance and end-of-life	**3,920**	**5,073**	**2,358**	**3,532**
	Total	**7,985**	**8,879**	**6,053**	**6,934**

7. Conclusions

Transport is a key hotspot in New Zealand's national carbon footprint

Transport is currently responsible for roughly one fifth of New Zealand's total gross GHG emissions. When considering the carbon footprint of products and services that New Zealanders consume – excluding those that are destined for offshore markets – transport's contribution jumps to over 40%.

Two complementary courses of action

There are two complementary courses of action: technology (e.g. switching from petrol and diesel vehicles to electric vehicles, biofuels and/or hydrogen fuel cells) and behavioural change (e.g. ride-sharing and public transport). Importantly these two paths are multipliers rather than being mutually exclusive, meaning they can be pursued together to increase the rate and scale of change.

Technological change will be the biggest win, but will take time to roll out

A reduction in domestic GHG emissions of up to 88% is possible from technology alone by 2050, provided that the entire fleet was converted to run on renewables. Electric vehicles (EVs) offer the greatest potential for emissions reductions in the New Zealand context, particularly if we can move our electricity grid closer to 100% renewable. Biofuels and/or renewable hydrogen are also likely to play an important part in the transport energy mix, even though their carbon footprint is higher than straight electric vehicles. This is particularly true for heavy and long-range vehicles, such as heavy trucks, courier vans, trains, ships and planes, which are less well suited to battery-electric technology. Except for drop-in biofuels, which are not yet available at scale, all other technologies require a complete refresh of the vehicle fleet, meaning that change will likely take decades.

Behavioural change will be most effective if it happens now

Behavioural change will be more effective in reducing the carbon footprint of today's fossil fuelled transport fleet than it will be in 2050. This is because behavioural change primarily reduces demand for passenger cars and these cars are already beginning to transition towards electric.

The total effect of all behavioural changes considered in this study is an estimated 29% reduction in the carbon footprint of the transport sector, assuming these changes happened tomorrow, but this reduction falls to 10-15% by 2050 as the impact of passenger vehicles diminishes. Early carbon savings through quick implementation will buy time and space in the carbon budget for longer-term technology development.

Ride-sharing has the potential to contribute to the greatest overall improvement in carbon footprint from behaviour change, followed by increased uptake of public transport. Importantly, the uptake of ride-sharing can be increased dramatically very quickly with minimal investment while also providing the additional benefits of reducing congestion and helping to recreate a sense of community.

Achieving a transition to low-carbon transport by 2050 is possible, but requires trade-offs

Achieving reductions in GHG emissions of 80-90% of 2015 levels by 2050 is possible, but it comes with trade-offs. Electricity generation would need to nearly double, or 5% of all agricultural land in New Zealand would need to be converted to biofuel production.

Time for government and business to act

A reduction in transport emissions by 90% would reduce New Zealand's total gross GHG emissions by 17%, assuming that the share of emissions from transport remains constant in the future. In addition to making up a considerable share of our total emissions, transport also seems likely to be a quicker and easier climate win for New Zealand compared to, say, agriculture.

The role of government and business, as we see it, is to make these low-carbon choices easy and convenient. Encouraging uptake of ride-sharing through widespread use of carpool lanes and other incentives offers the potential for a quick-win, alongside creating a pricing model for electric vehicles that makes them attractive to New Zealand consumers. Investment in biofuels and renewable hydrogen, together with continued investment in renewable electricity generation, seem like logical next steps beyond this.

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Annex A Detailed results

Table 4: Production- and consumption-based emissions for technology shift, 2015 electricity grid (kt CO_2e)

