Evaluating the opportunity to engineer transition to a low carbon freight transport system in New Zealand

Phase 1: Baseline of direct tank-to-wheel transport greenhouse gas emission for key commodities and modes

- Data Interaction Report

Commissioned by: Swire Shipping New Zealand

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Executive summary

This report presents the work and results for the last component (data interaction) of the project titled: “Evaluating the opportunity in the heavy domestic freight sector to contribute to the decarbonisation of the transport task in New Zealand - Phase 1: Baseline of direct tank-to-wheel transport Greenhouse Gas emissions for key commodities”. The first component (data gathering), provided a general overview of the freight sector, and identified the most relevant official sources of freight data in New Zealand. The second component (data filtering) elaborated on the arrangement of data structures and relational data model, and addressed data considerations to estimate transport activity. The Data Integration report (submitted on the completion of the third component) presented the consolidation of the datasets for the estimation of transport activity.

This report addresses work associated with the data interaction stage. Energy use and GHG emissions are estimated across all freight transportation modes (Road, Rail, and Coastal Shipping). The heavy freight road transportation analysis is more detailed, due to the availability of more comprehensive data sources. The sector's carbon footprint is assessed from two perspectives: the vehicle fleet and from a commodity type basis. The two-sided analysis serves to provide model validation.

The vehicle fleet is analysed using Copert software (Ntziachristos et al., 2009) to estimate energy use and associated emissions for different truck categories. NZTAs vehicle inspection dataset was the main input. One of the advantages of Copert is its capability to include vehicle operation parameters, including circulation variables such as peak and off-peak driving share, rural/highway and associated speed limits. Furthermore, a sensitivity analysis is included to explore the impact of load utilisation and road slope on emissions. The results indicate that energy use and emissions are highly sensitive to driving conditions (road slope) and vehicle utilisation. Our estimates suggest that the overall utilisation factor for the heavy truck fleet ranges from 50% to 75%. This is a key aspect to consider when designing future decarbonisation plans, as consolidation strategies can increase the overall loading factor and enhance significant emission reductions per tkm.

Commodity-specific freight flows are analysed across the network. The main data inputs include region-to-region matrices from the national freight demand model, road network vector data, and sector-specific energy intensities reported in the scientific literature. Flows were allocated to the road links to quantify transport activity across the network and by commodity. Energy intensity figures were adjusted for the execution of a simulation-based model to explore the variability of energy use as a function of truck utilization. LEAP software (Heaps, 2016) was used to estimate the emissions associated with every sector. One of the advantages of the software is its capability to assess every branch and level of an energy system, allowing it to quantify interdependencies between demand and resource processing. The energy model used in this study is a valuable tool that could be used in future studies to quantify the emissions associated with scenarios that change modal share, vehicle types, and fuels (including electricity).

For rail and coastal shipping modes, the assessment was purely commodity specific; the activity and energy intensity of every mode and commodity type was input into LEAP to obtain direct and indirect emissions. Rail transportation was analysed similarly to road, by allocation of region-to-region flows over the rail network. In the absence of manifest records, rail activity was assessed on a case-by-case basis, with information about facility locations and freight logistics obtained from sector-specific reports and open-source geographic data. From the road and rail network analysis, the activity of ferry freight movements was able to be quantified which represents, 22.7% of total shipping emissions (~97.5 thousand tonnes of CO_2e). For the remaining shipping movements of petroleum, bulk (cement, limestone, and fertiliser), and containerised commodities, freight activity was estimated as a function of region-to-region movements, port-to-port distances from the nautical almanac, and manifest data provided by Pacifica Shipping. Pacifica provided fuel use records, which allowed energy intensity figures for containerised shipments to be estimated. Based on the analysis of manifest records, it was estimated that the average utilisation of container shipping is approximately 70%. A shift of inter-island “General” road freight movements to coastal shipping can potentially increase ship utilisation to 90%, leading to an annual reduction of 161.7 kt CO_2, which represents approximately 5.1% of direct heavy freight carbon emissions. Further analysis is required to verify the feasibility of modal shift, as it is likely that upgrades in capacity, resources, and infrastructure will be necessary. Moreover, further analysis is needed to understand potential trade-offs between emissions and transport costs (i.e. travel time).

Our results show that road transport is the dominant mode of heavy freight transport, with a 79.7% share of total freight activity (~37,382 million tkm), and a 94.5% share of total emissions (~3248 thousand tonnes of CO_2e). Activity and emissions were also determined from region-to-region freight movements. The model described in this report provides a solid foundation for future initiatives aiming to develop a national freight model, which can be an important resource to understand future changes in the freight task and the corresponding impacts.

To a lesser extent, the report investigates embedded emissions related to vehicles and infrastructure. The embedded emissions presented in this report are not based on an accredited lifecycle analysis, but provide insight around the scale relative to direct emissions, the major source of emissions. Considering all the emission sources investigated, our estimates show that road emissions are between 2.4 and 2.7 times higher than rail, and between 5 and 5.6 times larger than coastal shipping emissions.

The main datasets and results from the project have been consolidated into a web-based dashboard[1], where users can navigate and visualize data inputs, activity, energy use, and emissions associated with freight transport.

[1] Transport Dashboard, https://epecentre-nzfreight-i7y49.ondigitalocean.app/

Contents

Definitions

API	Application Programming Interface can be thought of as a contract that allows communication between applications using requests and responses.
Library	A software package used for software development, for example the matplotlib is a python-based library, provides visualisation functionality.
Numpy	Python library that provides functionality for fast operations on arrays, including mathematical, logical, shape manipulation, sorting, selecting, basic linear algebra, and basic statistical operations.
Python	A general-purpose programming language used for Application Development, Data Science, Geospatial Analysis and Scientific Computing.
SciPy	SciPy is a collection of mathematical algorithms and convenience functions built on the NumPy extension of Python.

Acronyms

ASIF	Activity, Structure, Intensity, and Fuel
BAU	Business-as-usual
CSSA	Complex Systems Strategic Analysis
DVA	Development Vector Analysis
DWT	Deadweight tonnage
EEOI	Energy Efficiency Operational Indicator
GCM	Gross Combined Mass.
GHG	Greenhouse Gas
GVM	Gross Vehicle Mass
HHD	Heavy-Heavy-Duty trucks
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LWT	Lightweight tonnage
MHD	Medium Heavy-Duty trucks
NFDS	National Freight Demand Study
NZTA	New Zealand Transport Agency
ONRC	One Network Road Classification
OD	Origin to Destination
PTW	Pump To Wheel
PWC	Population-weighted centroid
TA	Territorial Authority
TEU	Twenty-Foot Equivalent Unit
TKM	Tonne-kilometres
VEPM	Vehicle Emissions Prediction Model
VKT	Vehicle kilometres travelled.
WTP	Well to Pump
WTW	Well To Wheel

1 Road Heavy Freight Transport

The assessment of direct and indirect emissions associated to heavy freight road transport is undertaken from two perspectives. The first focuses on road energy use and emissions by vehicle categories, and the second focuses on road energy use and emissions by commodity type.

1.1 Emissions for truck categories

The methodology to estimate the annual distance travelled by vehicle was presented in the Data Interaction report (Gallardo et al., 2022b). Further processing was executed to include vehicle categories consistent with the format of the Copert emission calculator software (Ntziachristos et al., 2009). The stock configuration for heavy-duty trucks includes two segments: rigid and articulated; the latter is often recognized for carrying a detachable trailer. Furthermore, trucks are categorized as a function of Gross Vehicle Mass (GVM) and Gross Combined Mass (GCM). The gross weight of a trailer is typically around 20 tonnes (Metcalfe and Peeters, 2020). It was assumed that vehicles where the difference between GCM and GVM was higher than 20 tonnes correspond to the articulated category. Subcategories for the rigid segment were based on GVM. Subcategories for the articulated segment were based on GCM. Figure 1 illustrates the results of the data processing to categorize rigid and articulated segments.

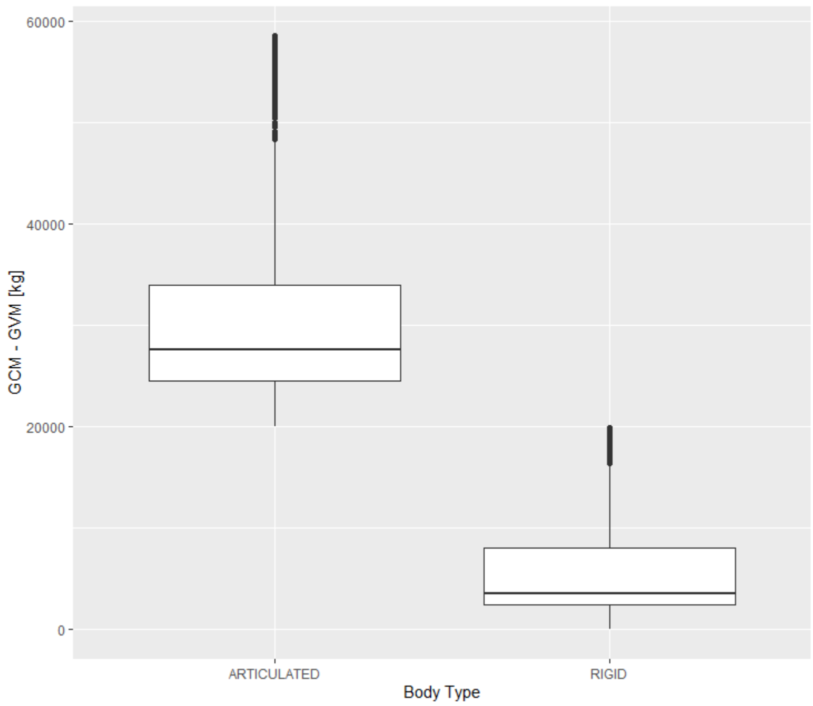


Figure 1 Fleet Distribution of Heavy trucks as a function of the difference GCM and GVM

Annual distance travelled was not calculated for every truck, as there was insufficient information (i.e. vehicle inspection records) to run estimates. Once vehicle categories were assigned to each truck (a row in the dataset), the dataset was grouped into categories, and the annual average travel distance was obtained for every group. Missing values for annual distance travelled were replaced by the corresponding category averages.

Records of year of manufacture were also available for every truck. The age of the vehicles along with the mean distances were used to calculate lifetime cumulative activity for every category type. The stock and activity data for the fleet are presented in Figure 2.

Vehicle				Stock & Activity		
Category	Fuel	Segment	Euro Standard	Stock [n]	Mean Activity [km]	Lifetime Cumulative Activity [km]
Heavy Duty Trucks	Diesel	Rigid <=7,5 t	Conventional	26,887	16,609.67	79,928.66
Heavy Duty Trucks	Diesel	Rigid 7,5 - 12 t	Conventional	17,282	27,794.73	134,154
Heavy Duty Trucks	Diesel	Rigid 12 - 14 t	Conventional	2,215	17,385.36	81,984.52
Heavy Duty Trucks	Diesel	Rigid 14 - 20 t	Conventional	6,857	23,600.72	134,291.08
Heavy Duty Trucks	Diesel	Rigid 20 - 26 t	Conventional	7,762	28,277.05	153,290.36
Heavy Duty Trucks	Diesel	Rigid 26 - 28 t	Conventional	458	31,963.06	171,509.11
Heavy Duty Trucks	Diesel	Rigid 28 - 32 t	Conventional	1,706	36,957.56	185,833.77
Heavy Duty Trucks	Diesel	Rigid >32 t	Conventional	464	53,345.06	260,259.26
Heavy Duty Trucks	Diesel	Articulated 20 - 28 t	Conventional	1	15,613.55	93,681.31
Heavy Duty Trucks	Diesel	Articulated 28 - 34 t	Conventional	29	66,085.44	256,998.93
Heavy Duty Trucks	Diesel	Articulated 34 - 40 t	Conventional	553	28,602.02	177,094.91
Heavy Duty Trucks	Diesel	Articulated 40 - 50 t	Conventional	7,479	29,896.2	195,991.99
Heavy Duty Trucks	Diesel	Articulated 50 - 60 t	Conventional	22,744	56,436.33	292,828.13

Figure 2 Copert User Interface of Vehicles Stock and Activity Data

One of the advantages of using the Copert software as an emissions calculator is the capability to input meticulous parameters related to circulation regimes and driving conditions. Circulation activity accounts for the operation and speed of vehicles within urban, rural, and highway regimes. Unfortunately, the circulation data for the New Zealand case was not available. However, circulation data for Australia was available and used as a proxy; Figure 3 shows the circulation parameters used.

Vehicle			Share				Speed			
Fuel	Segment	Euro Standard	Urban Peak [%]	Urban Off Peak [%]	Rural [%]	Highway [%]	Urban Peak [km/h]	Urban Off Peak [km/h]	Rural [km/h]	Highway [km/h]
Diesel	Rigid <=7,5 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Rigid 7,5 - 12 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Rigid 12 - 14 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Rigid 14 - 20 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Rigid 20 - 26 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Rigid 26 - 28 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Rigid 28 - 32 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Rigid >32 t	Conventional	15%	25%	25%	35%	35	50	70	90
Diesel	Articulated 20 - 28 t	Conventional	5%	20%	35%	40%	25	30	60	80
Diesel	Articulated 28 - 34 t	Conventional	5%	20%	35%	40%	25	30	60	80
Diesel	Articulated 34 - 40 t	Conventional	5%	20%	35%	40%	25	30	60	80
Diesel	Articulated 40 - 50 t	Conventional	5%	20%	35%	40%	25	30	60	80
Diesel	Articulated 50 - 60 t	Conventional	5%	20%	35%	40%	25	30	60	80

Figure 3 Copert User Interface of circulation parameters

In regards to vehicle operation, Copert also includes parameters associated with driving conditions, including load utilisation and road slope. Load utilisation data was not available, but the assessment accounted for two schemes: 50% and 75% load utilisation. Furthermore, a complementary commodity-specific utilisation analysis is presented in section 1.2.

Environmental conditions have an effect on the efficiency of fuel combustion. Accordingly, the calculations were based on monthly weather data for New Zealand. Local environmental information, fuel specification, and implied emission factors are provided in Appendix A, Appendix B, and Appendix C, respectively.

1.2 Emissions by commodity sectors

The analysis of road freight transport energy use and emissions by commodity was carried out for two spatial resolutions: region-to-region and district-to-district. In both cases, the main data inputs were the National Freight Demand Study (NFDS) (Richard Paling Consulting, 2019), road network vector data (LINZ, 2019), and commodity-specific energy intensity figures. The district-to-district analysis also required the use of land cover data (LRIS, 2015) and socio-economic statistics (New Zealand Government, 2022).

The approach is adapted from the ASIF methodology (Schipper and Marie-Lilliu, 1999), where emissions (G) are dependent on the level of freight transport activity (A) in tonne-km, the mode distribution (S), the fuel intensity of each mode (I) and the carbon content of the fuel or emission factor (F).

Equation 1

$$G_k = A * S_k * I_k * F$$

For our case study, the activity (A) depends on the magnitude of the flows in tonnes and routed distances. Every commodity type (k) has a specific share of the total activity (S_k) and specific energy intensity (I_k). The emission factors correspond to the heavy goods vehicles diesel category (Ministry for the Environment, 2020).

For the calculation of mode and commodity-specific energy demand and emissions, LEAP software was used as a calculator. LEAP, shorthand for the Low Emissions Analysis Platform, is a modelling tool for integrated energy planning and climate change mitigation assessment (Heaps, 2016). The software can be used to track energy consumption, production, and resource extraction in all sectors of an economy. In the context of this study, LEAP is used for the calculation of transport energy demand and emissions. Demand, Transformation, and Resource data structures in a LEAP model are organized through a hierarchical tree, hence, allowing to track energy use and emissions along every stage, from energy resource extraction to final demand. At the demand level, every sector is characterized in terms of activity (i.e. tkm), energy intensity, and load shape (percentage of annual load in every time slice). The transformation level is more complex as it captures energy distribution, generation, and resource extraction; every stage is defined in terms of capacity, process efficiency, costs (capital, operational, and maintenance), availability, and lifetime, amongst other parameters. The model (LEAP area) used in this study is an upgrade of a previous model used to assess Electric Vehicle policy in New Zealand (Gallardo et al., 2019). Specifically, the LEAP area has been updated with more recent data (2018 base year) and the demand for freight transport has been modified to reflect the level of commodity-based disaggregation used in this study. Figure 4 illustrates the logic behind the model, as flows connect different levels of the energy system, ranging from extraction to final demand. Losses associated with energy conversion and transportation are also accounted for, hence, allowing for the quantification of emissions associated with resource extraction and transformation. The demand branch for heavy freight transport can be further disaggregated by mode and by commodity, as the software was also used to estimate emissions from rail and coastal shipping. Environmental effects are allocated to each technology; these are based on the Intergovernmental Panel on Climate Change's (IPCC) emission factors. For specific combustion technologies, a Tier 2 method is applied, please refer to Appendix D for more information on transport-related (Tier 2) emission factors used in the commodity-specific analysis.

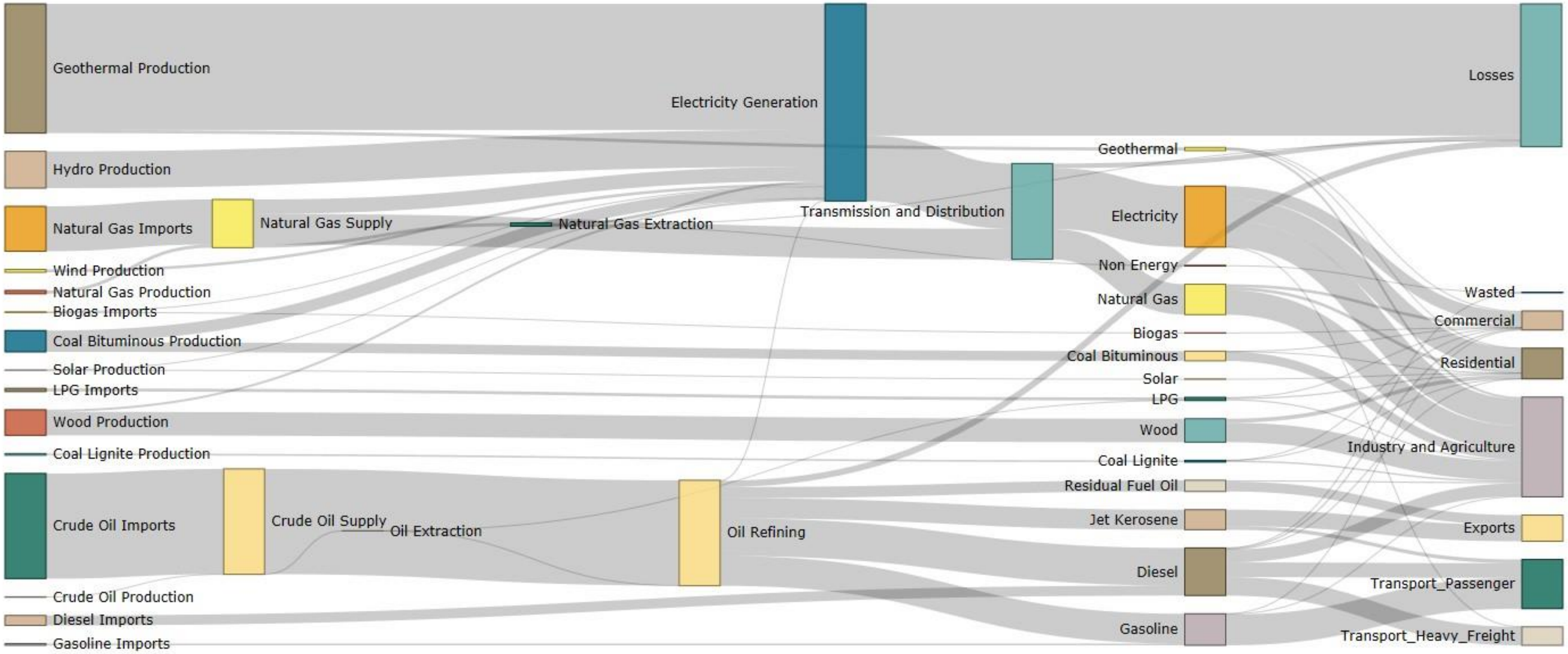


Figure 4 Sankey diagram of New Zealand Energy System

1.2.1 Network Analysis

The estimation of transport activity across commodities is based on the allocation of regional freight flows over the road network. The starting point is the analysis of inter-regional flows. For every Origin-Destination (OD) pair, the shortest route is estimated (Gallardo et al., 2022b). Once a route is identified, the flows in tonnes are aggregated to the traffic attributes from the links that integrate the route. Road links may be part of more than one shortest route, and connect more than one of the OD pairs across all commodity types. Accordingly, every link is associated with a unique object index and will have attributes for the flow values for each commodity type; the overall concept is presented in Figure 5.