	Vehicle class	Current tech	All biofuels	EVs & biofuels	EVs & hydrogen	Mostly EVs
Production	**Domestic**	**15,568**	**6,784**	**4,008**	**5,531**	**2,653**
	Passenger cars	*8,457*	*3,850*	*1,092*	*1,092*	*1,092*
	Light commercial	*1,971*	*942*	*942*	*1,139*	*338*
	Motorcycles	*52*	*24*	*6*	*6*	*6*
	Trucks	*2,448*	*1,124*	*1,124*	*2,286*	*499*
	Buses	*358*	*162*	*162*	*262*	*72*
	Passenger trains	*18*	*18*	*18*	*18*	*18*
	Freight trains	*155*	*63*	*63*	*127*	*28*
	Domestic passenger aircraft	*856*	*391*	*391*	*391*	*391*
	Domestic ships	*456*	*185*	*185*	*185*	*185*
	Domestic freight aircraft	*54*	*25*	*25*	*25*	*25*
	Domestic fossil fuel production	*743*	-	-	-	-
Consumption	**International**	**5,631**	**1,276**	**1,276**	**1,276**	**1,276**
	International aircraft (total)	*2,307*	*1,053*	*1,053*	*1,053*	*1,053*
	International ships	*551*	*223*	*223*	*223*	*223*
	International fossil fuel production	*2,773*	-	-	-	-
	Vehicle manufacture, maintenance and end-of-life	**2,693**	**2,693**	**2,693**	**2,693**	**2,693**
	Total	**23,891**	**10,753**	**7,976**	**9,499**	**6,622**

Table 5: Production- and consumption-based emissions for technology shift, 2050 electricity grid (kt CO_2e)

	Vehicle class	Current tech	All biofuels	EVs & biofuels	EVs & hydrogen	Mostly EVs
Production	**Domestic**	**15,547**	**4,622**	**2,200**	**1,410**	**826**
	Passenger cars	*8,456*	*2,628*	*222*	*222*	*222*
	Light commercial	*1,971*	*643*	*643*	*231*	*69*
	Motorcycles	*52*	*17*	*1*	*1*	*1*
	Trucks	*2,448*	*767*	*767*	*464*	*101*
	Buses	*352*	*111*	*111*	*53*	*15*
	Passenger trains	*4*	*4*	*4*	*4*	*4*
	Freight trains	*155*	*43*	*43*	*26*	*6*
	Domestic passenger aircraft	*856*	*267*	*267*	*267*	*267*
	Domestic ships	*456*	*126*	*126*	*126*	*126*
	Domestic freight aircraft	*54*	*17*	*17*	*17*	*17*
	Domestic fossil fuel production	*743*	*-*	*-*	*-*	*-*
Consumption	**International**	**5,633**	**873**	**961**	**1,462**	**1,044**
	International aircraft (total)	*2,307*	*719*	*719*	*719*	*719*
	International ships	*551*	*152*	*152*	*152*	*152*
	International fossil fuel production	*2,773*	*-*	*-*	*-*	*-*
	Imported electricity emissions (Solar panel production)	*2*	*2*	*90*	*591*	*173*
	Vehicle manufacture, maintenance and end-of-life	**2,693**	**2,693**	**2,693**	**2,693**	**2,693**
	Total	**23,873**	**8,187**	**5,854**	**5,564**	**4,563**

Annex B Technology assumptions

Electricity grid mix

The New Zealand electricity grid mix has been modelled using data from the 2015 calendar year for the current scenarios (MBIE, 2018) and Transpower estimates for the 2050 scenarios (Transpower, 2018). In both cases, the electricity generation and fugitive emissions have been modelled using the GaBi 2018 Life Cycle Inventory Database (thinkstep, 2018). Emissions for each electricity generation type include production and end of life of facilities as well as any direct generation emissions. The electricity grid mixes used are given below in Figure 8.