Link_ID	O_ID	D_ID	Milk	Manufactured dairy
1	1	12	0	0
1	2	12	0	0.000127224
1	3	12	0	0
1	4	12	0	0
1	5	12	0	0
1	6	12	0	0.000890335
1	7	12	0	0
1	8	12	0	0
1	9	12	0	0
1	10	12	0.0015	0.00937573
1	11	12	0.2802	0
1	12	1	0	1.33478E-06
1	12	2	0	8.69264E-05
1	12	3	0	0
1	12	4	0	0
1	12	5	0	0
1	12	6	0	0.000122998
1	12	7	0	6.72479E-05
1	12	8	0	0
1	12	9	0	0
1	12	10	0	0.010880753
1	12	11	0.633	0.238283984
1	12	13	0	0
1	12	14	0	0
1	13	12	0	0
1	14	12	0	0

Link_ID	Milk	Manufactured dairy
1	0.9147	0.259836533
2	0.0015	0.021552549
3	0.9133	0.265034427
4	0.0015	0.048302991
5	0.0015	0.048302991

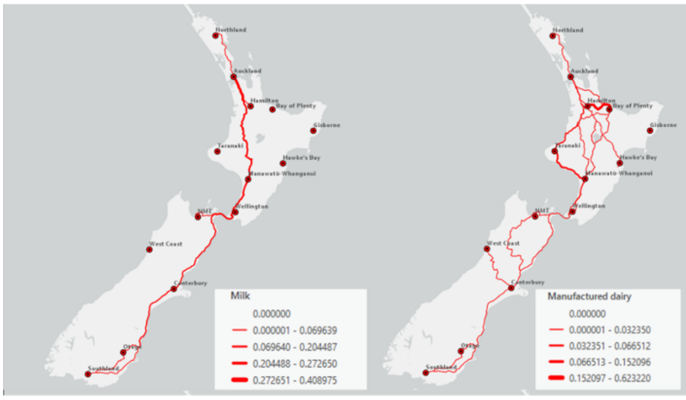


Figure 5 Road Network Analysis Representation

Every region is illustrated by a representative node. The population-weighted centroids (PWC) were used to represent each region in the network analysis for road movements. Figure 6 shows the locations of PWCs that were calculated by averaging the point centroids of 2018 mesh-blocks.

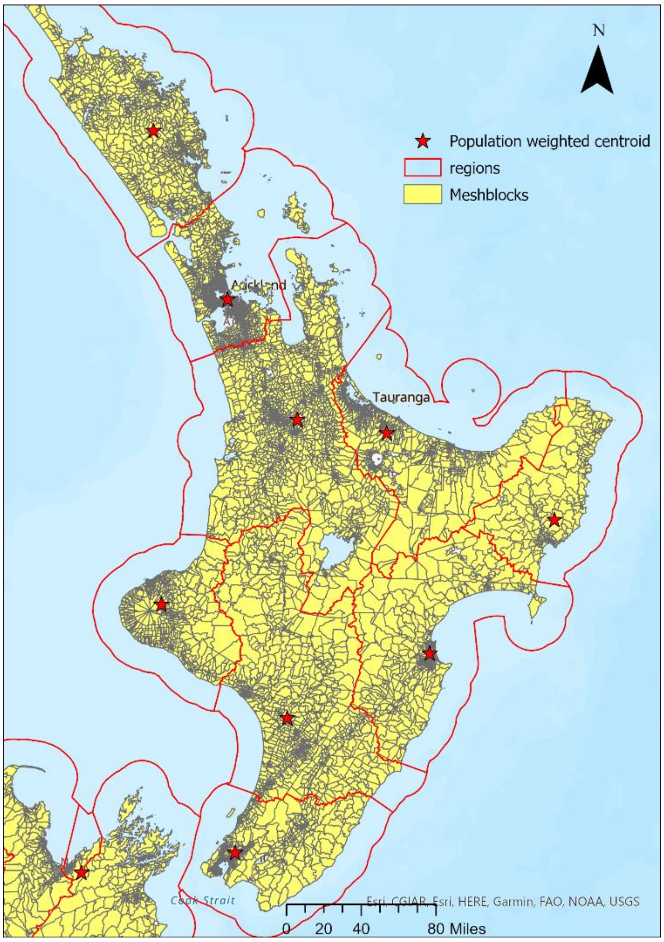


Figure 6 Representative region nodes for road network analysis

Network analysis permits quantifying traffic associated with inter-regional flows. For intra-regional flows, distances cannot be obtained through network analysis as the origin and destination are located over the same representative point. In these cases, the shortest distance (r_d) is assumed to be equivalent to the radii of a circle with an area equivalent to the surface area (A) of a region (R).

$$r_d = \sqrt{\frac{A_R}{\pi}}$$ **Equation 2**

To complement the study of intra-regional flows, Section 1.2.3 documents the implementation of a road freight transport model with a district-to-district spatial resolution.

The average slope of the road segment was calculated based on a digital elevation model with 24-metre resolution (Airbus, 2022). The average slope is obtained by weighing the three-dimensional length of each slope for each section along the road and then determining the average value. This results in longer sections having a greater but realistic effect on the resulting value than shorter sections. The sign of the slope is allocated to outgoing and incoming flows using North as a reference. For example, in Figure 7, B is located north of A and the slope of the road segment for traffic going from A to B is positive; the sign of the slope for traffic going in the opposite direction (B to A) is negative.

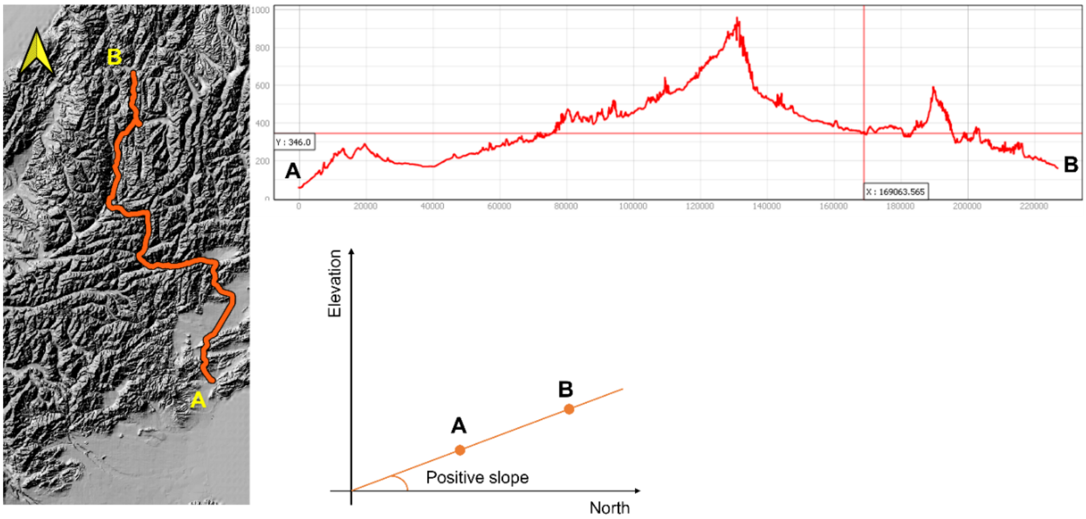


Figure 7 Illustration for slope calculation

A weighted average ($\overline{m}_{road}$) was calculated to assess the impact of slope on the emissions from road transportation. Every link has a slope (m_l) and an activity attribute (tkm) that was used as a weight (w_l).

Equation 3

$$\overline{m}_{road} = \frac{w_l * m_l}{\sum w_l} \cong 0.016$$

1.2.2 Sector Energy Intensity

Once the activity is estimated the next step is to identify sector-specific energy intensity figures. Andrés and Padilla (2015) applied a decomposition analysis to provide a better understanding of the changes in energy intensity of road freight transport in Spain. Their study accounted for the estimation of energy intensity figures for different commodity groups and years (Andrés and Padilla, 2015). These values have been adjusted to discard the impact of empty running, which has been estimated to be 22.9% for the Spanish case. The adjustment process is inspired by the Noortman and Van Es model which assumes that the number of empty trips between nodes i an j is a function of the commodity flow in the opposite direction j to i, multiplied by a constant p that represents the probability of returning empty (Gonzalez-Calderon et al., 2021).

Equation 4

$$z_{ij} = x_{ij} + p x_{ji}$$

Assuming that the number of trips is proportional to energy use, the following relationship can be applied:

Equation 5

$$E_{t,c} = E_{ij,c} + E_{ji,c}$$

For any sector c, the total energy of a roundtrip ($E_{t,c}$) is equal to the sum of energy used between i and j, and vice versa. The total energy use ($E_{t,c}$) is also equivalent to the product between the activity (tkm_c) and the sectoral energy intensity (I_c):

$$E_{t,c} = tkm_c I_c$$ **Equation 6**

The empty return will have lower energy demand. In fact, from empirical studies it is estimated the difference in fuel demand between full and empty heavy trucks ranges between 8% to 20%, depending on the speed regime (Zhang et al., 2017). Hence, Equation 5 can be rewritten:

$$E_{t,c} = E_{ij,c} + p_c(1 - r_c)E_{ij,c}$$ **Equation 7**

The energy use of the fully-loaded leg of the trip is the product of the activity (tkm_c) and the energy intensity of a full vehicle ($I_{c,full}$)

$$E_{ij,c} = tkm_c I_{c,full}$$ **Equation 8**

Accordingly, the commodity-specific energy intensity of full trips can be obtained by combining equations 4 – 7:

$$I_{c,full} = \frac{I_c}{1 + p_c(1 - r_c)}$$ **Equation 9**

Accordingly, the total energy use from road freight transportation is:

$$E_t = \sum_c E_{t,c}$$ **Equation 10**

The probability of an empty return (p_c) will depend on the nature of the commodity being transported. For instance, there is a high probability of an empty return for a tanker transporting milk from a farm to a factory. On the other hand, a truck moving containers between populated cities has a lower probability of running empty trips. Moreover, the percentage reduction in fuel demand (r_c) between full and empty trucks will range depending on the type of commodity being transported (dense vs light) (García-Álvarez et al., 2013).

Monte Carlo simulation was implemented to study the variability in total and sector-specific energy use for a range of fuel reduction parameters (r_c) and empty trip probabilities (p_c). The process was iterative; during each iteration, parameters are obtained randomly from a uniform distribution, given minimum and maximum values for all parameters. The ranges of values are based on empirical studies published in the literature (Zhang et al., 2017, García-Álvarez et al., 2013, Franzese and Davidson, 2011). Once parameters are set, energy use is calculated for every commodity type (Equation 7) and for the whole sector (Equation 10). Table 1 presents the adjusted energy intensity figures related to full trips for every commodity sector, minimum and maximum values for empty trip probabilities and percentage reduction in fuel use parameters.

Table 1 Parameters for estimation of road transport energy use across commodity types

Sector	Adjusted Energy Intensity for full trip (MJ/tkm)	Minimum probability of empty return	Maximum probability of empty return	Minimum percentage reduction of fuel use from full trip	Maximum percentage reduction of fuel use from full trip
Aggregate	1.26	0.9	1	0.13	0.2
Coal	1.96	0.9	1	0.13	0.2
Fish	1.02	0.3	0.5	0.083	0.108
General	1.27	0.3	0.5	0.083	0.108
Horticulture	0.89	0.3	0.5	0.083	0.108
Limestone	1.43	0.9	1	0.13	0.2
Livestock	1.75	0.8	1	0.13	0.2
Logs	1.40	0.9	1	0.13	0.2
Manufactured dairy	1.02	0.3	0.5	0.083	0.108
Meat	1.02	0.4	0.6	0.083	0.108
Milk	1.54	0.9	1	0.13	0.2
Other agriculture	0.89	0.4	0.6	0.083	0.108
Other minerals	1.31	0.9	1	0.13	0.2
Petroleum	0.77	0.9	1	0.13	0.2
Processed timber	1.01	0.3	0.5	0.083	0.108
Steel aluminum	1.37	0.3	0.5	0.083	0.108
Waste	1.00	0.9	1	0.13	0.2
Wool	1.33	0.3	0.5	0.083	0.108
Concrete	1.37	0.8	1	0.13	0.2

1.2.3 Road freight transport model for district-to-district assessment

In a previous report (Gallardo et al., 2022b), a transport model was validated over an artificial network. This section describes the implementation of the model with data for the case study. Model inputs include production and attraction attributes for every district, traffic count records and network analysis data; details about the datasets can be found in Gallardo et al. (2022a).

Link flows are expressed as a function of the OD matrices representing each of the eight commodity groupings (Aggregate, General Freight, Agriculture, Logs, Manufactured Dairy, Liquid Milk, Timber, Other). Parameters are estimated so that the errors between the estimated (V_l) and observed ($\widehat{V}_l$) link flows are minimised (Tamin and Willumsen, 1989). The problem is:

$$to\ minimise\ S = \sum_l (V_l - \widehat{V}_l)^2 \qquad \textbf{Equation 11}$$

The estimation process is based on a non-linear least-squares optimization method (Branch et al., 1999). The function in Equation 12 is adapted from the models reported in Högberg (1976) and Tamin and Willumsen (1989), where the flow (V_l) in a particular link l is the summation of the contributions of all trips between zones to that link. Equation 13 presents the cost function which contemplates two additional parameters that are also commodity specific.

$$V_l = \sum_c \sum_i \sum_j A_{p,i,c} b_c \frac{A_{a,j,c} f(d_{ij})}{\sum_k A_{a,k,c} f(d_{ik})} \cdot p_{ij}^l \qquad \textbf{Equation 12}$$

$$f(d_{ij}) = {d_{ij}}^{\beta_c} e^{\theta_c (\ln d_{ij})^2} \qquad \textbf{Equation 13}$$

Where:

V_l	Flow in link l
$A_{p,i,c}$	District i production attribute for trips associated to commodity c
$A_{a,j,c}$	District j attraction attribute for trips associated to commodity c
$f(d_{ij})$	Cost function
d_{ij}	Cost attribute between districts i and j
β_c	Cost function coefficient for commodity c
θ_c	Cost function coefficient for commodity c
b_c	Commodity c coefficient
i, j, k	District indexes
c	Commodity index
p_{ij}^l	Proportion of trips from district i to district j whose trips use link l
l	Link index

The array p_{ij}^{l} can be estimated from an all-or-nothing assignment:

$$p_{ij}^{l} = \begin{cases} 1 \; if \; trips \; from \; district \; i \; to \; district \; j \; use \; link \; l \\ 0 \; otherwise \end{cases}$$

Given a set of observed traffic counts ($\widehat{V}_l$), for N districts, and C sectors, there will be N^2 x C unknown flows (T_{ij}) to be estimated from a set of L equations, where L is the total number of traffic counts (i.e. monitoring sites with heavy traffic observations).

The model was implemented in Python, presented in Figure 8 as a step-by-step implementation diagram. Initially, data inputs (traffic count data, production and attraction attributes, and network costs) were cleaned, processed, and arranged into Numpy vector forms. The process included the implementation of network analysis routines to obtain the shortest paths and deliver costs (travel times) between all possible district-to-district combinations. A key outcome from the network analysis is the arrangement of an H-matrix, which is a mathematical representation of all shortest paths that enhances the transformation of OD flows into network traffic. The H-matrix consolidates all the p_{ij}^{l}'s. Flows, where the origin and destination are the same district, are not considered for model calibration as the cost function applies to d_{ij}'s greater than zero; consequently, a central component involves the removal of these exceptions. Another process focuses on the sum-product terms in the denominators from Equation 12, which had to be arranged as vectorised operations. The arrangement of the optimisation function involves the estimation of flows across all links (dot product between H matrix and Tij), and the arrangement of differences between observed and estimated link flows. Finally, model calibration uses functionality from python's Scipy nonlinear least-squares problem solver. The optimisation solver takes vectors of initial coefficient values and coefficient boundaries. The final output is a vector of 24 estimated coefficients: 8 sector coefficients and 16 cost coefficients.

Different cost formulations and geographic scopes were assessed for model accuracy. The standard error ($\hat{\sigma}$) was used as the metric, and in the context of this study it quantifies the average difference between observed and predicted traffic counts; mathematically it is expressed as:

$$\hat{\sigma} = \sqrt{\frac{\sum_l \left(V_l - \widehat{V}_l\right)^2}{n - t}} \qquad \textbf{Equation 14}$$

Where n is the number of observations and t is the number of coefficients. Table 2 presents a summary of the arrangements considered for different model tests. For instance, the formulation for test 1 only included 10 coefficients, that is, there were only two coefficients related to the cost function, and the model was applied given traffic count observations for the whole country. In test 2, the model formulation was modified to account for sector-specific cost coefficients, which led to a small reduction in the standard error. Road links in the vicinity of the Auckland districts have traffic records that are significantly greater than the country average. Accordingly, in test 3, the model was calibrated with a subset of traffic count observations that only accounted for records with less than 300,000 heavy traffic counts per year. The two final tests were restricted to traffic observation within the North Island and South Island respectively. The highest accuracy is associated to test 3, where the standard error decreased despite the reduced number of observations. Figure 9 illustrates the difference between observed and predicted traffic counts across different geographic extents. Overall, average difference between predicted and observed counts is 6,037, which is approximately 6% of the average annual traffic per link (94,554).