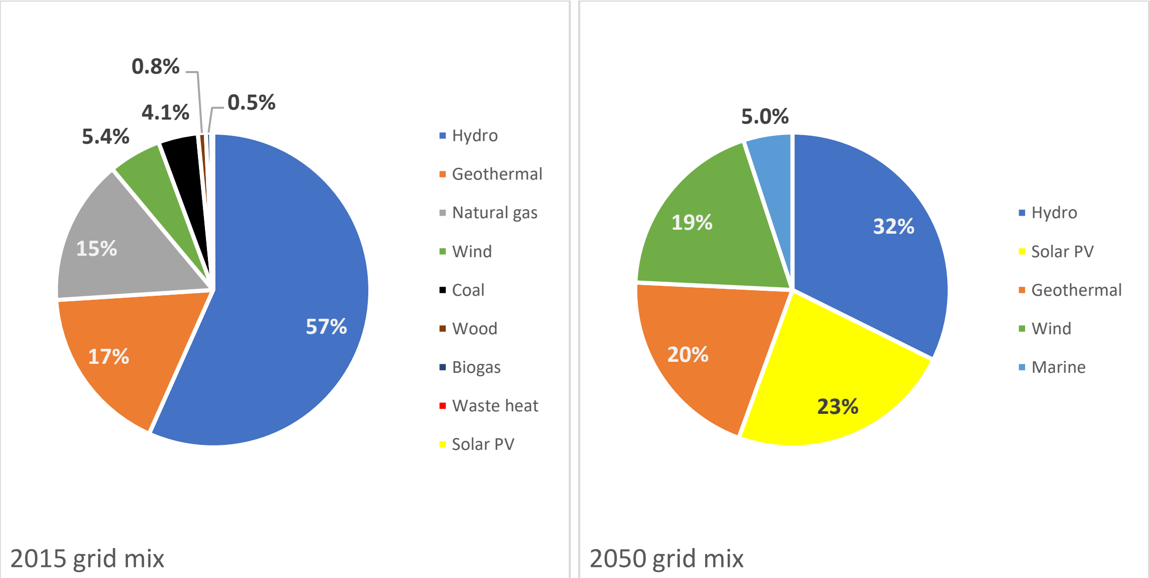

Figure 8: New Zealand electricity grid mix for 2015 and forecasted grid mix for 2050

Geothermal and coal generation emissions have been modelled using grid emission factor data (MBIE, 2018). All other electricity generation types have been modelled using datasets from the GaBi database (thinkstep, 2018). All emissions are assumed to occur within New Zealand, except for solar PV, which is assumed to occur offshore due to the production of solar panels.

Biofuels

Emissions from the generation of biofuels have been estimated based on the “hydrothermal liquefaction (HTL)” process, using forest waste residues (Nie & Bi, 2018). Forest residues used in the process have been assumed to be waste products which carry no production burden as all impacts of forestry are assumed to be allocated to the primary forestry products (logs).

Current hydrothermal liquefaction processes utilise natural gas in their production for thermal energy and also the production of hydrogen via steam reformation. It has been assumed that the future source of thermal energy for biofuel production will come from biomass combustion, which has been treated as carbon neutral due to any carbon emitted being sequestered earlier in the production cycle with any carbon emissions assumed to be carbon dioxide. Steam reformation has been remodelled assuming the production of hydrogen in the future will be via electrolysis.

All bio-based waste products generated in the production process are assumed to be utilised in an anaerobic digestion processes, with the resulting gas used in directly in the biofuel production process, or used directly for thermal energy generation elsewhere, resulting in all carbon being emitted as carbon dioxide back into the atmosphere (carbon neutral).

The forecasted 2050 electricity grid mix (see Electricity grid mix) has been used to satisfy any electricity requirements within the biofuel production model for the 2050 scenarios and the 2015 grid mix was used for calculating biofuel emission factors for the 2015 scenarios.

Emissions from the production of biofuels via HTL are largely driven by direct emissions in the production of chemicals – mostly soda. Some uncertainty exists surrounding the amount of chemicals required as the process is not yet widely used or optimised. Considerable uncertainty exists surrounding the type of feedstock used in the future or the specific conversion process. Biofuels can also be made from waste products such as converted from used cooking oils in flexi-fuel vehicles. Adding a portion of flexi-fuel vehicles running on waste-derived biofuels could result in more favourable emissions reductions. This scenario however has not been explored due to the limitations in scalability of feedstock production and quality of fuel produced for all vehicle types.

Total consumption of biofuel required for each scenario was calculated in MJ and converted to litres. The land area required to per litre of biofuel is back-calculated from the New Zealand biofuels roadmap technical report (Scion, 2018) and scaled up to meet the biofuel demand in each scenario. The percentage of land required over the area available (arable land, forest area, agricultural land, excluding protected areas) for planting trees is given in Figure 6.

Hydrogen production

Emission factors for the use of hydrogen in fuel cell vehicles assume hydrogen is produced via proton exchange membrane (PEM) electrolysis of water. This process uses electricity, which has been assumed to come from the forecasted 2050 grid for all 2050 scenarios and the 2015 grid for all current scenarios. The conversion efficiency is taken as the lower range of state-of-the-art PEM electrolyser technology (Carmo, et al., 2013). This results in a 57% conversion efficiency from electricity to hydrogen, based on the lower heating value.

Vehicle fuel economy

The following fuel economies were calculated based on literature data for each vehicle class and applicable fuel type and are given in Table 6. Fuel economies are calculated per vehicle-kilometre for passenger vehicles, light commercial vehicles and public transport and per tonne-kilometre for freight vehicles.

Table 6: Fuel economy per fuel type and vehicle class

	Fuel economy (MJ/unit)	Units	Source
Light passenger vehicle			
Petrol	2.93	MJ/km	(Wang, et al., 2015)
Diesel	3.64	MJ/km	(Wang, et al., 2015)
Bioethanol	2.93	MJ/km	(Wang, et al., 2015)
Biodiesel	3.64	MJ/km	(Wang, et al., 2015)
Electric	0.670	MJ/km	(U.S. Department of Energy, 2018)

	Fuel economy (MJ/unit)	Units	Source
Light commercial vehicle			
Petrol	2.93	MJ/km	(Wang, et al., 2015)
Electric*	1.05	MJ/km	(Transport & Environment, 2017)
Diesel	3.64	MJ/km	(Wang, et al., 2015)
Biodiesel	3.64	MJ/km	(Wang, et al., 2015)
Hydrogen	2.00	MJ/km	(Hyundai, 2016)
Motorcycle			
Petrol	1.31	MJ/km	(EMSD, 2018)
Electric	0.241	MJ/km	(Zero Motorcycles, 2017)
Bioethanol	1.31	MJ/km	(EMSD, 2018)
Heavy truck			
Diesel	1.31	MJ/tkm	(Deutsche Bahn, 2018)
Electric*	0.468	MJ/tkm	(Transport & Environment, 2017)
Biodiesel	1.31	MJ/tkm	(Deutsche Bahn, 2018)
Hydrogen*	1.22	MJ/tkm	(Transport & Environment, 2017)
Bus (max capacity 80)			
Petrol	14.7	MJ/km	(Lozanovski, et al., 2016)
Diesel	14.7	MJ/km	(Lozanovski, et al., 2016)
Electric*	5.26	MJ/km	(Transport & Environment, 2017)
Biodiesel	14.7	MJ/km	(Lozanovski, et al., 2016)
Hydrogen	10.8	MJ/km	(Lozanovski, et al., 2016)
Rail, passenger (max capacity 1000)			
Electric	64.8	MJ/km	(Hitachi Rail Italy, 2013) (AnsaldoBreda S.p.A., 2011)
Rail, freight			
Electric*	0.167	MJ/tkm	(Transport & Environment, 2017)
Diesel	0.467	MJ/tkm	(MfE, 2017)
Biodiesel	0.467	MJ/tkm	(MfE, 2017)
Hydrogen*	0.433	MJ/tkm	(Transport & Environment, 2017)
Air, passenger, domestic			
Jet A-1 kerosene	9.13	MJ/km	(MfE, 2017)
Jet A-1 biofuel	9.13	MJ/km	(MfE, 2017)
Air, freight, domestic			
Jet A-1 kerosene	9.82	MJ/tkm	(Deutsche Bahn, 2018)

	Fuel economy (MJ/unit)	Units	Source
Jet A-1 biofuel	9.82	MJ/tkm	(Deutsche Bahn, 2018)
Sea, freight			
Heavy fuel oil / light fuel oil	1.63	MJ/tkm	(MfE, 2017)
Biodiesel / bio-HFO	1.63	MJ/tkm	(MfE, 2017)

* Calculated from other emission factors within this vehicle class based on the difference in tank-to-wheel efficiencies of each technology type (Transport & Environment, 2017).

Emission factors

The emission factors given in Table 7 are used to calculate the emissions from the use of fuels or other energy sources within New Zealand. Fossil fuel emission factors include the combustion emissions only, as production emissions for each fuel type could not be disaggregated easily. The production of fossil fuels occurring within New Zealand have been included in the inventory based on figures from the NZ GHG inventory (MfE, 2017). Emission factors for Biofuels and Electricity-based energy sources include fuel production emissions occurring within New Zealand.