Table 2 Tests for different modelling arrangements

Test ID	Geographic Scope	No. of observations	No. of coefficients	Standard Error
1	National	994	10 (8 sector-specific and 2 for cost function)	3913.9
2	National	994	24 (8 sector-specific and 16 for cost function)	3788.1
3	National	956	24 (8 sector-specific and 16 for cost function)	2973.7
4	North Island	652	24 (8 sector-specific and 16 for cost function)	6037.2
5	South Island	341	24 (8 sector-specific and 16 for cost function)	4877.4

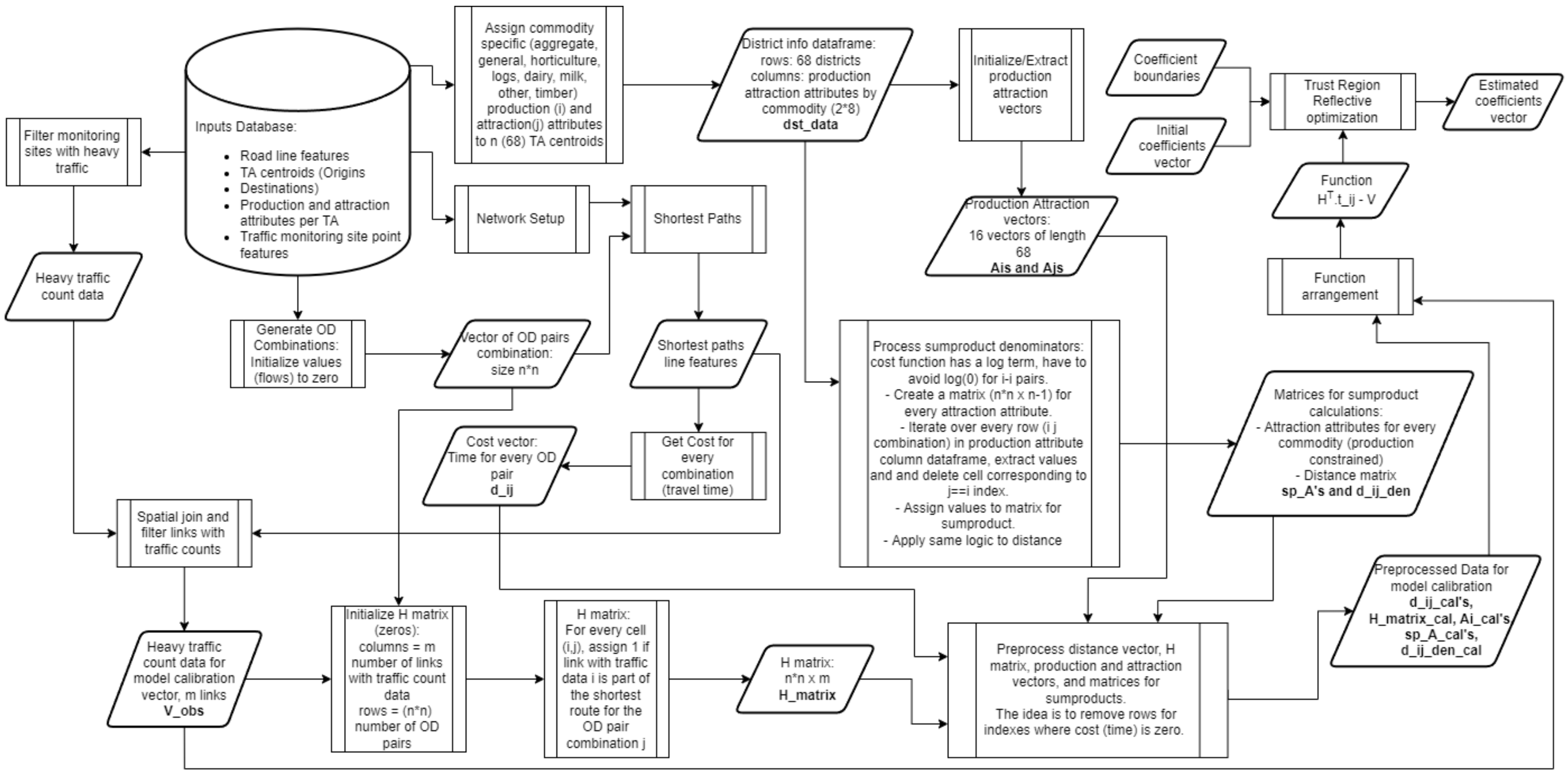


Figure 8 Road Freight Transport Model Implementation

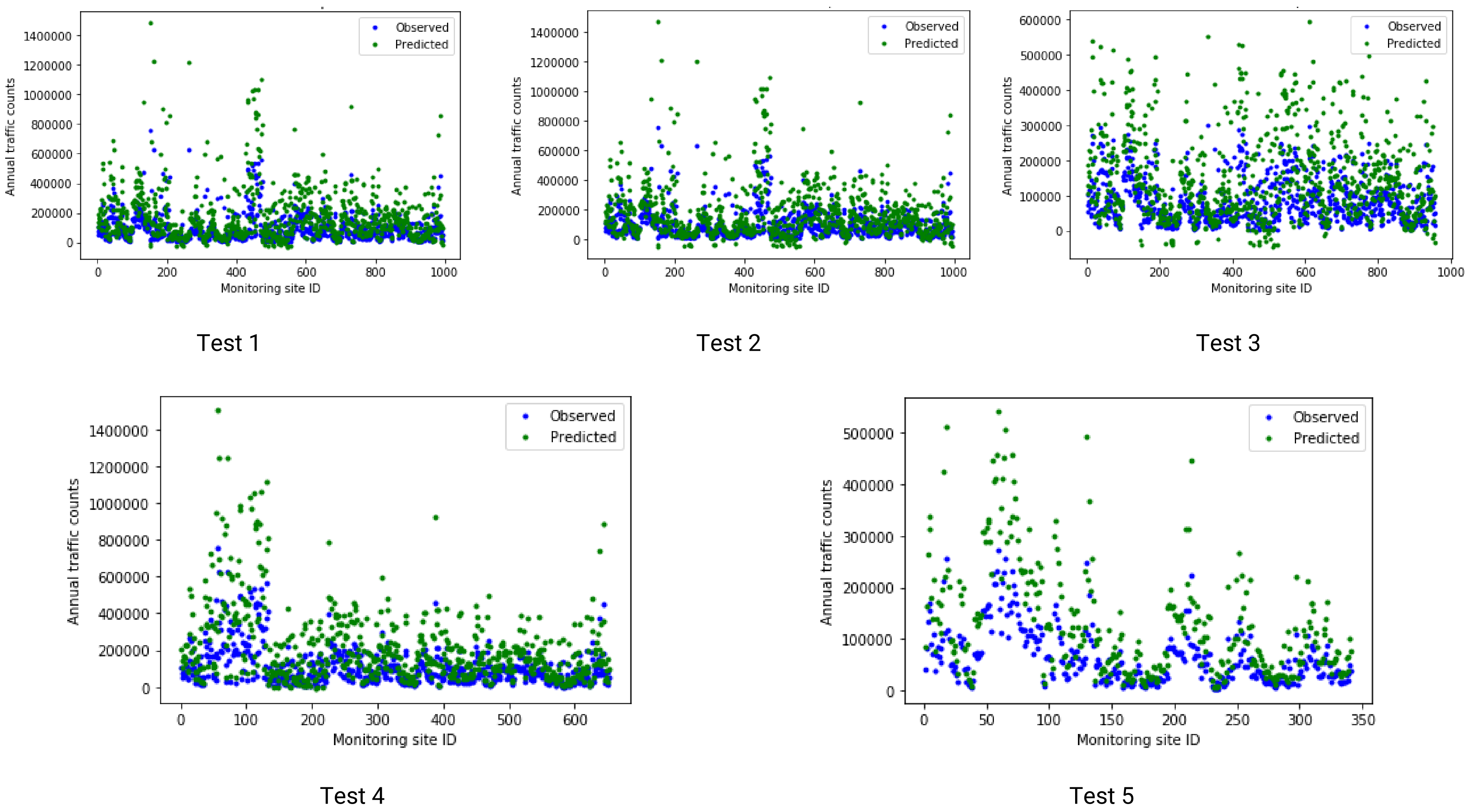


Figure 9 Predicted versus observed traffic counts for different modelling arrangements

2 Rail Heavy Freight Transport

The assessment of direct and indirect emissions associated to heavy freight rail transport is based on activity reported in the latest NFDS (Richard Paling Consulting, 2019).

2.1 Emissions by commodity sectors

The analysis of rail freight transport energy use and emissions by commodity was also based on the ASIF (Activity, Structure, Intensity, and Fuel) methodology described in section 1.2. Freight transport activity, energy demand, emissions depend on the magnitude of the flows in tonnes and travelled distances.

2.1.1 Network Analysis

The estimation of transport activity across commodities is based on the allocation of regional freight flows over the rail network. Network analysis allows quantifying traffic associated with inter-regional flows. Every region is represented by the rail station closest to the population-weighted centroid, as shown in Figure 10.

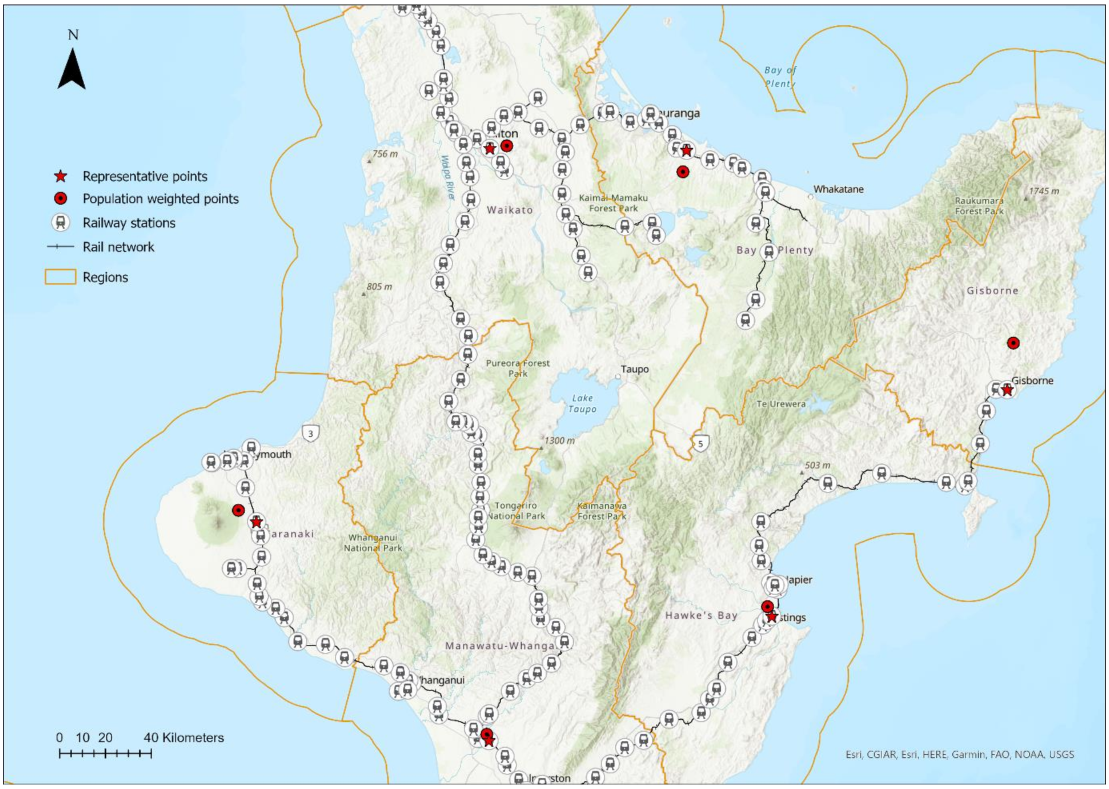


Figure 10 Representative region nodes for rail network analysis

The process of traffic allocation is similar to that reported for road transport in section 1.2.1. Every rail segment is associated with a unique object index and will have attributes for the flow values for each commodity type. Flows that were either generated and/or delivered to the stations at the ends of the electrified segment from the North Island main trunk, were assumed to be transported through electric trains. The network and representative nodes are shown in Figure 11.

Figure 12 shows freight tonnages for intra-regional movements across different commodity groups. In terms of tonne flows, most of the intra-regional activity takes place within Auckland, Bay of Plenty, and Canterbury. In these cases, the distances were evaluated on a case-by-case basis.

Figure 11 Rail Network

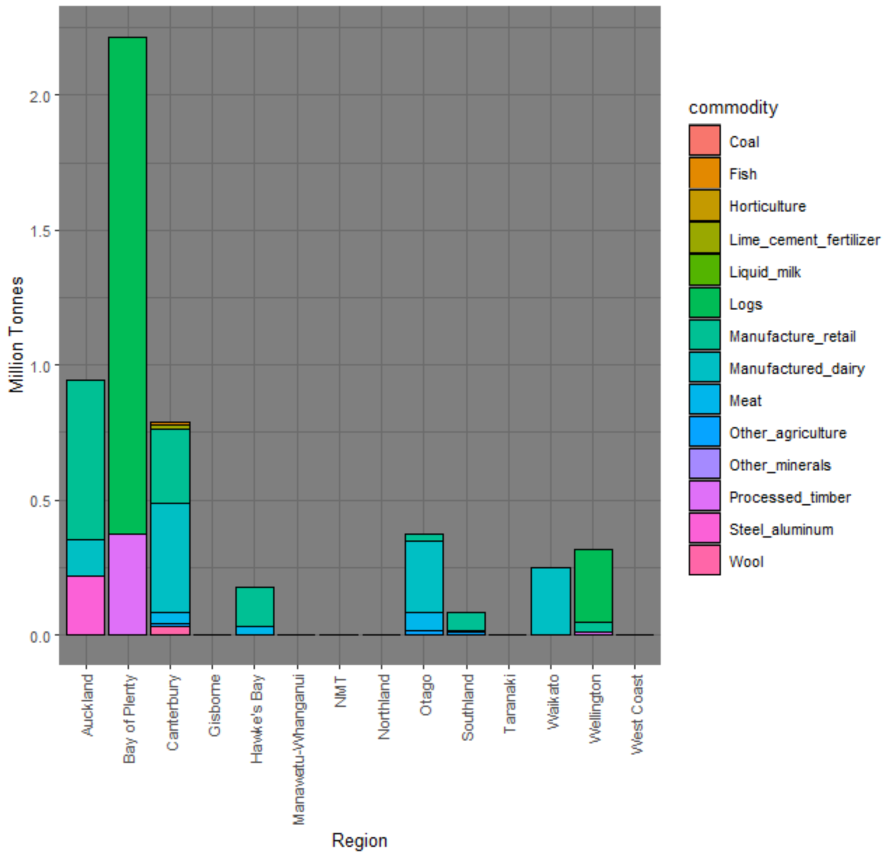


Figure 12 Intra-regional rail freight flows by commodity group

For the movement of logs, it was assumed that intra-regional trips by rail take place between log collection hubs and regional ports. For instance, Figure 13 shows that in Wellington logs are shipped from the Waingawa Log Hub to CentrePort (Sanderson and Robertson, 2020)

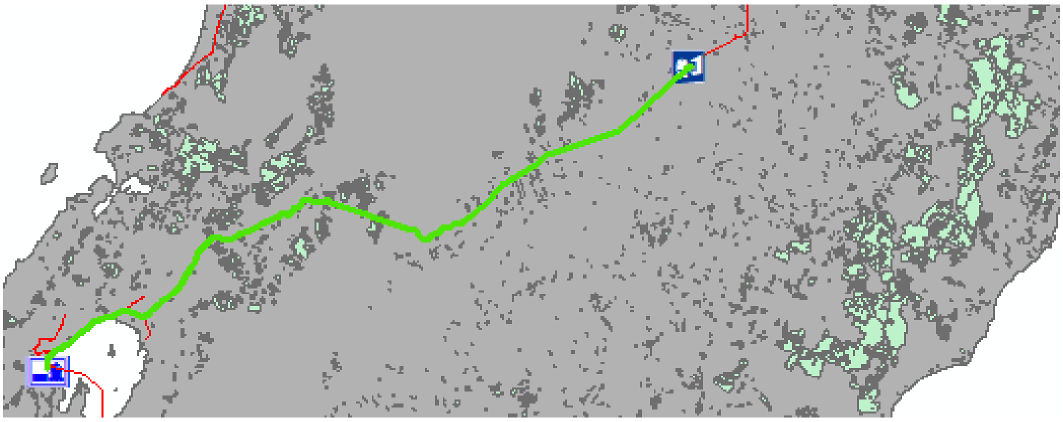


Figure 13 Rail route for log movements within Wellington Region

For the movements of dairy products, intra-regional distances were assumed to be the average of the routed distances by rail between dairy factories and ports/freight hubs. The locations of relevant dairy factories were obtained through a Google Places API. Queries were generated iteratively for every commodity sector (i.e. dairy factories, meat processing plants, wool scouring plants, sawmills) and region. Figure 14 illustrates the process for the Waikato Region, where dairy products are moved from different factories to a central freight hub on Hamilton's Crawford Street (Murray King & Francis Small Consulting, 2011).

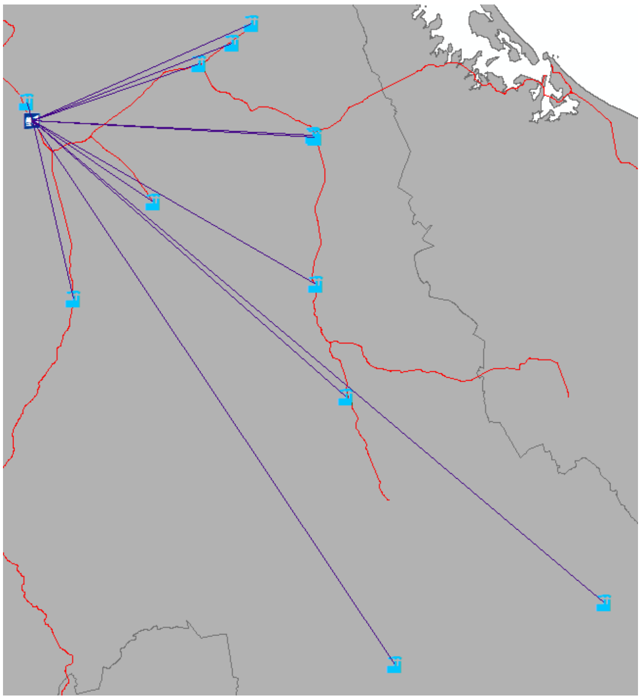


Figure 14 Origin destination analysis for dairy products movements within Waikato Region

For general freight, intra-regional distances were estimated as weighted averages between a port and statistical areas that intersected with the railway lines; population figures were used as weights. Figure 15 illustrates the process of estimating the intra-regional distance for general freight movements by rail within Auckland. Table 3 summarizes the estimation process across all commodities and regions.