Table 7: Domestic emission factors per fuel type – Emitted in New Zealand

Fuel type	2015 (kg CO_2e/MJ)	2050 (kg CO_2e/MJ)	Source(s)
Fossil fuels			
Petrol	0.0675	-	(MfE, 2017)
Diesel (road)	0.0702	-	(MfE, 2017)
Diesel (rail)	0.0779	-	(MfE, 2017)
Jet A-1 kerosene	0.0690	-	(MfE, 2017)
Heavy fuel oil	0.0779	-	(MfE, 2017)
Marine fuel oil	0.0740	-	(MfE, 2017)
Biofuels			
Bioethanol (first gen)	0.0292	-	(UK Government, 2018)
Biodiesel (first gen)	0.0105	-	(UK Government, 2018)
Bioethanol (HTL drop in)	0.0315	0.0215	(Nie & Bi, 2018)
Biodiesel (HTL drop in)	0.0315	0.0215	(Nie & Bi, 2018)
Jet A-1 biofuel (HTL drop in)	0.0315	0.0215	(Nie & Bi, 2018)
Electricity-based			
Electricity	0.0392	0.00794	(MBIE, 2018) (Transpower, 2018) (thinkstep, 2018)
Hydrogen from electrolysis using electricity from the grid	0.0690	0.0140	(Carmo, et al., 2013)

Table 8 shows the emission factors for fuels imported from overseas. Emissions for fossil fuels are due to the production processes not within New Zealand. Emissions factors for the Electricity-based fuel sources are due to the production of solar panels, which make up a significant portion of the New Zealand grid mix in the 2050 scenario. These panels are assumed to be produced overseas and are therefore counted as imported emissions. The production of hydrogen is assumed to be via electrolysis of water using the same electricity grid.

Table 8: International emission factors for fuel production occurring offshore – Imported fuel production emissions

Fuel type	2015 (kg CO_2e/MJ)	2050 (kg CO_2e/MJ)	Source(s)
Fossil fuels			
Petrol	0.0182	-	(MfE, 2017)
Diesel (road)	0.0174	-	(MfE, 2017)
Diesel (rail)	0.0174	-	(MfE, 2017)
Jet A-1 kerosene	0.0182	-	(MfE, 2017)
Heavy fuel oil	0.015	-	(MfE, 2017)
Marine fuel oil	0.015	-	(MfE, 2017)
Electricity-based (emissions from solar panel production)			
Electricity	-	0.00386	(MBIE, 2018) (Transpower, 2018) (thinkstep, 2018)
Hydrogen from electrolysis using electricity from the grid	-	0.00680	(Carmo, et al., 2013)

Consumption of vehicles

Table 9: GWP impacts for the manufacturing, importing, maintenance and disposal of on-road fleet

Fleet type	Fuel	GWP	Unit	Source(s)
On-road				
Light passenger: ICE	Petrol, bioethanol	0.05	kg CO2e/km	(Energy Efficiency and Conservation Authority, 2015)
Light passenger: ICE	Diesel, biodiesel	0.053	kg CO2e/km	
Light passenger: EV	Electricity	0.063	kg CO2e/km	
Light commercial: ICE	Petrol	0.05	kg CO2e/km	
Light commercial: ICE	Diesel, biodiesel	0.053	kg CO2e/km	Assumed impacts are similar to a light passenger vehicle
Light commercial: H2	Hydrogen	0.16	kg CO2e/km	(Bartolozzi, et al., 2013)
Motorcycle: 25kW	Petrol	0.02	kg CO2e/km	(Patterson, 2018)
Motorcycle: 25kW	Electric	0.03	kg CO2e/km	
Heavy truck:	Petrol, diesel, biodiesel	0.008	kg CO2e/km	(Patterson, 2018) Assume fuel cell truck impacts is double of the ICE truck, which is slightly higher than that of a hybrid truck
Heavy truck:	Hydrogen	0.016	kg CO2e/km	
Bus	Petrol, diesel, biodiesel	0.10	kg CO2e/km	(Patterson, 2018)
Bus	Hydrogen	0.20	kg CO2e/km	
Other fleet				
Train	Diesel, biodiesel, electric, hydrogen	0.389	kg CO2e/km	Assume same GWP impacts for all train types as ratio of impact from powertrain production is small in comparison to the glider (Downer & thinkstep, 2018)
Air	Kerosene, biofuel	381	kt CO2e	Based on dollar value of aircraft parts imported converted to emissions via the EIO-LCA database (Vickers, et al., 2018)
Ship	Heavy fuel, biofuel	126	kt CO2e	80% of GWP impacts of ships are from propulsion, 10% from fuel, 10% is construction, maintenance, end of life. (Ringvold, 2017). The GWP impacts from coastal ship and ocean-going ship are used in the calculation.

*Air and ship represent total annual impacts rather than per km travelled

Annex C Behavioural assumptions

Behavioural progressive scenarios

The behavioural progressive scenarios explore the impact of reducing light passenger journeys and net effect of modal shifts to other fleets (i.e. public transport). They are built on the purpose of travel found by the New Zealand household travel survey (MoT, 2018).

Table 10: Share of journeys by purpose

Purpose of travel	Share	Assumptions	Number of journeys (urban + rural)
Total light passenger fleet	100%	Based on km in car or van as a driver or passenger / trip legs (MoT, 2018), average distance per journey = 8.74 km Total vehicle km travelled 34E+09 km (MoT, 2016) / average distance = number of journeys	3.89E+09
Shopping, purchasing of goods and groceries	31% (16%)	Assume 50% split between journeys taken for shopping and personal appointments from the household survey report	6.03E+08
Personal appointment & services – e.g. dentist, car repairs	(16%)		6.03E+08
Social visits & entertainment	23% (15.3%)	Assume equal split between journeys taken for social visits, entertainment and eating out	5.96E+08
Meals & eating out	(7.7%)		2.98E+08
Sports & exercise	6%		2.33E+08
Travel to work or study	20%		7.78E+08
Work related travel, business trips	9%		3.50E+08
Driving or accompanying someone	11%		4.28E+08

Table 11: Factors affecting journeys

Factors affecting number of journeys	Current	Behavioural progressive	Assumptions and source(s)	Impact
Population	4.75 million (current) 6.1 million (2050)		(Stats NZ, 2016)	Journeys in 2050 are scaled by increase in population
Urbanisation	87% (current) 91% (2050)		(UN Population Division, 2018)	Journeys are split into urban and rural, factors were applied **only** to urban journeys
Vehicle occupancy/ Ride-sharing	1.48	3	Current vehicle occupancy calculated from (MoT, 2014). Assume vehicle occupancy of 3 based on example and productivity of T3 lanes in Auckland (Fitzgerald, 2016). Vehicle occupancy is lowest in commutes to work at 1.15 (Sullivan & O'Fallon, 2003). Higher occupancy is expected with more transit lanes in urban areas, along with ride-sharing apps. Affects all purposes aside from trips under 'work related travel', which are irregular business trips not part of the daily commute.	Reduces number of light passenger car journeys.
Teleworking	21%	39%	Current teleworking percentage based on 11% working from home full-time, and half of 20% working from home part-time (HorizonPoll, 2015). Assume the 39% who answered their job could be done remotely will shift to working remotely (HorizonPoll, 2015). Affects journeys for 'travel to work & study' and 'work related travel'.	Reduces number of light passenger car journeys.
Online shopping, e-commerce	7.6%	85%	Current online annual spend is 7.6% of total retail spend (NZ Herald, 2018) 15% of kiwis prefer to shop in a physical store, assume the other 85% will shift to shopping online (NZ Herald, 2018) Affects journeys for 'shopping, purchasing goods and grocery'.	Reduces number of light passenger car journeys. Increase distance travelled by light commercial fleet, modal shift impacts are shown in **Table 14**
Food delivery, online ordering apps – e.g. Uber Eats	15%	50%	Current 15% is based on share of revenue of global online food delivery ($83 billion USD) in the $570 billion world food industry (statista, 2018). 50% of meals purchased from restaurants are eaten at home, assume these will all be delivered (Nation's Restaurant News, 2017). Affects journeys for 'meals & eating out'.	Reduces number of light passenger car journeys. Increase distance travelled by light commercial fleet, modal shift impacts are shown in **Table 14**