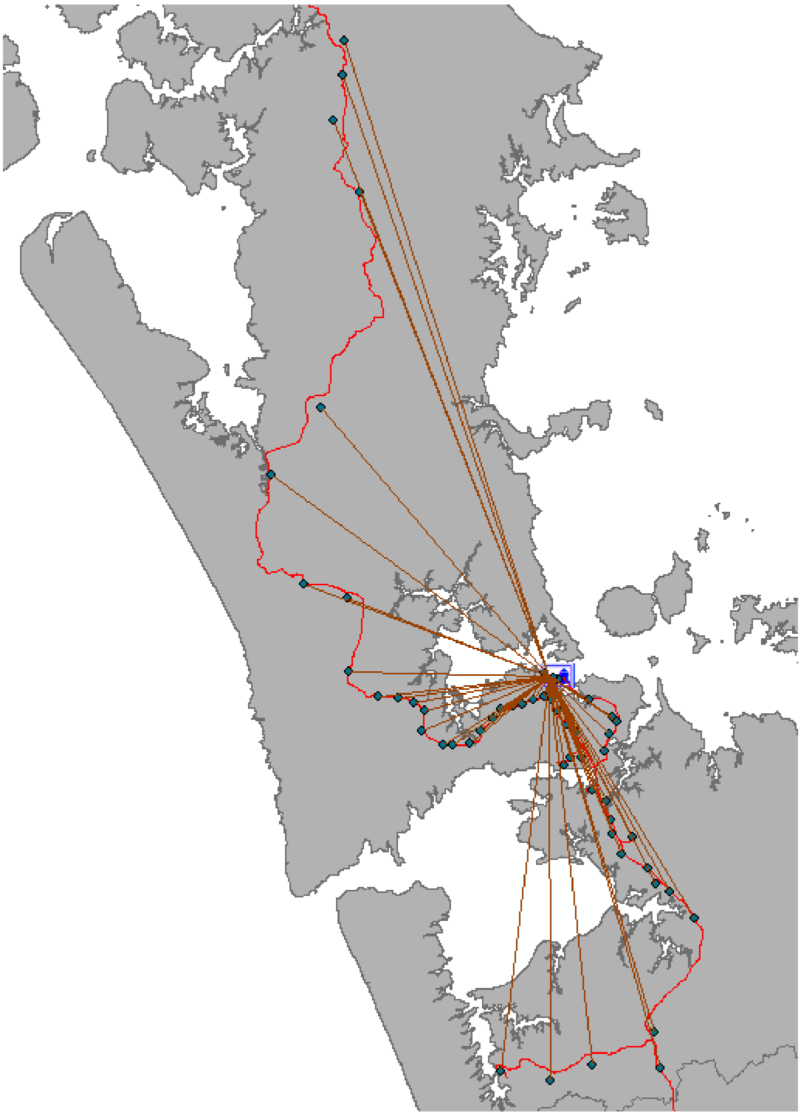


Figure 15 Origin destination analysis for general movements within Auckland Region

Table 3 Process description for intra-regional distance estimation

Region	Sector	Intra-regional Distance (km)	Process description
Auckland	Manufacture retail	24.0	Weighted average of distances between statistical areas and port (population as weight)
Auckland	Manufactured dairy	20.0	Average distance between relevant dairy factories (Fonterra TipTop and Fonterra Takanini) and Ports of Auckland
Auckland	Steel aluminum	51.0	Movements between Pacific Steel and Bluescope Steel
Bay of Plenty	Logs	140.0	Distance between inland log hub with surrounding forest areas and port
Bay of Plenty	Processed timber	59.3	Average distance between wood processing facilities (sawmills) and port
Hawke's Bay	Manufacture retail	52.6	Weighted average of distances between statistical areas and port (population as weight)
Hawke's Bay	Meat	25.2	Routed distance between meat processing facility and port
Canterbury	Manufactured dairy	53.0	Average distance between relevant dairy factories (Fonterra Studholme, Fonterra Darfield, Synlait Dunsandel) and ports (Timaru and Lyttelton)
Canterbury	Manufacture retail	51.0	Weighted average of distances between statistical areas and port (population as weight)
Canterbury	Meat	29.5	Average distance between relevant meat processing facilities and port
Canterbury	Wool	16.0	Weighted average of distances between wool scouring plants and port (regional exports as weight)
Otago	Manufactured dairy	91.0	Routed distance between relevant dairy factory (Fonterra Stirling) and ports (Otago)
Otago	Meat	120.6	Routed distance between meat processing facility (Alliance) and port
Otago	Manufacture retail	59.3	Weighted average of distances between statistical areas and port (population as weight)
Waikato	Manufactured dairy	71.0	Routed distance between relevant dairy factories and freight hub (Crawford St)
Wellington	Logs	85.0	Routed distance between Waingawa log hub and CentrePort
Wellington	Manufacture retail	37.5	Weighted average of distances between statistical areas and port (population as weight)
Southland	Manufacture retail	60.8	Weighted average of distances between statistical areas and port (population as weight)

2.1.2 Energy Intensity

Two propulsion types were considered in the analysis for diesel and electric locomotives, respectively. The energy intensity for freighting goods by diesel trains (0.36 MJ/tkm) is based on KiwiRail estimates reported in their annual integrated report (KiwiRail, 2021a). The energy intensity for freighting goods by electric trains is assumed to be 0.025 kWh/tkm (Ligterink et al., 2017). Unlike the case for road, it was assumed that the energy intensity is uniform across commodity types. The emission factor for electricity production was modelled as a function of the country's power generation mix. The LEAP model used in this study and described in Gallardo et al. (2019), is based on New Zealand's power generation mix. Each power generation technology is characterised in terms of installed capacity and temporal availability, hence, estimates for indirect emissions account for the share of non-renewable generation throughout the year.

3 Coastal Shipping Heavy Freight Transport

The assessment of direct and indirect emissions associated to coastal shipping is based on activity reported in the latest NFDS (Richard Paling Consulting, 2019).

3.1 Emissions by commodity sectors

The analysis of coastal shipping energy use and emissions by commodity was also based on the ASIF methodology described in section 1.2. Freight transport activity, energy demand, emissions depend on the magnitude of the flows in tonnes and travelled distances.

Overall, coastal shipping runs inter-regional movements within New Zealand. The only intra-regional movements take place within the Canterbury region, specifically between the ports at Lyttelton and Timaru. Moreover, movements are only reported for petroleum, limestone, cement, fertilizer, and containerized shipments. Accordingly, the analysis is based on energy use associated to the operation of container, bulk, and tanker ships.

Calculations are based on the International Maritime Organization's (IMO) fuel to mass CO_2 conversion factor of 3.1144 t-CO_2/t-Fuel for Heavy Fuel Oil (Marine Environment Protection Committee, 2009) and on a calorific value of 42.8 TJ/kt for Heavy Fuel Oil (Eng et al., 2008). The direct and indirect emissions are carried out using LEAP software as an energy and emissions calculator, please refer to section 1.2.

3.1.1 Network Analysis

Network analysis for road and rail incorporated the quantification of traffic through an artificial link that provided the inter-island connection. In reality, intermediate inter-island legs are executed through ferry services. From the previous road and rail network analysis (sections 1.2.1 and 2.1.1), the activity associated to ferry services was estimated. Figure 16 shows the activity disaggregated by commodity and by land mode of access to a ferry terminal; it can be observed that most of the cargo arrives to the ferry terminals by road.

Network analysis was not applied for inter-regional coastal shipments as the routes cannot be directly assigned to a network. The activity (tkm) was based on port-to-port distances obtained directly from the New Zealand Nautical Almanac (Land Information New Zealand (LINZ), 2022).

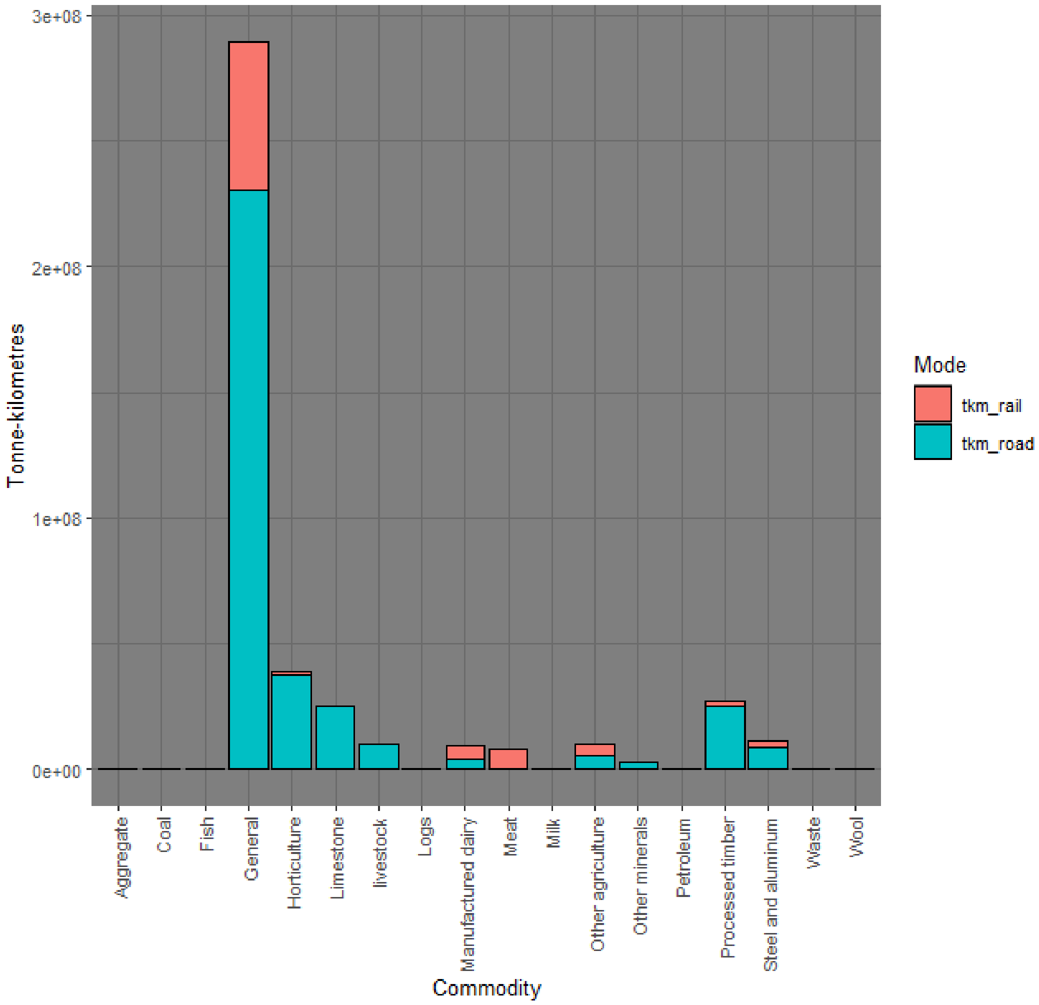


Figure 16 Freight activity associated to ferry movements

3.1.2 Energy Intensity

For container movements, Pacifica Shipping provided manifest records and fuel use associated with the operation of the "Moana Chief" vessel. It is common industry practice to record fuel consumption separately from cargo information. Therefore, individual container data was merged with the wider ship fuel records. The container dataset was filtered, cleaned and standardised to match journey dates from the fuel records dataset. Then containers were grouped by their origin and destination before being combined again into legs derived from the fuel records; the process is illustrated in Figure 17. The final outcome was a consolidated dataset with cargo weight and fuel use records, which were used to estimate the energy intensity associated with container movements for every leg. Figure 18 illustrates the observations from the final dataset, and the relationship between ship utilisation (TEU) and carbon intensity. The average carbon intensity is 0.0342 kg CO_2/tkm which is consistent with figures reported in official (Ministry for the Environment, 2020) and academic (Laffineur, 2015) sources.

	Container_ID	Type	Vessel	Voyage	Consignor	LOAD	DISCH	Commodity	Gross_Weight_KG	Tare_Weight_KG	ETD	ETA
0	AFLU1000490	20'DRY	MVMC	4258	DOMESTIC CARGO	NZAKL	NZLYT	Full CNTR	26080.0	3900.0	2021-01-08	2021-01-09
1	ALNZ0002278	20'DRY	MVMC	4258	DOMESTIC CARGO	NZAKL	NZLYT	FULL CNTR	25440.0	3900.0	2021-01-08	2021-01-09
2	SMAU8881300	20'DRY	MVMC	4258	DOMESTIC CARGO	NZAKL	NZLYT	FULL CNTR	25800.0	3900.0	2021-01-08	2021-01-09
3	RWNU9693640	20'DRY	MVMC	4258	DOMESTIC CARGO	NZAKL	NZNSN	FULL CNTR	5600.0	2550.0	2021-01-08	2021-01-11
4	CXSU1268492	20'DRY	MVMC	4258	DOMESTIC CARGO	NZAKL	NZNSN	FULL CNTR	5150.0	2550.0	2021-01-08	2021-01-11

	ETA	From	To	Nau_Mile	Consumption_T	KM_Travelled
0	2020-12-24	TGA	AKL	142	14.9	262.984
1	2021-01-09	AKL	LYT	680	66.6	1259.360
2	2021-01-11	LYT	NSN	265	26.3	490.780
3	2021-01-13	NSN	TGA	574	65.3	1063.048
4	2021-01-14	TGA	AKL	142	13.3	262.984

Figure 17 Container Shipping Dataset Relationships

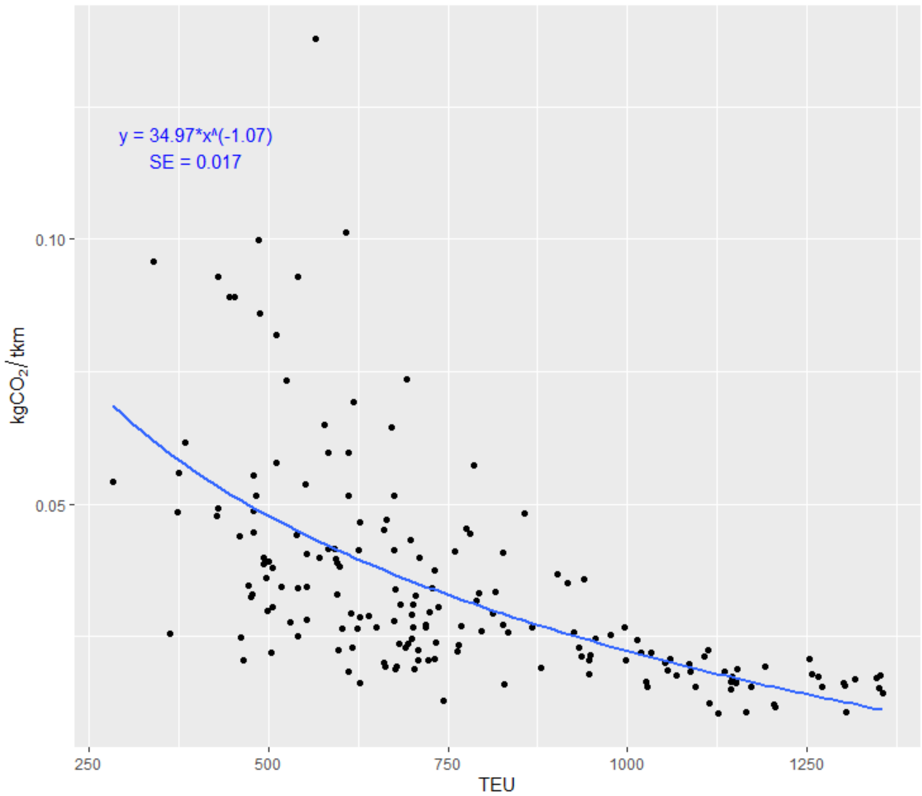


Figure 18 Carbon intensity as a function of ship's load (TEU)

The Energy Efficiency Operational Indicator (EEOI) is the IMO's standard metric to assess the performance of coastal ship fleets with regards to CO_2 emissions (Marine Environment Protection Committee, 2009). It can be interpreted as a carbon intensity indicator, it associates fuel consumption and transport work. Previous studies have used information collected on voyages from dry bulk vessels to fit EEOI as a function of ship's Deadweight tonnage (DWT) (Panagakos et al., 2019, Laffineur, 2015). DWT is defined as the sum of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers and crew. New Zealand registered company Coastal Bulk Shipping Ltd are the owners and operators of the M.V. Anatoki vessel which carries bulk cargoes within the country. There are two cement carriers; the Aotearoa Chief operates mostly in the North Island, hauling cement from Whangarei, and the Buffalo hauls cement from Timaru (Richard Paling Consulting, 2019). Carbon intensity for dry bulk shipping is based on the EEOI, which can be obtained as a function of the ships'

DWT (Laffineur, 2015), see Equation 15. The energy intensity can be further obtained after running a unit conversion process.

$$EEOI_{bulk}\left[\frac{gCO_2}{tonne * miles}\right] = 814.95 * DWT^{-0.39}$$ **Equation 15**

Emission estimates for coastal shipping are based on activity reported in 2018. In that year, petroleum-based products were transported through tankers from Marsden Point to New Zealand. Specifically, operations were executed by two coastal tankers (MT Kokako and MT Matuku) with DWTs of 49,218 and 29,735, respectively. There was no accessibility to fuel use records from tanker operations, hence, energy intensity for tanker shipping was also derived from Equation 15. For ferry movements, energy intensity is based on the international emissions factor reported in Ministry for the Environment (2020).

Table 4 Parameters for estimation of energy intensity across ship types

Commodity	Ship Name	DWT[2]	EEOI ($kgCO_2$/tkm)	EI (MJ/tkm)	Observations
Container	Moana Chief	23,305	0.0342	0.4653	Energy intensity obtained from manifest and fuel records
Bulk	Anatoki	447	0.0407	0.5597	Energy intensity calculated as a function of vessel's DWT
Bulk (Cement)	Aotearoa Chief	8024	0.0132	0.1815	Energy intensity calculated as a function of vessel's DWT
Bulk (Cement)	Buffalo	9092	0.0125	0.1729	Energy intensity calculated as a function of vessel's DWT
Tanker	MT Kokako	49,218	0.0065	0.0894	Energy intensity calculated as a function of vessel's DWT
Tanker	MT Matuku	50,143	0.0064	0.0888	Energy intensity calculated as a function of vessel's DWT
Ferry	NA	NA	0.051	0.7008	Energy intensity obtained from report (Ministry for the Environment, 2020)

[2] Deadweight Tonnages (DWT) obtained from MarineTraffic (https://www.marinetraffic.com/)

4 Results

Findings are presented for the heavy freight sector, transport modes and commodity types. The analysis of road heavy transport has greater detail, as estimates are contrasted for different units of observation, truck fleet and commodity types. These data sources and results can also be extracted and visualized from an online dashboard for the project[3]. This sections also includes the analysis of vehicle and infrastructure embedded emissions across all modes. Furthermore, this section includes a brief overview of accident associates to freight transport.

4.1 Road Emissions

The analysis of road emissions has a higher level of detail as it looks at the sector from two perspectives:

- Energy and emissions associated with the transportation of different commodities.
- Energy, emissions, and other pollutants for different heavy vehicle types.

For the commodity-based analysis, the assessment discriminated between intraregional and interregional movements. Figure 19 shows heavy freight road activity by commodity and by scope (inter vs intra-regional movements). Movement patterns are not consistent across commodity-types. Overall, 53.1% of freight activity remains within regions (intra-regional scope). Retail and manufactured products (i.e. General, dairy, timber) that can be containerised are likely to travel longer distances, which is reflected by their higher inter-regional activity. On the other hand, bulk-type products like aggregate material, concrete, milk, and waste tend to follow localised intra-regional movements that are likely to remain on heavy road transport.

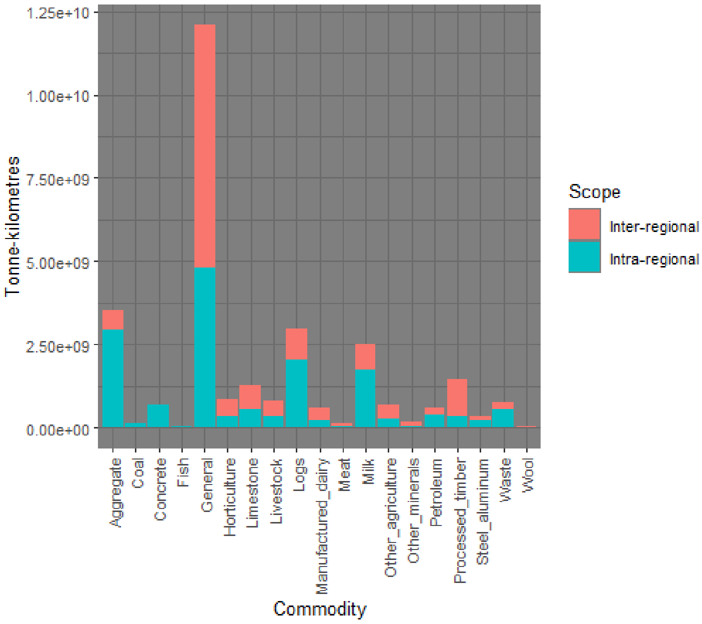


Figure 19 Total activity by commodity type, by scope

[3] Transport Dashboard, https://epecentre-nzfreight-i7y49.ondigitalocean.app/

A simulation approach was implemented to study the variability of energy use for the whole sector and across every commodity type. The method accounted for the impact of utilisation, i.e. the probability of empty returns, and product type on energy intensity. Figure 20 shows the distribution of energy use across different sectors, where energy use can vary as a function of vehicle utilisation and fuel economy parameters. Sectors that exhibit very low variability are generally associated with the movements of bulk products that have a high probability of an empty return. On the other hand, manufactured commodities have a lower probability of an empty return, hence energy use has a higher dispersion. The highest energy use corresponds to the 'General' category so this has been placed on a separate graph for ease of viewing (see Figure 21). On average, it uses approximately 41.5% of the total energy use of heavy road transport. Figure 21 shows the distribution of energy use specifically for the 'General' category which includes freight activity for retail and general manufactured products; energy use within this category shows a high dispersion, as there is a high uncertainty about the utilisation of the vehicles.

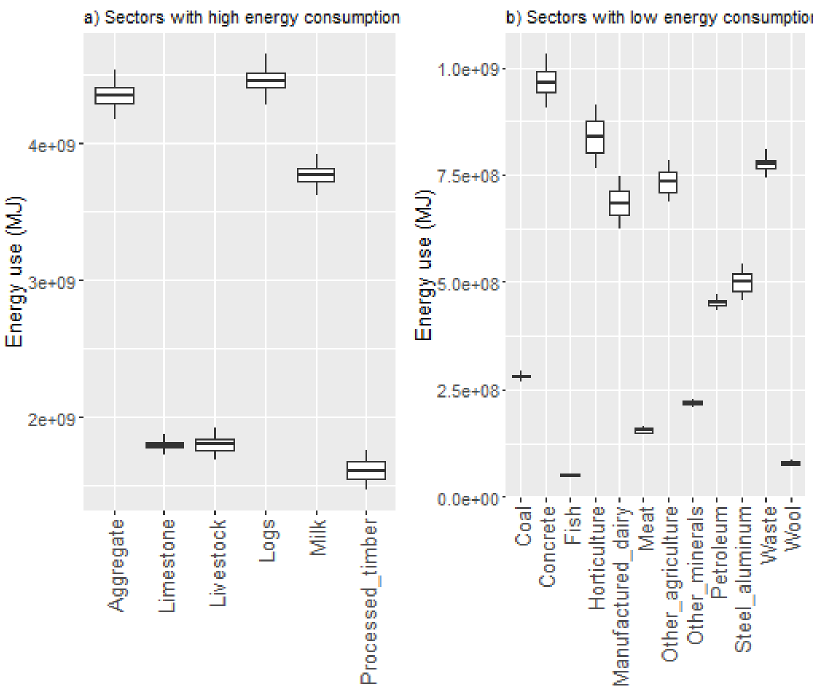


Figure 20 Distribution of energy use across different commodities (generated from simulation approach)

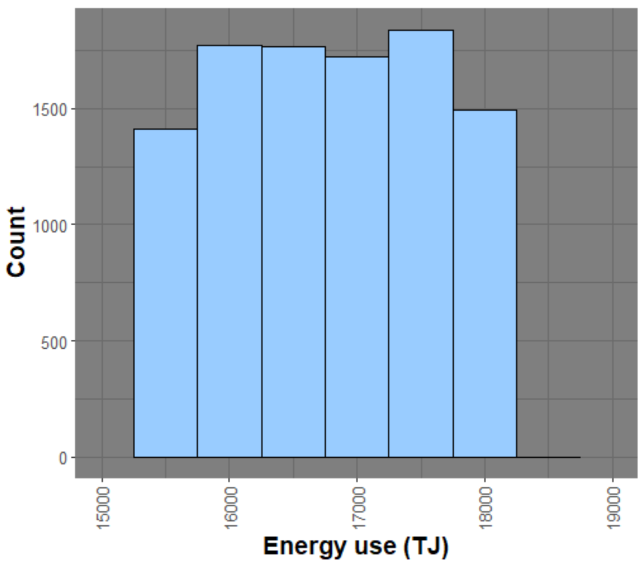


Figure 21 Distribution of energy use for 'General' road freight movements (generated from simulation approach

The evaluation of energy use and emissions from two perspectives provided a method of validation. Table 5 presents a sensitivity analysis to investigate the impact of slope and utilisation on energy consumption and carbon emissions; energy demand can vary between 13,917.6 TJ (50% utilization, -2% slope) to 92,627.3 TJ (75% utilization, 2% slope). The commodity-based approach estimates a range between 38,986 TJ (5th percentile) to 41,585 TJ (95th percentile), which is within the space defined by COPERT estimates associated to a 0% slope. Figure 22 shows the distribution of energy use for the whole sector; the average energy demand for road heavy freight transport is located within COPERT estimates for a fleet with 50% and 75% load utilisation, respectively. From the values reported in Table 5 and Figure 22, it can be deduced that the utilisation for the whole fleet ranges between 50% and 75%.

Table 5 Sensitivity analysis for impact of driving conditions on energy and emissions

Utilization	Slope	Energy (TJ)	CO_2 (tonnes)
50%	-2%	13,917.6	1,034,627.4
50%	0%	37,024.8	2,748,551.0
50%	2%	70,611.6	5,241,878.0
75%	-2%	15,234.7	1,130,954.8
75%	0%	45,114.8	3,349,115.5
75%	2%	92,627.3	6,876,216.3

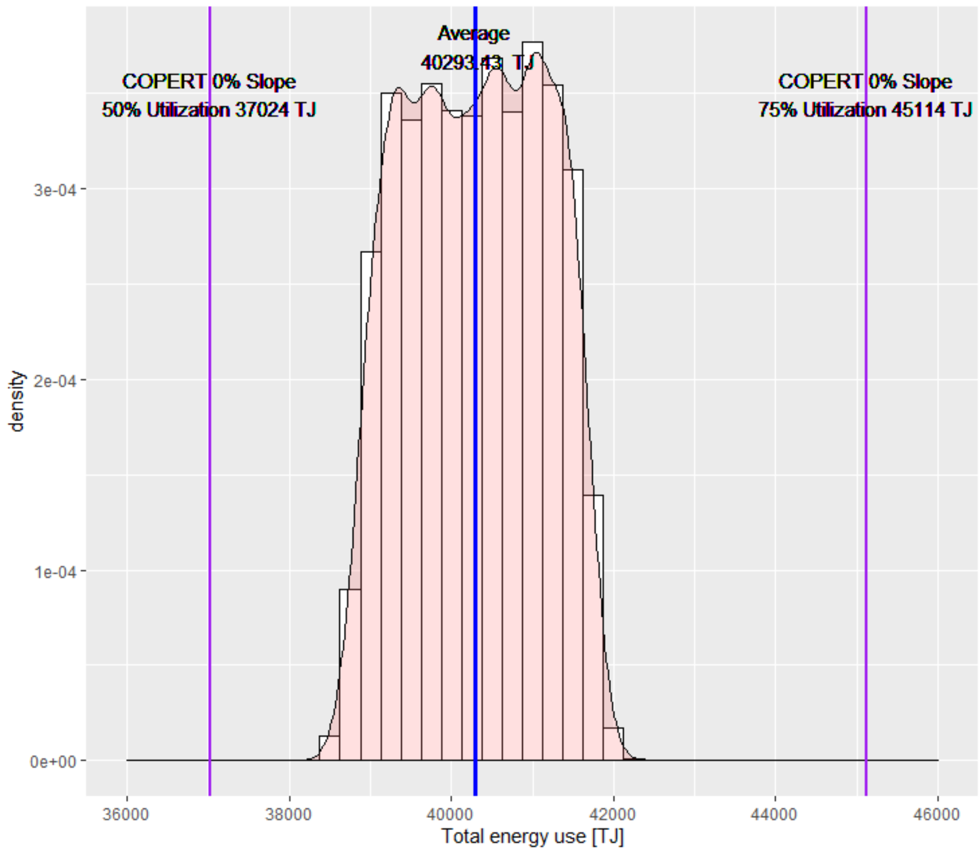


Figure 22 Commodity-based and vehicle-based energy demand analysis

The road network was divided into 109 segments; each segment has a specific slope value (for two orientations, north-south and south-north), and a specific weight (based on the length of the segment and on the traffic for each orientation). Figure 23 illustrates the logic behind the slope analysis where average slopes for both orientations are relatively near 0%. Figure 23 also shows the weights (activity in thousand tkm) associated with each road segment. COPERT reference boundaries in Figure 22 are based on driving conditions for flat roads (0% slope); this is consistent with an estimated weighted average of 1.6%, see Equation 3. The confirmation of the slope parameter is a key process as the driving conditions (slope and utilisation) can have drastic impacts on energy and emissions.

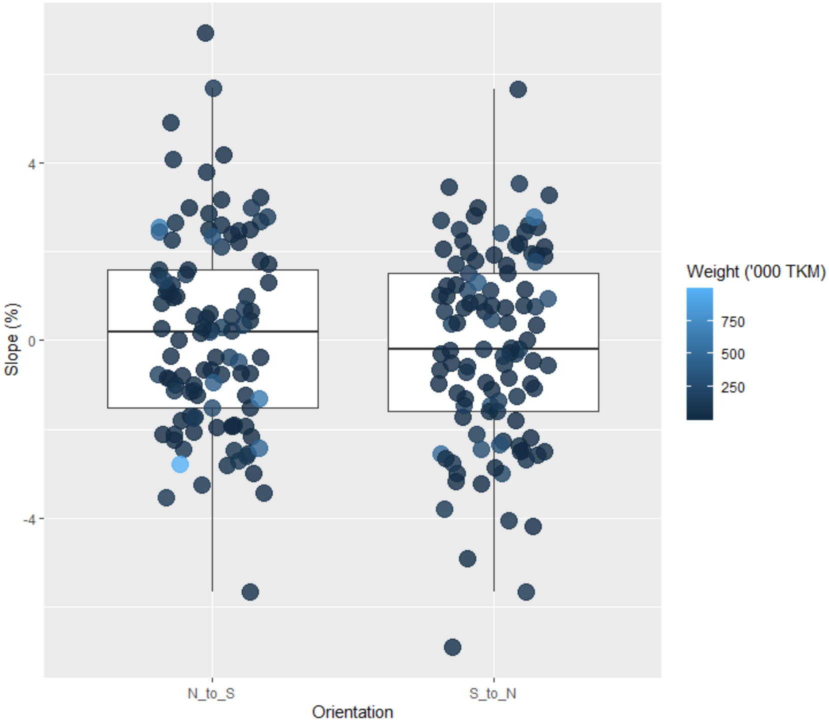
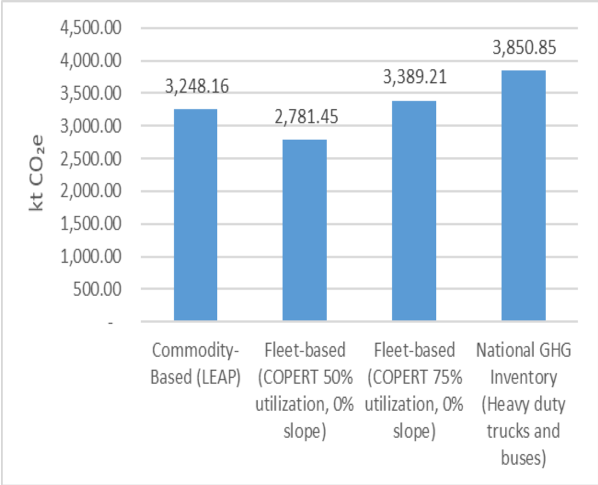
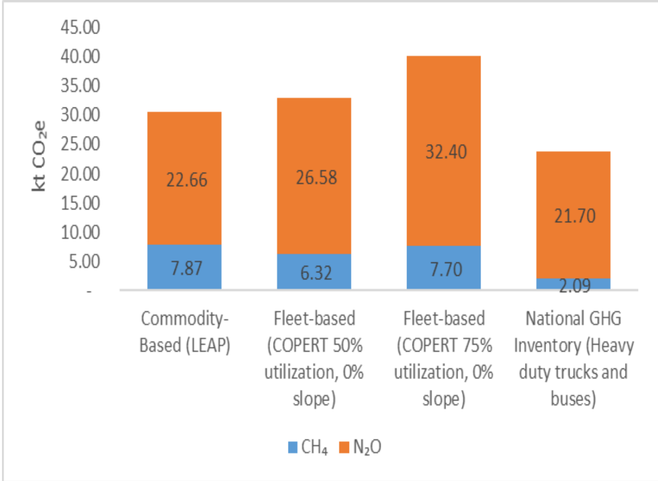


Figure 23 Slope analysis for road network segments

According to data supporting the most recent GHG inventory (Ministry for the Environment, 2022), heavy-duty trucks and buses produced 3,850.85 thousand tonnes of CO_2e in 2018. Unfortunately, the inventory does not have specific estimates for heavy-duty trucks, yet the value provides a reference upper threshold that is consistent with estimates from this report. Figure 24 contrasts direct emission estimates for both approaches adopted in this study, and for the national inventory; nitrous oxide and methane emissions are reported separately as the values are minimal (approximately 1.1% of direct emissions) when compared to carbon dioxide emissions. From Figure 24, it could also be inferred that the utilisation of the fleet lies within the 50% to 75% range; estimates are only based on direct emissions.



a)

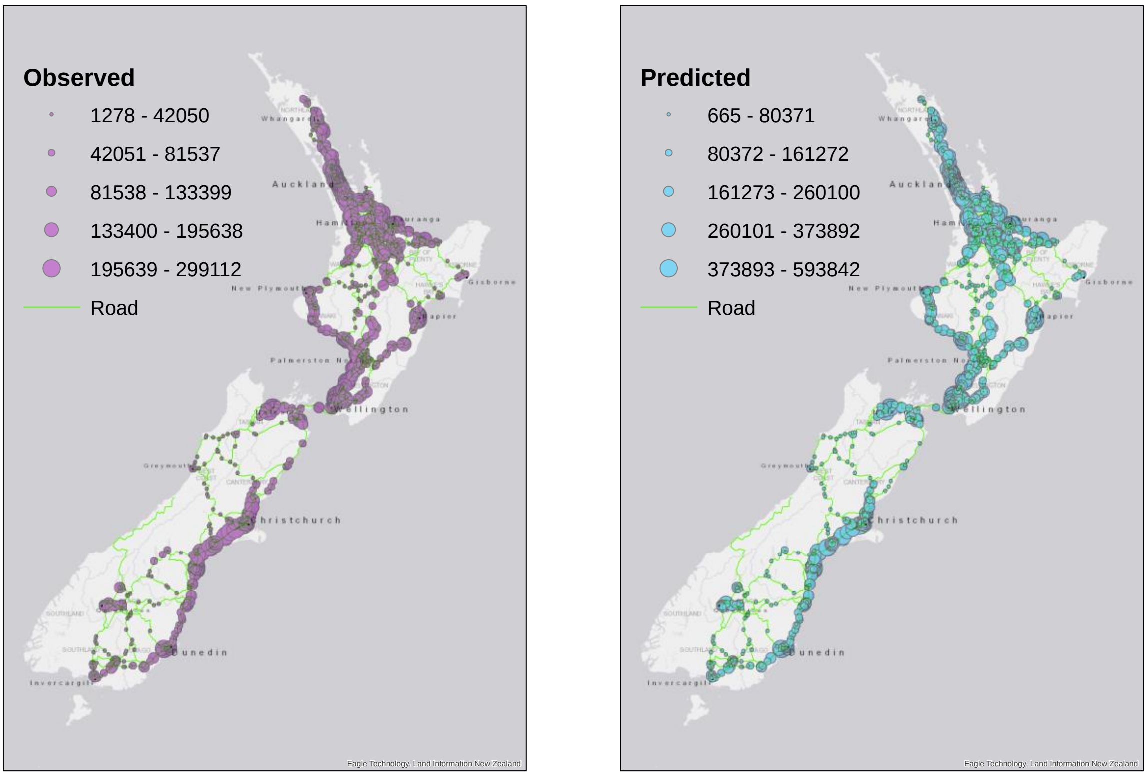


b)

Figure 24 Heavy freight road vehicles emissions according to different sources: a) Total emissions b) Emissions for other gases

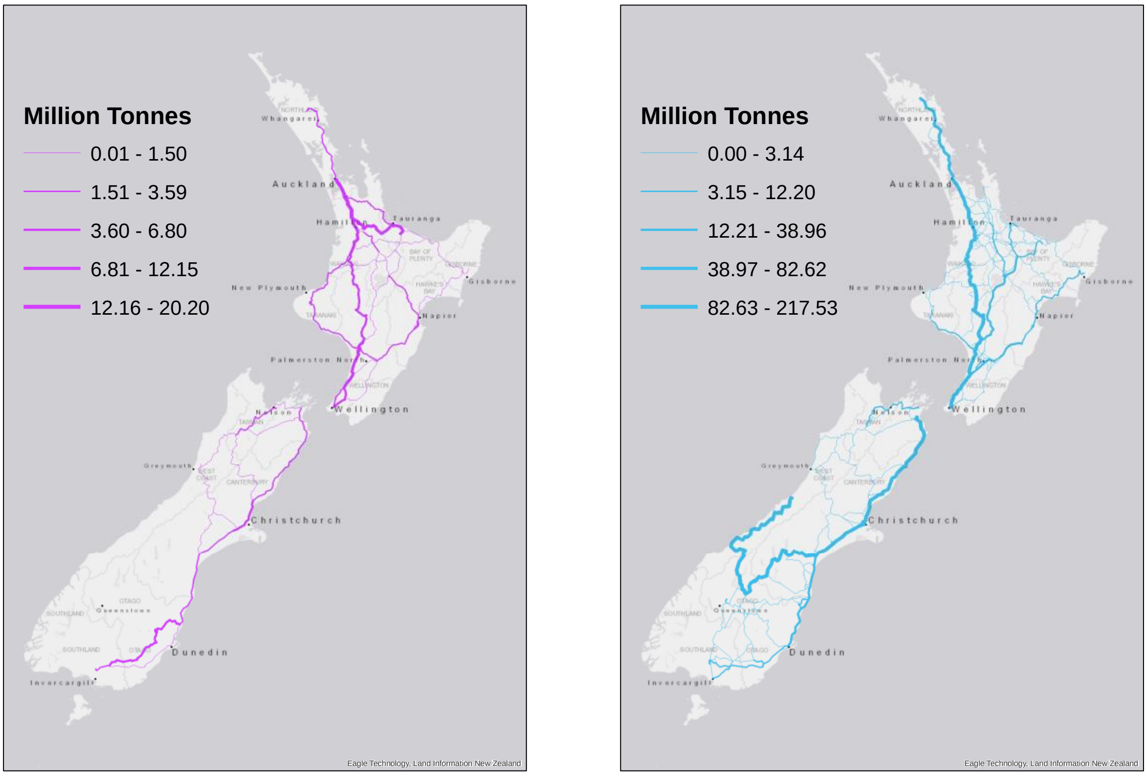
A freight transport model was calibrated with the goal of providing district-to-district resolution. Different model forms (i.e. with and without distance coefficients for every commodity type) and optimisation algorithms (i.e. bounded vs unbounded optimization) were tested, please refer to Table 2. Figure 25 shows that the model performs relatively well in the sense that heavy traffic patterns are congruous for both predicted and observed counts across the road network. However, model performance is limited when replicating underlying OD matrices. Figure 26 contrasts network analysis results for NFDS region-to-region matrices and estimated district-to-district matrices, that is, OD flows (i.e. based on regions or districts) for all commodities have been allocated to the road network. The most visible discrepancy is the East-West traffic in the South Island (Figure 26b), which may be owed to a cluster of heavy traffic observations with a relatively high number of counts (100,000+) around Queenstown (Figure 25a).