Factors affecting number of journeys	Current	Behavioural progressive	Assumptions and source(s)	Impact
Uptake of public transport (bus/ train/ ferry) **-Auckland** **-Wellington** **-Other urban areas**	 12% 21% 4%	 37% 57% 17%	Current uptake is the % of people who take public transport on 20+ days per month plus half of those who take PT on 10-19 days per month (MoT, 2018). Future uptake is the % of people who have taken public transport for at least 1 day in a month, as this shows they have access to the PT network (MoT, 2018). Affects journeys for all purposes except for shopping trips, sports and exercise, business travel and driving someone. Affects journeys with commute distances between 3 – 20km, and half of distance between 21-50km. Journey distances from (Stats NZ, 2009). Assume no increased uptake of PT in rural areas and frequency of ferry services remain the same in Auckland and Wellington.	Reduces number of light passenger car journeys. Increase frequency of bus and rail services by 30% to accommodate for increase in demand. Modal shift impacts are shown in **Table 15** Impacts are weighted for distance travelled and ratio of population within Auckland, Wellington and other urban areas.
Shift to non-motorised travel **-walking** **-cycling**	 13% 1%	 68% 30%	Current share of walking and cycling calculated from New Zealand household travel survey (MoT, 2018). Future uptake is the % of people who answered 'good' to how hassle free is walking (MoT, 2012) and cycling (MoT, 2012) Affects journeys for all purpose except for shopping trips, business travel and driving someone. Affects journeys with commute distances<2km for walking, and distances between 3-5km for cycling - the average commute distance for each mode respectively (Stats NZ, 2009).	Reduces number of light passenger car journeys. Impacts are weighted for distance travelled.

Table 12: Relationship between purpose of travel and factors affecting journeys

	Number of journeys		Net change (behavioural progressive now)	Effect due to factors						
	Current	Behavioural progressive now		Delivered shopping	Ride-sharing	Delivered meals	Tele-working	Public transport (bus, rail, ferry)	Cycling	Walking
Shopping, purchasing of goods and groceries	6.03E+08	1.23E+08	-4.80E+08	63%	37%	0%	0%	0%	0%	0%
Personal appointment & services	6.03E+08	2.85E+08	-3.18E+08	0%	34%	0%	0%	60%	5%	1%
Social visits & entertainment	5.96E+08	2.82E+08	-3.14E+08	0%	34%	0%	0%	60%	5%	1%
Meals & eating out	2.98E+08	9.93E+07	-1.99E+08	0%	27%	22%	0%	47%	4%	1%
Sports & exercise	2.33E+08	1.23E+08	-1.10E+08	0%	86%	0%	0%	0%	12%	2%
Travel to work or study	7.78E+08	3.08E+08	-4.70E+08	0%	30%	0%	14%	52%	4%	1%
Work related travel	3.50E+08	2.81E+08	-6.90E+07	0%	0%	0%	100%	0%	0%	0%
Driving or accompanying someone	4.28E+08	2.40E+08	-1.88E+08	0%	100%	0%	0%	0%	0%	0%

Heavy truck fleet utilisation

Current utilisation of trucks in New Zealand is 50%. Utilisation for the future truck fleet has been assumed to be 65%, based on current German statistics which have an upper limit in the low 60% (Kraftfahrt-Bundesamt, 2014). New Zealand is expected to have a lower utilisation because of geographical constraints, however improvements in technology and routing are likely to provide significant improvements.

Urbanisation

Urbanisation does not have a linear relationship with average distance travelled per journey. The extent of urbanisation is dependent on transportation technology; development of road and public transport network in turn allows for population to spread to less populated areas which are still accessible and 'urban' thus extending the radius of the city. The New Zealand census data for 1996 and 2006 supports this effect, with an all-round increase in commute distance to work for motorised modes of travel (Stats NZ, 2009). It was found that there is less distance travelled per person in more densely populated areas up to a certain level (Vilhelmson, 2005). As such it is difficult to portray an accurate representation of the net effect on average distance due to urbanisation.