Unconstrained gravity-based models have a deficiency; if a particular production attribute ($A_{p,i,c}$) and a particular attraction attribute ($A_{p,j,c}$) are each doubled, then the number of trips between zones would quadruple when it would obviously be more likely that is should double also (Ortúzar S and Willumsen, 2011). To improve on this, constrained formulations have been proposed. Equation 12 corresponds to a production-constrained formulation, yet it can still overestimate trips as it only accounts for one set of balancing factors; a gain in accuracy could potentially be achieved with a doubly constrained formulation that accounts for two sets of balancing factors. Furthermore, gravity-based models exhibit the independence-from-irrelevant-alternatives axiom which can lead to counterintuitive behaviour. In other words, the model fails to recognise the effects of contiguity between an origin and all possible destinations (Wills, 1986). Potentially, the model form could be upgraded to a gravity-opportunity approach which requires additional algebraic transformations to generate ordered OD matrices and to account for intervening-opportunity effects (Tamin and Willumsen, 1989). Moreover, potential model upgrades could also follow more recent formulations that incorporate a complementary model of empty trips (Holguín-Veras and Patil, 2008).



a) b)

Figure 25 Observed (a) vs. (b) predicted heavy traffic counts



a) b)

Figure 26 Network analysis results for: a) reported region-to-region matrices b) estimated district-to-district matrices

Carbon dioxide estimates reported in Table 5 represent vehicle fuel combustion emissions. Figure 27 provides a more disaggregated view of road emissions by segment type, following the stock configuration assumptions described in Section 1.1. Estimates are based on different utilisation factors, yet, the fleet size and vehicle kilometres travelled (VKT) remain constant. In practice, higher utilisation rates can lead to a reduction in trip numbers, which is not reflected in this analysis. There is uncertainty on the utilisation of the heavy vehicle fleet; Copert estimates provide an insightful range that validates the estimates from the commodity-based analysis. The results suggest that the heavy fleet is underutilised and potentially this can be owed to vehicles not using their full loading capacity and/or to a high number of empty trips.

Furthermore, Copert software has additional functionality, allowing study of the impact of lubricant emissions and fine particulate matter (PM) pollutants associated with fuel combustion, tyre and brake wear, and road abrasion. Figure 28 shows that the highest source of fine particulate emissions is related to fuel combustion in engines. The quantity of total PM emissions for fuel combustion is the same for PM 2.5 and PM 10, as all particulates associated with this source have a diameter of 2.5 micrometres or less. PM 10 emissions from fuel combustion do vary for different utilisation rates; 80.4% of 1550.7 tonnes for 50% load utilisation, and 81.4% of 1785.4 tonnes for 75% load utilisation. Estimates also suggest that utilisation does not have an impact on PM emissions from other sources (tyre wear, brake wear, and road abrasion), that is, the calculation accounts for fleet numbers, vehicle segments, VKTs, but not loading parameters.

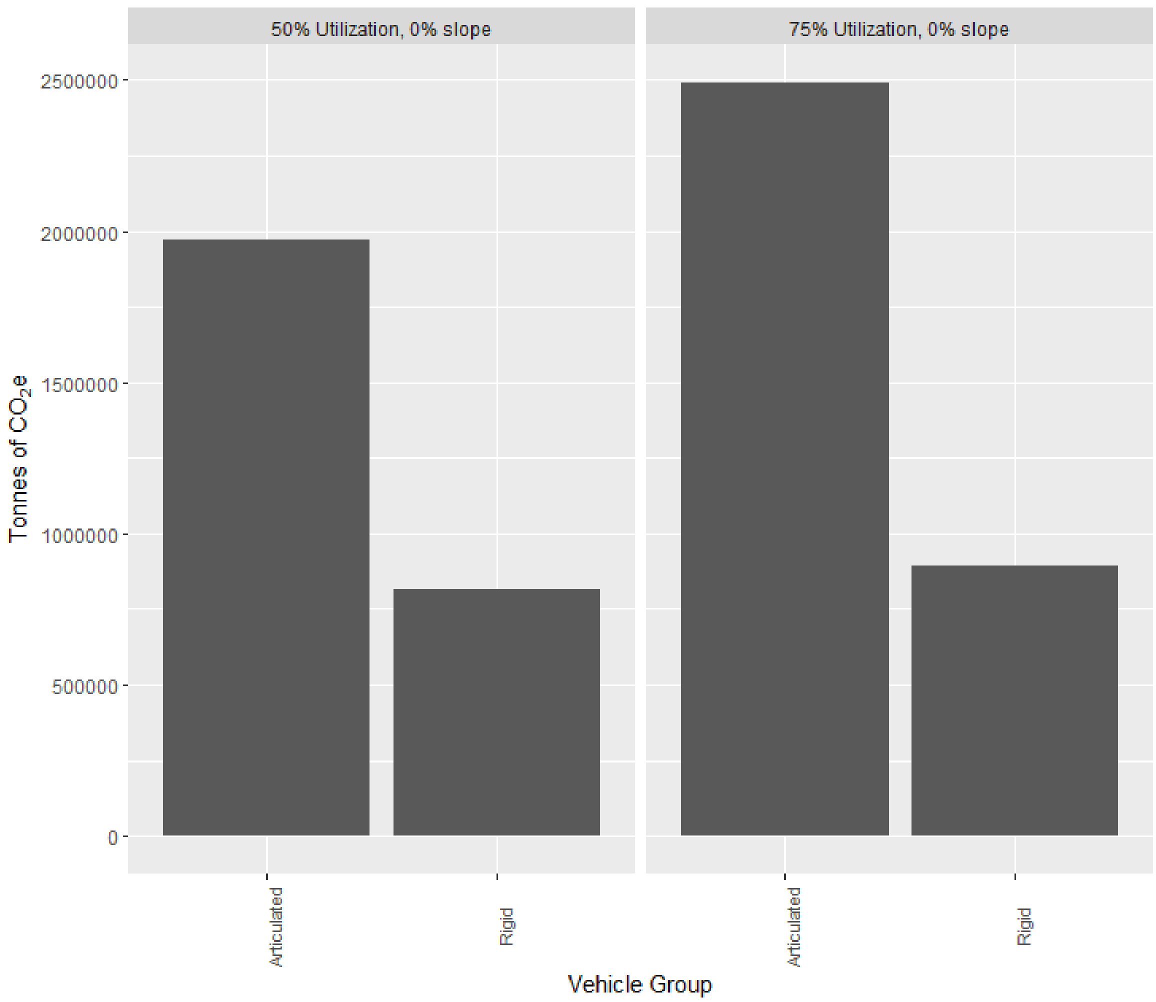


Figure 27 Road GHG emissions breakdown by vehicle category, by model setup

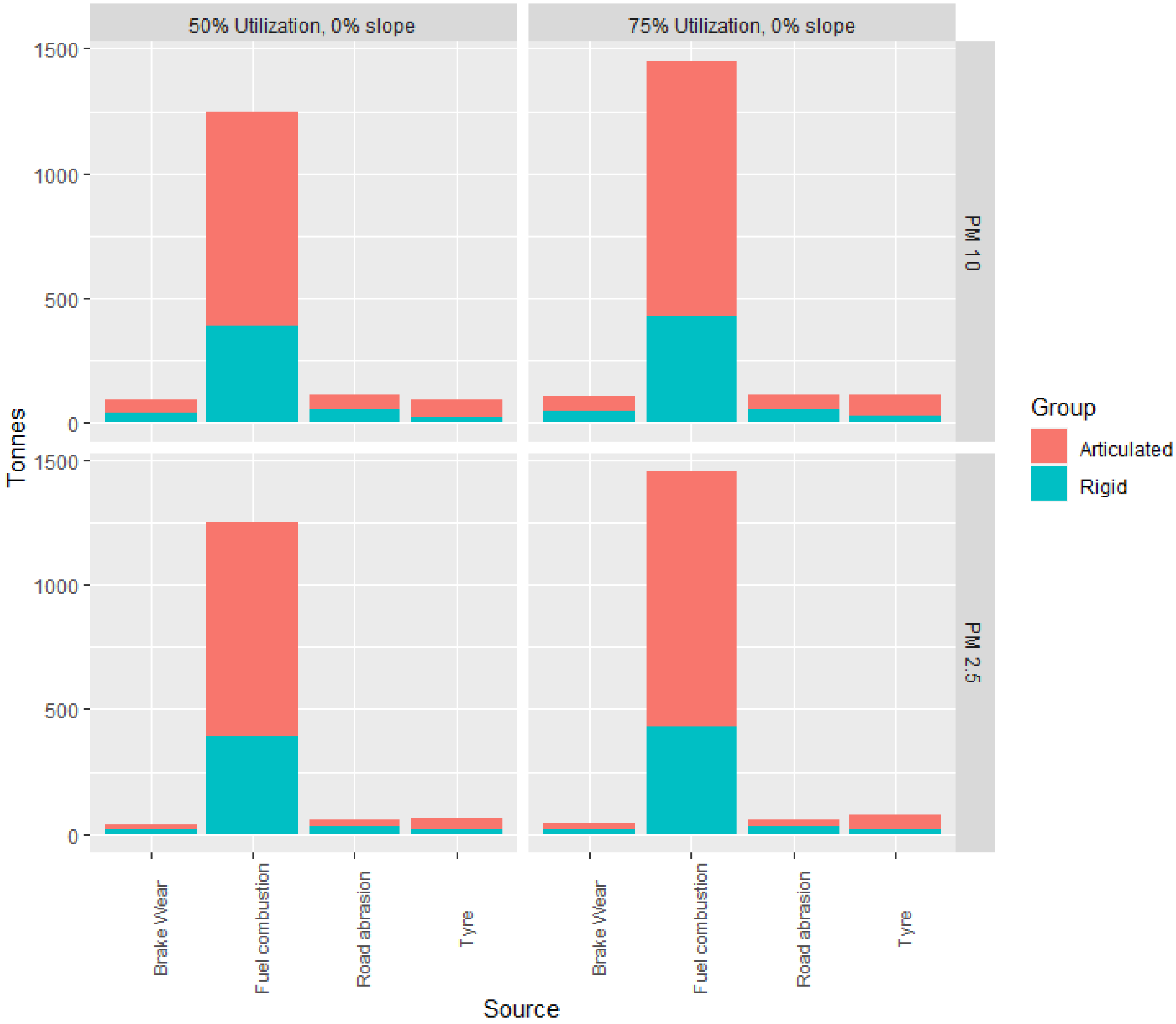


Figure 28 Analysis of Particulate Matter (PM)

4.1.1 Embedded Road Emissions

4.1.1.1 Truck Lifecycle Emissions

Truck lifecycle emissions were estimated from an Argonne Labs GREET model (Greenhouse gases Regulated Emissions and Energy use in Technology) (Cai et al., 2015). Three truck types are analysed, long-haul and short-haul trucks of the articulated variety which are also characterised as heavy-heavy duty (HHD) trucks and rigid trucks (medium-heavy duty (MHD)). The main assumptions are provided in Table 6. Instead of assigning a life-time in years, the life-time is assigned in terms of VKT (vehicle kilometre travelled). The simulation year was set at 2018, the target year for the study and the truck age varied from new, 5 years old and 10 years old. Embedded emissions were not significantly affected by truck age, however the Pump-To-Wheel (PTW) emissions improve for newer trucks.

Table 6 Life cycle assumptions made for the three types of heavy-duty trucks assessed

Truck	Lifetime VKT	Payload (t)	Urban Share %	Mileage (km/l)
Long-Haul	1,609,344	17.27	0.05	7.77
Short-Haul	1,609,344	17.27	0.9	7.25
Rigid	482,803	5.09	0.92	8.74

The truck fuel is assumed to be a low-sulphur diesel that is obtained from crude oil. Table 7 breaks down the embedded vehicle emissions into –

- Assembly, Disposal and Recycling (ADR),
- Components, which includes the powertrain system, motor, transmissions system/gearbox and chassis, axles, suspension, brakes, wheels, tyres etc.
- Fluids which includes engine oil, lubricants, transmission fluids, coolant and windshield fluid.
- Battery (lead acid)
- Trailers

The total embedded emissions are presented in column 8 of Table 7 and the percentage attributable to Wheel-To-Pump (WTP) and Pump-To-Wheel (PTW) for comparison. Note that for the articulated trucks, the embedded emissions are only 3.9%, while the rigid trucks have embedded emissions almost double the articulated trucks due to their lower carrying capacity. The total embedded emissions are illustrated in Figure 29.

Table 7 Breakdown of emissions for heavy duty truck types and proportion of emissions attributed to embedded, WTP and PTW

		GHG-100 (kg/tkm)						Emissions (%)		
Truck	Manufacture Date	ADR	Components	Fluids	Battery	Trailer	Total Embedded	WTP %	PTW %	Embedded %
Long-	2008	7.08E-05	0.0011	1.75E-04	7.04E-06	0.0016	0.0030	16.9	79.2	3.9
Haul	2013	7.08E-05	0.0011	1.75E-04	7.04E-06	0.0016	0.0030	16.9	79.2	3.9
	2018	7.08E-05	0.0011	1.75E-04	7.04E-06	0.0016	0.0030	16.9	79.1	3.9
Short-	2008	6.70E-05	0.0011	1.82E-04	1.06E-05	0.0016	0.0030	16.9	79.2	3.9
Haul	2013	6.70E-05	0.0011	1.82E-04	1.06E-05	0.0016	0.0030	16.9	79.2	3.9
	2018	6.70E-05	0.0011	1.82E-04	1.06E-05	0.0016	0.0030	18.1	78.0	3.9
Rigid	2008	0.0136	0.0018	1.21E-05	2.79E-04	NA	0.0157	16.3	76.1	7.6
	2013	0.0136	0.0018	1.21E-05	2.79E-04	NA	0.0157	16.3	76.5	7.2
	2018	0.0136	0.0018	1.21E-05	2.79E-04	NA	0.0157	16.4	76.8	6.7

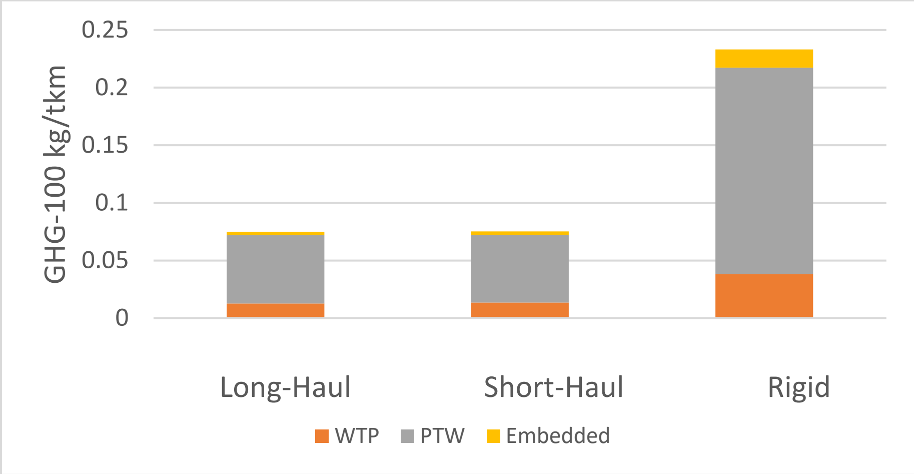


Figure 29 Truck emissions from GREET for long-haul, short-haul and rigid truck types for trucks manufactured in 2018

4.1.1.2 Road Infrastructure

The road infrastructure analysis considers emissions due to resealing of roads, not emissions associated with the initial roading infrastructure. Road maintenance is a significant source of emissions owing to the high component of fossil fuel based raw materials such as kerosene and bitumen. While heavy truck traffic is only a small fraction of traffic in terms of total vehicle numbers, the high weight per axle compared to light passenger vehicle traffic means they have a disproportionate impact on road damage. Pavement damage from heavy vehicles is reported to follow a generalised fourth power law in terms of axle loads (Research, 1962, Yiu, 2020) which was observed from American Association of State Highway Officials tests conducted in the 1950s. In order to make an estimate of the proportion of pavement damage attributable to heavy trucks the equation below was applied:

$$\left(\frac{W_1}{W_2}\right)^4 \qquad \textbf{Equation 16}$$

Where W_1 is the weight per axle of the truck compared to W_2 the weight per axle of a light passenger vehicle. A weighted average truck weight per axle (W_1) was estimated as 6333 kg from NZTA Motor Vehicle Register open data (Waka Kotahi NZ Transport Agency, 2022b). This report used data for GCM (Gross Combined Mass) and VKTs to calculate the estimate. To provide some sensitivity analysis an unloaded weight of 3500 kg was estimated using the GVM. An estimate of 1000 kg was assigned for W_2 taken from a German study where light passenger vehicles were weighed at the entry/exit point of parking buildings (Kemper et al., 2022).