Annex D Behavioural breakdown

The behavioural progressive scenarios explore the impact of reducing light passenger journeys and net effect of modal shifts to other fleets (i.e. public transport). They are built on the purpose of travel found by the New Zealand household travel survey (MoT, 2018) and provided in Table 10. The relationship between the factors influencing the number of light passenger journeys and the assumptions behind the factors are further detailed in Table 12.

Table 13: Net impacts of factors on journey reduction

Number of journeys: Purpose of travel		Current	Behavioural progressive now	Behavioural progressive 2050	Influenced by
Total light passenger fleet		**3.89E+09**	**1.74E+09**	**2.10E+09**	Population
Total light passenger fleet (rural)		**5.25E+08**	**5.25E+08**	**4.50E+08**	Urbanisation
Total light passenger fleet (urban)		**3.36E+09**	**1.22E+09**	**1.65E+09**	Urbanisation
Urban	Shopping, purchasing of goods and groceries	5.21E+08	4.18E+07	5.64E+07	Online shopping Ride- sharing
	Personal appointment & services	5.21E+08	2.04E+08	2.76E+08	Ride sharing Public transport Non-motorised travel
	Social visits & entertainment	5.16E+08	2.02E+08	2.73E+08	Ride sharing Public transport Non-motorised travel
	Meals & eating out	2.58E+08	5.90E+07	7.97E+07	Food delivery Ride-sharing Public transport Non-motorised travel
	Sports & exercise	2.02E+08	9.19E+07	1.24E+08	Ride-sharing Non-motorised travel
	Travel to work or study	6.73E+08	2.03E+08	2.75E+08	Teleworking Ride-sharing Public transport Non-motorised travel
	Work related travel	3.03E+08	2.34E+08	3.16E+08	Teleworking
	Driving or accompanying someone	3.70E+08	1.83E+08	2.47E+08	Ride-sharing

Net impact of modal shift

Reduction in passenger trips for shopping and meals will result in additional burden on the light commercial fleet to deliver the goods and food. Uptake of public transport will increase demand on the network. The net impact of these modal shifts is provided below in Table 14 and Table 15. The average distance on a light passenger journey is 8.74 km, while the average postal difference between stops is 0.4 km (Crew & Kleindorfer, 2012) (ratio = 0.137).

Table 14: Net impact of modal shift: Online shopping and food delivery

	Light passenger (km)		Light commercial (km)	
	Behavioural progressive now	Behavioural progressive 2050	Behavioural progressive now	Behavioural progressive 2050
Shopping, goods and groceries	-2.64E+09	-3.57E+09		
Meals & eating out	-0.38E+09	-0.52E+09		
Total	**-3.02E+09**	**-4.09E+09**	**+4.15E+08**	**+5.61E+08**

Table 15: Net impact of modal shift: Public transport uptake

	Light passenger (km)		Public transport (kg CO2e)
	Behavioural progressive now	Behavioural progressive 2050	
Personal appointment & services	-1.67E+09	-2.25E+09	GWP impacts from modal shift between passenger fleet to public transport is set at 30% to account for extra services to meet additional demand.
Social visit & entertainment	-1.65E+09	-2.23E+09	
Meals & eating out	-0.82E+08	-1.10E+09	
Travel to work or study	-2.14E+09	-2.88E+09	
Total	-6.27E+09 -18.4%	-8.47E+09 -19.4%	

About thinkstep Australasia

thinkstep's mission is to enable organisations worldwide to succeed sustainably, by developing strategies, delivering roadmaps and projects, and implementing leading software solutions. thinkstep was established 25 years ago to support the German automotive industry and today provides expertise to clients from all sectors worldwide. Local clients include Fletcher Building, Freightways, Sanford, Meridian and Villa Maria. thinkstep in Australasia is locally owned and part of the global thinkstep group, with 300 sustainability experts worldwide.

Contact us

Auckland
+64 9 889 0250

Wellington
+64 4 889 2520

Hamilton
+64 7 808 0701

Sydney
+61 2 8007 5201

Melbourne
+61 3 9015 9455

Perth
+61 8 6102 7478

www.thinkstep-anz.com

anz@thinkstep.com

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