Waka Kotahi heavy traffic counts were used for State Highway segments. Where necessary, traffic counts were interpolated to complete the dataset.

The damage attributable to heavy traffic was applied along each segment of New Zealand's state highways using the equation below:

$$\frac{traffic_1 W_1 a_1}{traffic_1 W_1 * a_1 + (1 - traffic_1) W_2 a_2} \qquad \textbf{Equation 17}$$

Where $traffic_1$ is the percentage of heavy traffic on each road segment and a_1 and a_2 are the number of axles for truck and light passenger vehicles respectively which were 4.8 and 2 respectively.

Resultant proportions of damage attributable to heavy traffic over the state highways when loaded and unloaded trucks were considered and shown as box and whisker plots in Figure 30. The box represents the upper and lower quartiles with the centre line the median, the mean is marked with an 'X'. The whiskers show the variability of the upper and lower quartile and the points outside of the whiskers are outliers. Given the very high proportion attributable to trucks, in this analysis, resealing emissions were fully allocated to road freight.

Road resealing creates significant CO_2 emissions as bitumen is made from fossil fuels such as crude oil. The carbon footprint for two road resealing products that includes the full life-cycle costs are reported in Table 8 (Downer New Zealand, 2013) for a 1km section of sealed road 7m wide. For this analysis the Hot Bitumen road resealing emissions are used as that was the status quo in 2018. At this time bitumen was refined at Refining NZ in Marsden, however the closure of refining operations at Marsden mean bitumen product will need to be imported from overseas so these numbers have potentially worsened.

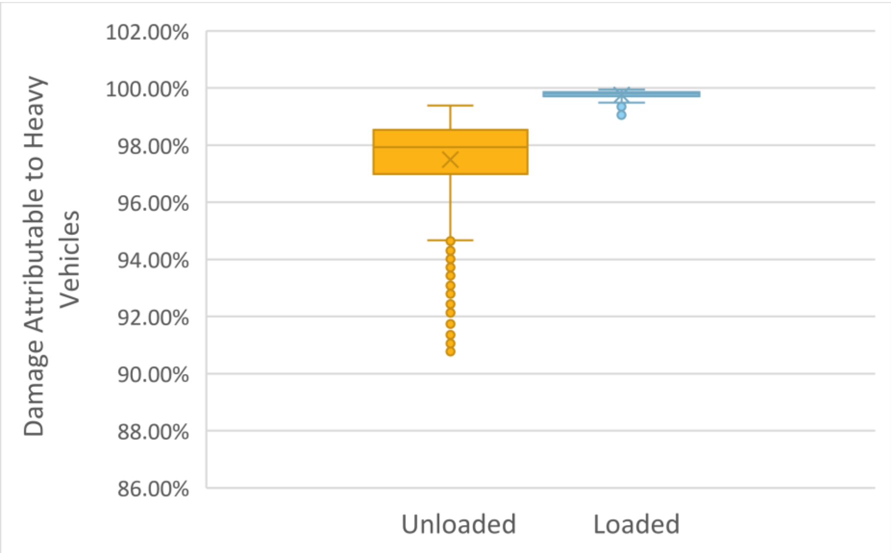


Figure 30 Box and whisker chart showing the spread of damage attributable to heavy vehicles on State Highways for loaded and unloaded conditions

Table 8 Carbon footprint of two road surface sealing products and capturing their full lifecycle costs (Downer New Zealand, 2013)

Sealing	Carbon footprint per linear km
Hot Bitumen ($kgCO_2e$)	1419.76
Bitumen Emulsion ($kgCO_2e$)	558.2

Based on the One Network Road Classification (ONRC) resealing is set at 7 years (Waka Kotahi NZ Transport Agency, 2022d) for the high truck volume roads such as arterial, high volume, national, national strategic, primary collector and regional. Secondary collector roads were set to a reseal frequency of 11 years and the remaining access, low volume and NA (undefined) set to 17.5 years. Using the product life-cycle costs for hot bitumen and bitumen emulsion, the resealing emissions are reported in Table 9 for the state highways and aggregated thin-surfaced flexible roads, the most common road type as shown in Figure 31. An annualised emission figure based on the expected road type resealing cycles is also presented in rows 4 and 5 in Table 9 for state highways and aggregated sealed highways respectively. Finally, an emissions per tkm are presented in the final row of Table 9 which is included in the embedded emissions figure for truck freight.

An annualised figure for highway resealing emissions is presented in column 3 of Table 9, based on the assumption that high traffic roads are typically resealed every 7 years (Waka Kotahi NZ Transport Agency, 2022d).

Future highway resealing emissions are due to reduce with Waka Kotahi NZ Transport agency announcing in June 2021 (Waka Kotahi NZ Transport Agency, 2021) that the bitumen emulsion product is to be phased in for highway sealing operations over the next few years. This move should reduce emissions by almost a factor of three assuming it has the same lifetime.

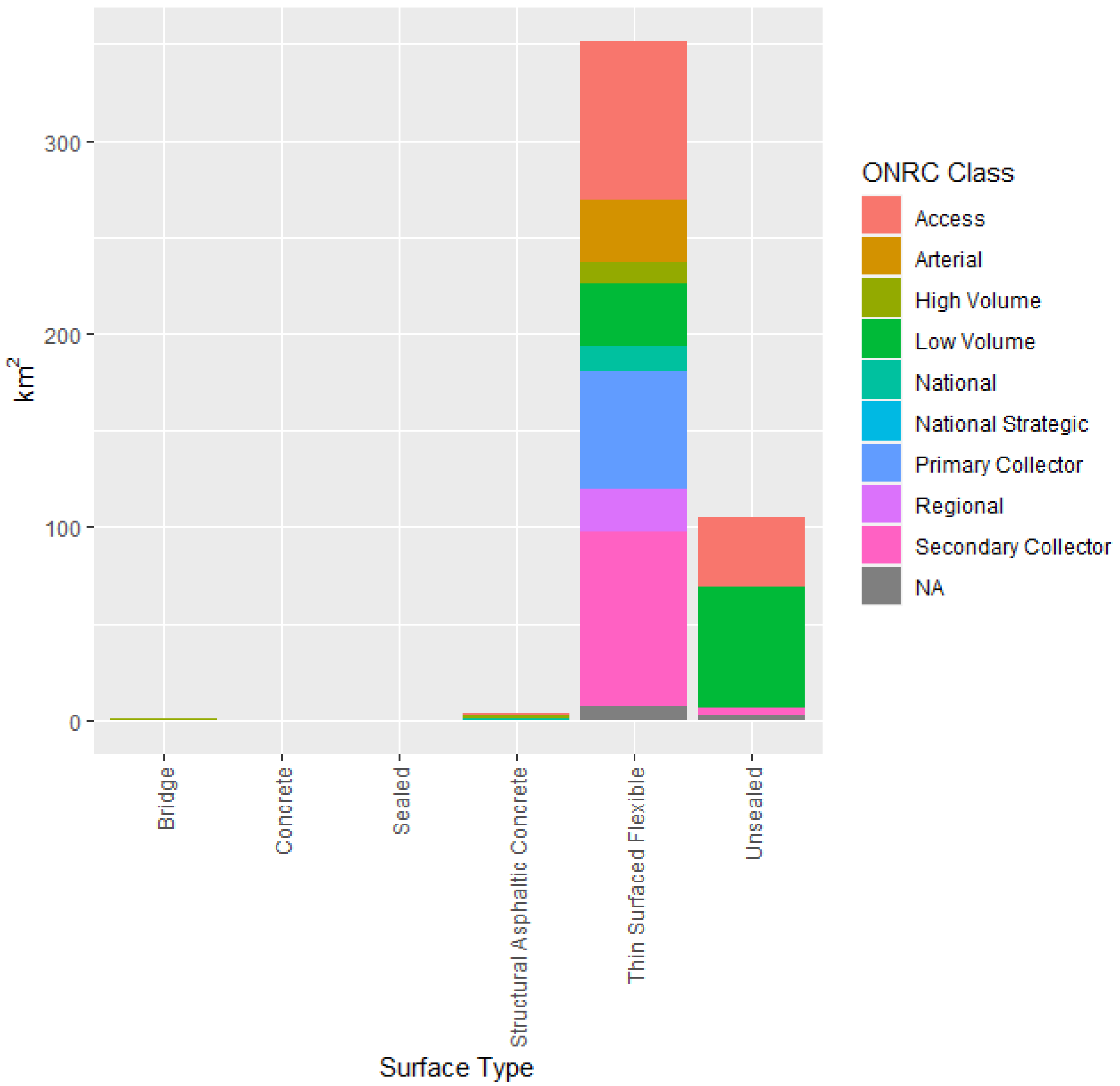


Figure 31 Road surface area as a factor of surface type and ONRC classification

Table 9 Carbon footprint for State Highways in NZ for two resealing products (Downer New Zealand, 2013)

	Road Area (km^2)	Hot Bitumen	Bitumen Emulsion
State Highway Reseal Emissions (full replenish) (tCO_2e)	92.5	17,837.4	7,013.1
Thin Surface Flexible Reseal Emissions (full replenish) (tCO_2e)	351.3	71,255.8	28,015.3
Annual State Highway Resealing Emissions (tCO_2e)	92.5	2,548.2	1,001.9
Annual Thin Surface Flexible Reseal Emissions (tCO_2e)	351.3	7,110.2	2,795.5
Thin Surface Flexible Reseal Emissions (gCO_2e/tk)	351.3	0.239	0.094

An estimate of the resealing emissions for the full thin surface flexible roads using hot bitumen resealing equates to 0.239 gCO_2e/VKT, using a reference of 29.8 billion tkm. Note this is a conservative estimate as it uses all the tkms, including those associated with unsealed roads. The resealing emissions per tkm are an order of magnitude smaller than the embedded articulated truck emissions in Section 4.1.1.1.

4.2 Rail Emissions

KiwiRail and Ernst & Young (EY) estimated that the freight activity in 2018 was approximately 4,031 million tkm (Ernst & Young, 2021). This study estimated a figure of 3,185 million tkm. Manifest data with specific origins and destinations, and fuel records were not available, hence assumptions had to be made in regard to representative origins and destinations, and travelled distances by rail; it is likely that the difference in activity is owed to these assumptions. Figure 32 shows the contrast between emissions estimates given different rail freight activities (this study vs. EY's value of rail report); the overall share of activity amongst commodity sectors is based on this project's estimates.

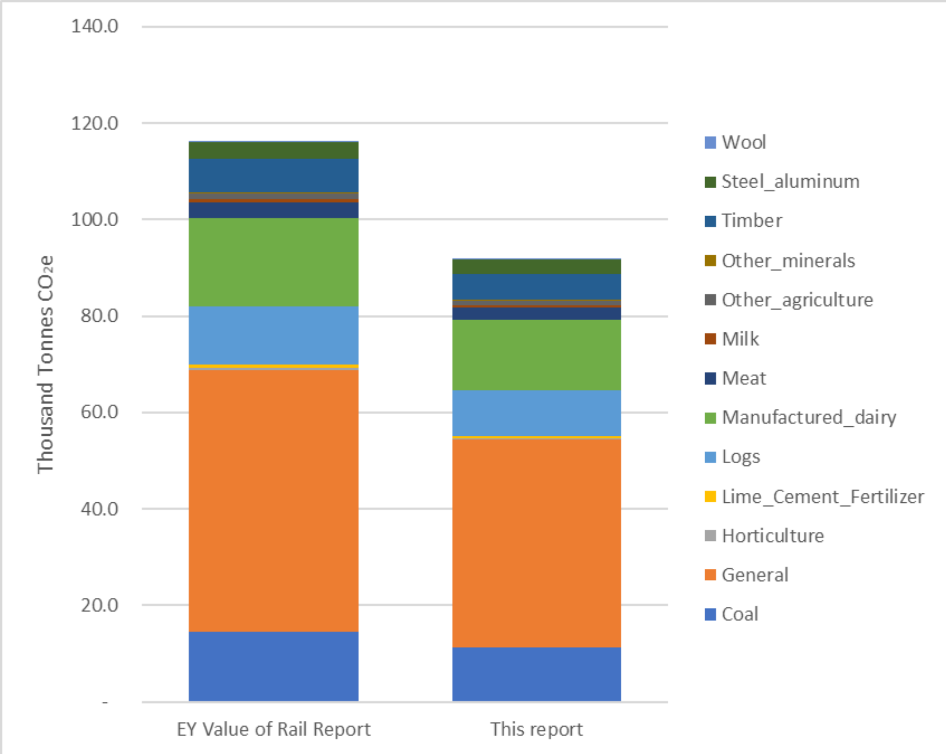


Figure 32 Direct emission estimates for rail freight transport broken down by sector

Figure 39 includes a 'General_electric' category to capture 'General' movements by electric rail. Figures related to this category cannot be visually identified as the activity is negligible (0.1% of total tkm by rail) in comparison to other segments. In terms of emissions, freight movements through electric rail accounted for only 15.5 tonnes of CO_2e, which corresponds to a carbon intensity factor of 3.2 g CO_2e per tonne-km. The calculation of the emission factor for electric rail assumed a constant electricity load; a more precise estimation will require power load profiles associated with electric train operation. The methodology that supports the calculation of emission factors for electricity use is a key component that could be further exploited in future studies that aim to investigate the potential of transport electrification options.

A remarkable aspect of the New Zealand railway system is that patterns do not necessarily follow international modal share trends where freight shipments over short and medium distances (below 300 km) remain on trucks (Tavasszy and van Meijeren, 2011). Figure 33 shows the volume of intra-regional rail flows across many regions. There are some examples where effective coordination between industry and the railway system operator has enhanced the movement of trains within relatively short segments. For example, Figure 33c shows that there is a high volume of intra-regional flows (300,000 – 400,000 tonnes) from dairy products within Waikato, Canterbury, and Otago regions, which is supported by the operation of strategic hubs like Crawford St Hub in Waikato (Murray King & Francis Small Consulting, 2011). Another relevant case is the movement of logs within Wellington which is supported by the operation of the Waingawa log hub (Sanderson and Robertson, 2020).

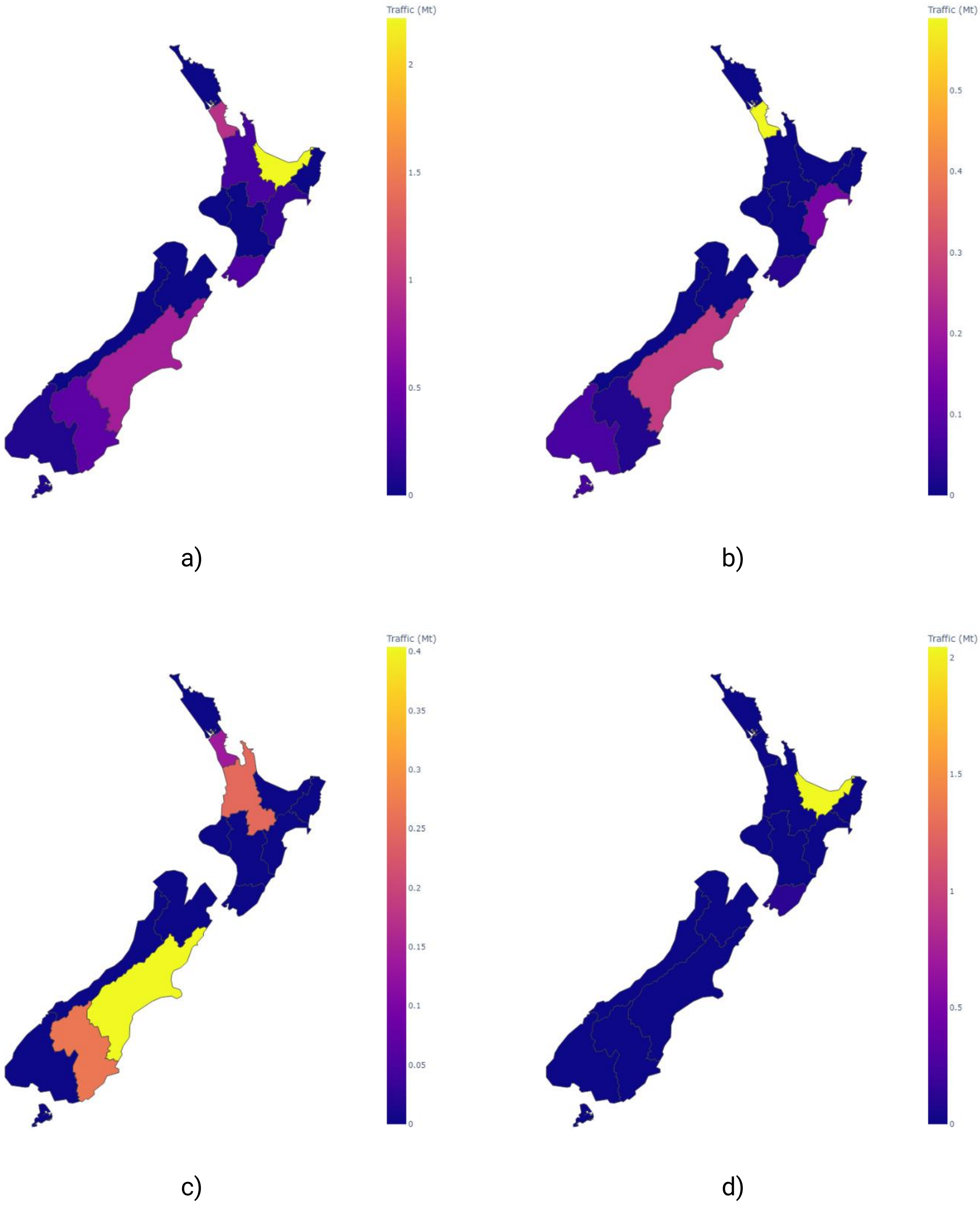


Figure 33 Intra-regional freight task by rail, by region. a) All sectors b) retail and manufacture c) dairy d) logs

Network analysis allowed for the allocation of activity over the railway network. Figure 34 shows the traffic associated with inter-regional flows from the sectors with the highest rail emissions (sectors identified in Figure 32). Traffic is concentrated across the regions of Auckland, Waikato, and Bay of Plenty. Hamilton appears as a key location as it provides a strategic connection point between Ports of Auckland (POA) and Ports of Tauranga (POT). There is a novel synergy between these ports, POA being specialised on container imports, but have managed to balance the flows through operations at inland terminals like MetroPort. Shipping lines contracted to use MetroPort Auckland call at the POT where import cargo destined for Auckland is offloaded at the Tauranga Container Terminal. Cargo is then railed to MetroPort Auckland before distribution to its final destination. The same process happens in reverse for Auckland-sourced export cargo (Port of Tauranga, 2022).

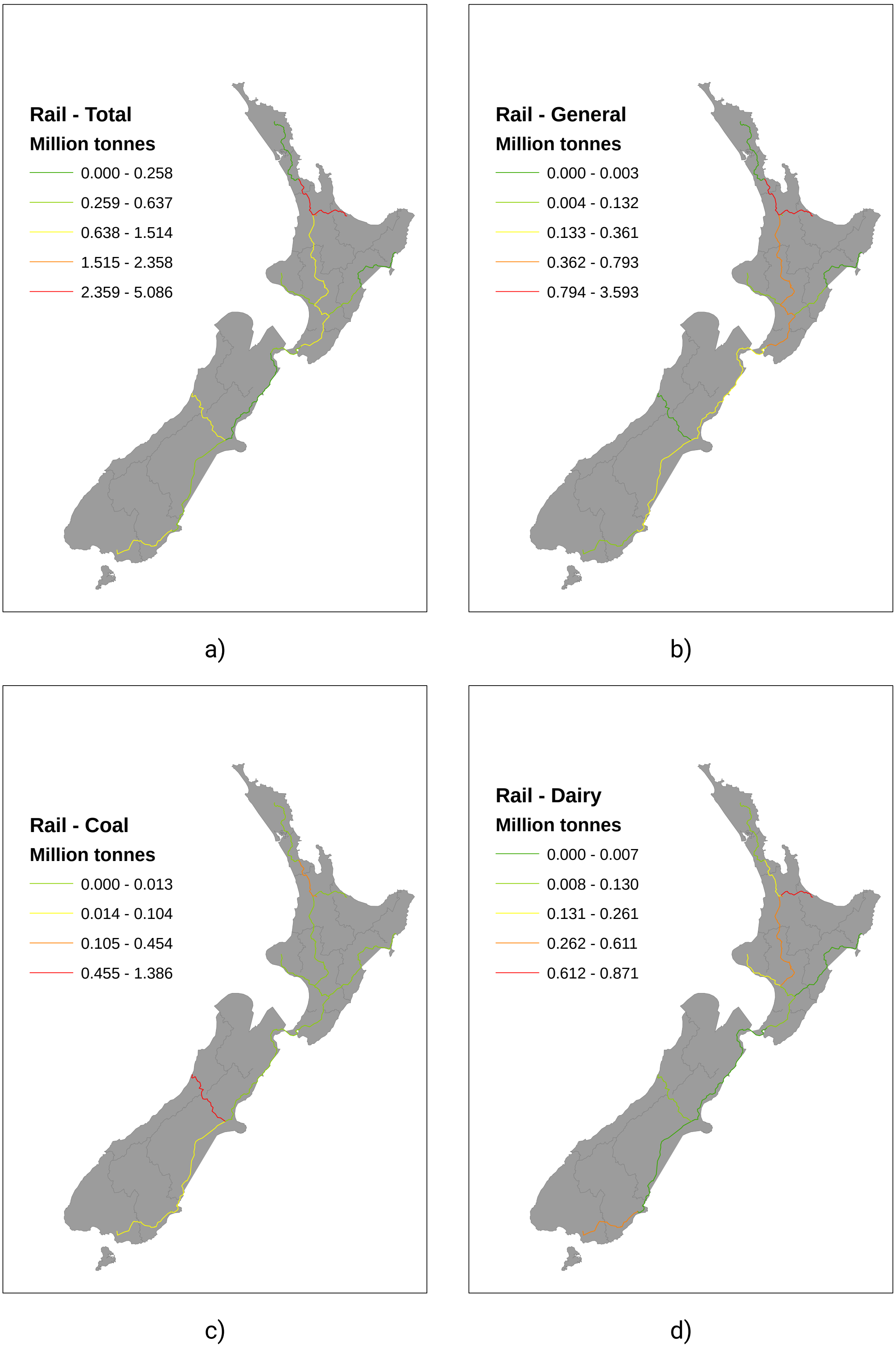


Figure 34 Inter-regional freight flows by rail. a) All sectors b) retail and manufacture c) coal d) dairy

4.2.1 Embedded Rail Emissions

This section looks at the emissions from rolling stock and rail track infrastructure. Additional infrastructure associated with the rail network such as tunnels, bridges, power signalling and telecom systems are not considered in this analysis.

4.2.1.1 Locomotives and Wagons

The stock of locomotives and wagons for the analysis year of 2018 is considered. As at the present day, some of this stock has been retired and new stock introduced, particularly new electric locomotives. The average weights for the 194 locomotives and 1920 wagons are reported in Table 10. Reported manufacturing and maintenance emissions for goods wagons from Åkerman (2011) are used to estimate embedded emissions. A lifetime of 35 years is assumed (Nahlik et al., 2016). Emissions for the rail fleet are reported in Table 11, normalised on the total rail tkms of 3.2 billion.

Table 10 Embedded emissions from manufacturing and maintenance of rolling stock

	Average Weight (t)	Manufacturing (tCO2e)	Maintenance (tCO2e)	Lifetime (years)
Locomotive	90.17	305	294	35
Goods wagon	17.77	60	58	35

Table 11 Rail fleet embedded emissions for rolling stock

Fleet	Emissions (tCO2e)	Annualised Emissions (tCO2e)	Emissions (gCO2e/tkm)
Locomotive	116,206	3,320.2	1.0425
Goods wagons	226,560	6,473.1	2.0325
Total Fleet			3.0750

4.2.1.2 Track Infrastructure

The track infrastructure is defined as two rails attached to sleepers. New Zealand's track infrastructure is reported as 3700km (KiwiRail, 2021b) with approximately 6 million sleepers of which 50% of those are steel reinforced concrete; the remaining being wood. The sleeper composition was taken from Stripple and Uppenberg (2010) and concrete and steel emission figures were used as reported by BRANZ's embodied carbon and energy values for building materials (BRANZ, 2022). Emissions for the track and sleepers are calculated and reported in Table 12. Lifetime figures are taken from (Kiani et al., 2008, Hua et al., 2019).

Table 12 Estimate of rail infrastructure emissions based on the rail track

	Quantity	Steel (kg/km/rail)	Concrete (kg/unit)	Total Emissions (tCO_2e)	Lifetime	Annualised Emissions (tCO_2e)	Emissions gCO_2e/tkm
Rail Track	3700 km	50	-	1,054,500	25	42,180	13.244
Concrete Sleepers	3 million	11.3	250	171,615	25	6,865	2.155

4.3 Coastal Shipping Emissions

The analysis of shipping emissions was based on:

- Energy and emissions associated with the transportation of different commodities.
- Energy and carbon intensity for different ship sizes and types.

Some results from road and rail network analysis were incorporated in this section, as they allowed quantifying the activity associated with ferry interisland movements (Section 3.1.1). Figure 35 shows emissions associated with coastal shipping, including two categories ("From_rail" and "From_road") related to freight movements by ferry; names for these categories indicate which land mode the freight used to arrive at the ferry terminal. A significant share (~67%) of activity from ferry movements (~393 million tkm) is related to shipments of general manufactured and retail commodities.

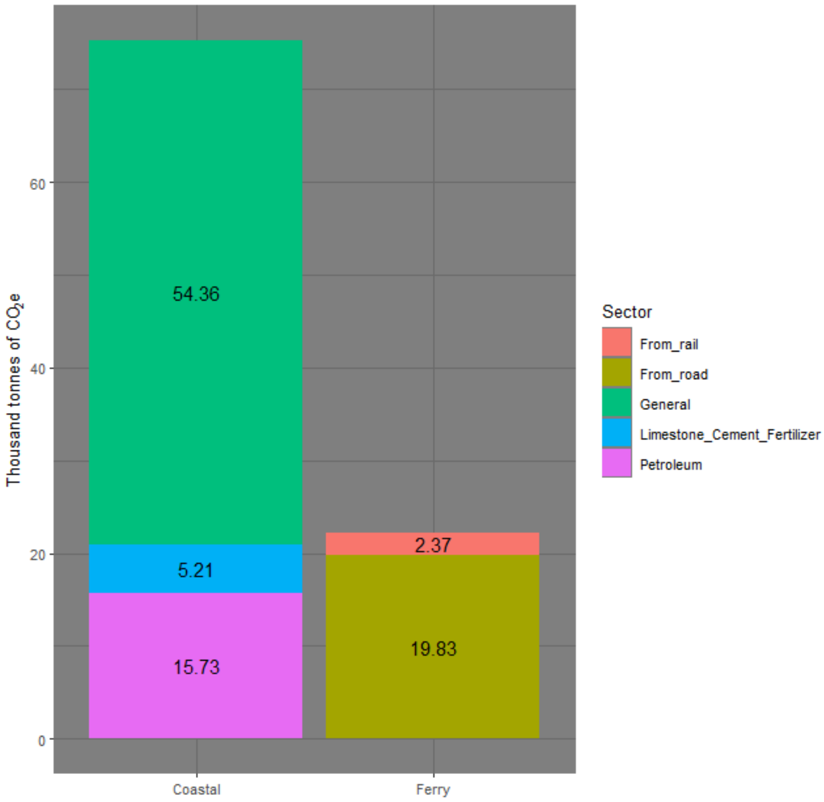


Figure 35 Total coastal shipping emissions by sector

Figure 36 shows freight movements for different commodity groups. The analysis is mostly based on interregional flows with some exceptions within Canterbury (where there are two ports, Lyttleton and Timaru). Ports provide clear origin and destination points. The arcs in Figure 36 illustrate flows between regions but do not represent actual shipping routes. Distances were based on the nautical almanac. Looking at movement of all commodities (Figure 36 a) it is evident that there is a strong connection between the main ports (i.e. Auckland, Tauranga, and Lyttelton). Marsden Point in the Northland region appears as a strategic location for the distribution of petroleum products (Figure 36 b), which is based on the operation of two tanker ships (MT Matuku and MT Kokako). The movement of manufactured and retail goods (Figure 36 c) is more dispersed than any other sector and the activity is related to operations from Pacifica Shipping. Finally, bulk shipping is represented by the movement of limestone, cement, and fertilizer (Figure 36 d).

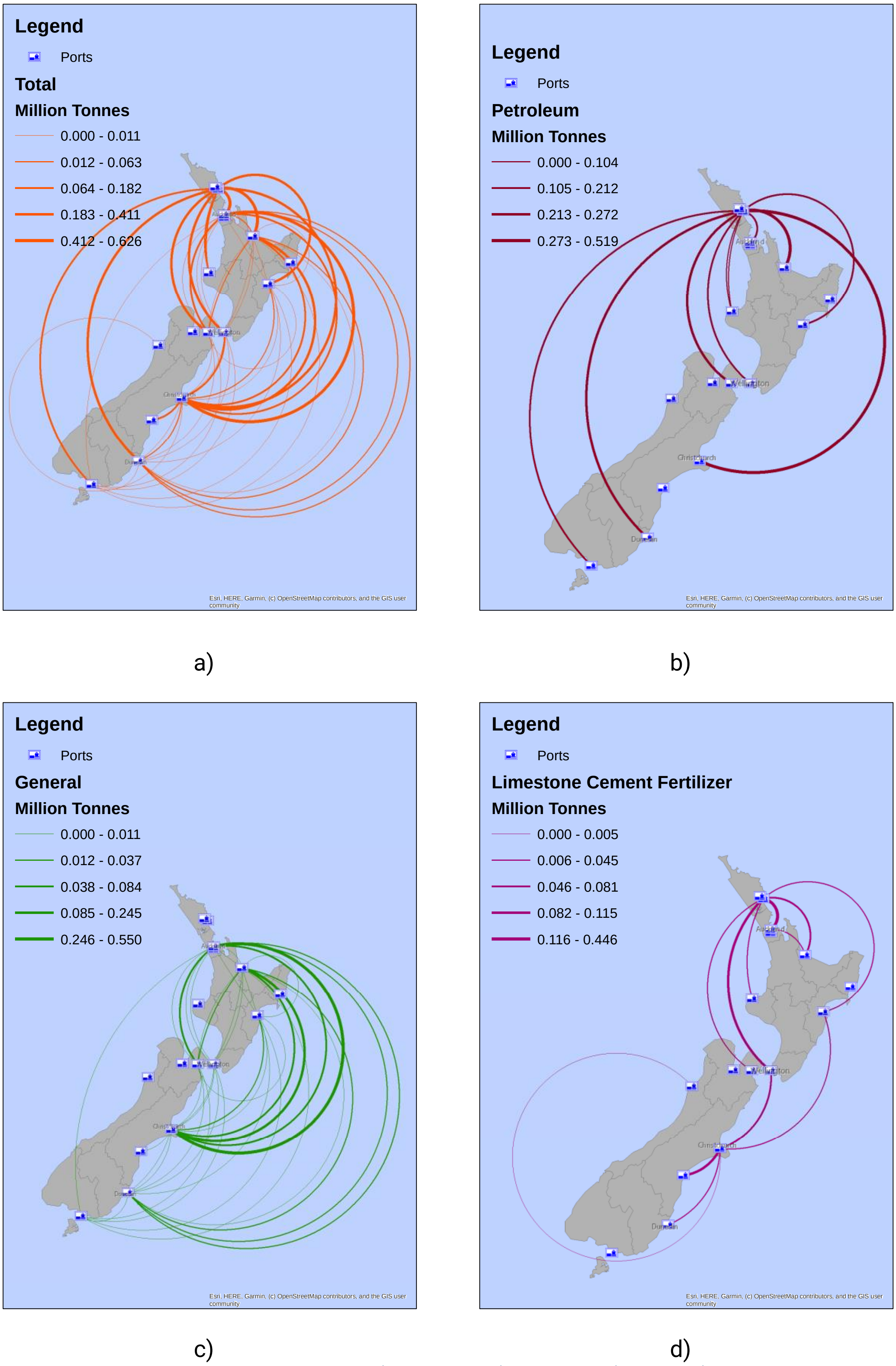


Figure 36 Regional flows by coastal shipping. a) All sectors b) Petroleum c) General (manufacture and retail) d) Limestone, Cement, and Fertilizer

It is shown in Figure 42 that coastal shipping has the smallest carbon intensity of all freight transport modes; to a large extent, this is due to the high share of activity related to bulk movements (i.e. low energy intensity). Further reductions in carbon intensity can be obtained by increasing the load utilisation of ships. Figure 37 shows a right-skewed distribution for the load utilisation (%) of 178 leg observations from the Moana Chief (assuming a carrying capacity of 1100 TEU). It can be observed that mid-range legs (green area in Figure 37, 491 to 1260 km) tend to have the largest utilisation factors. On average, the ship's utilisation is approximately 69.6% (766 TEU). An increase to 90% utilisation is estimated to result in a 45% reduction in container shipping emissions per tkm. Potentially, utilisation can increase by shifting inter-island road general cargo, which accounts for approximately 195,000 annual TEU's, most of which are associated with shipments between Auckland and Canterbury, (see Figure 38). Assuming a 90% utilisation of container shipping, a shift of inter-island "General" road freight movements to coastal shipping can potentially lead to a reduction of 161.7 kt CO_2, which represents approximately 5.1% of direct heavy freight carbon emissions.

The calculation of carbon intensity for coastal shipping is based on the assumption that ships run on residual fuel oil, also known as bunker fuel. The emission calculator model tracks energy use and emissions along different stages including resource extraction, refining, and transportation. Moreover, the model has the capability to track emissions associated with power generation, transmission and distribution. Potentially, the same model could be implemented to investigate the impacts and benefits of different scenarios related to future propulsion technologies (i.e. hydrogen, ammonia, methanol) that are suitable for shipping (McKinlay et al., 2021).

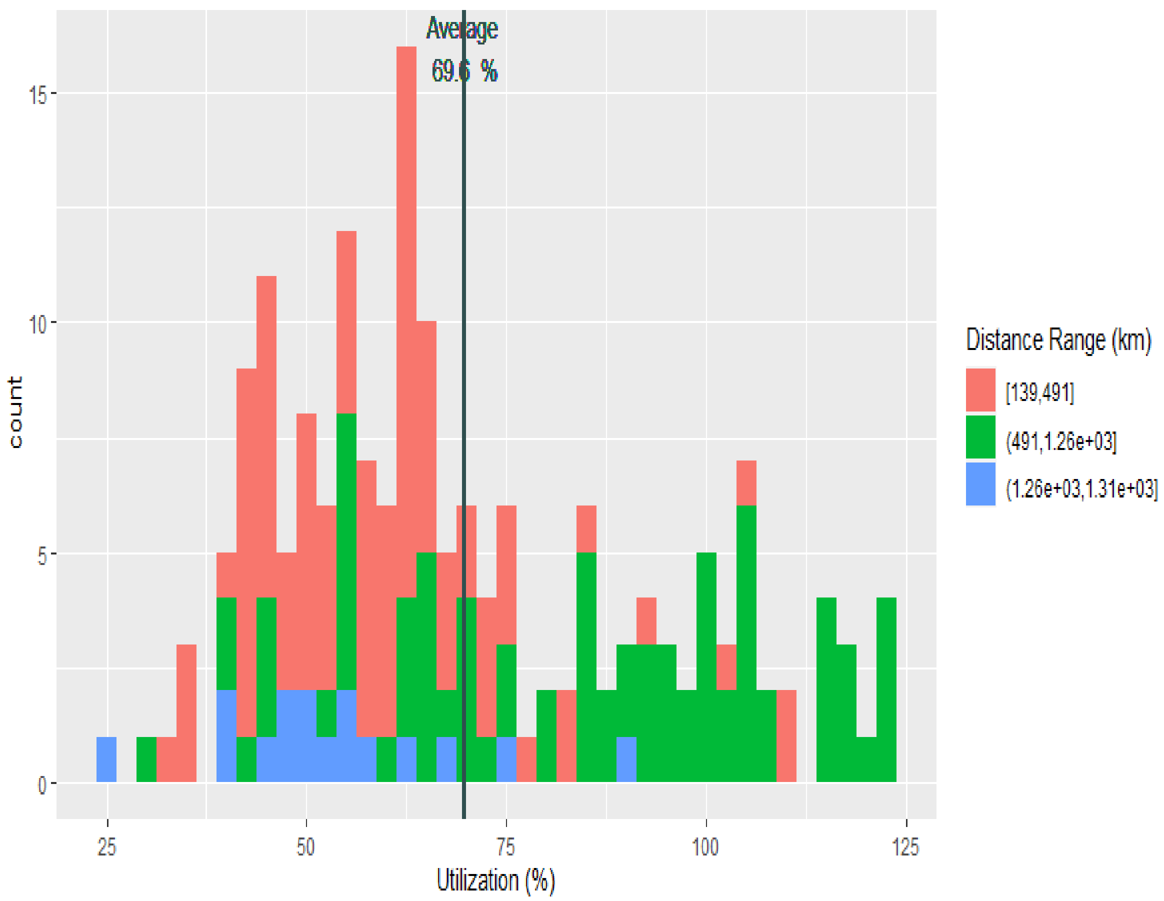


Figure 37 Moana Chief load utilisation analysis

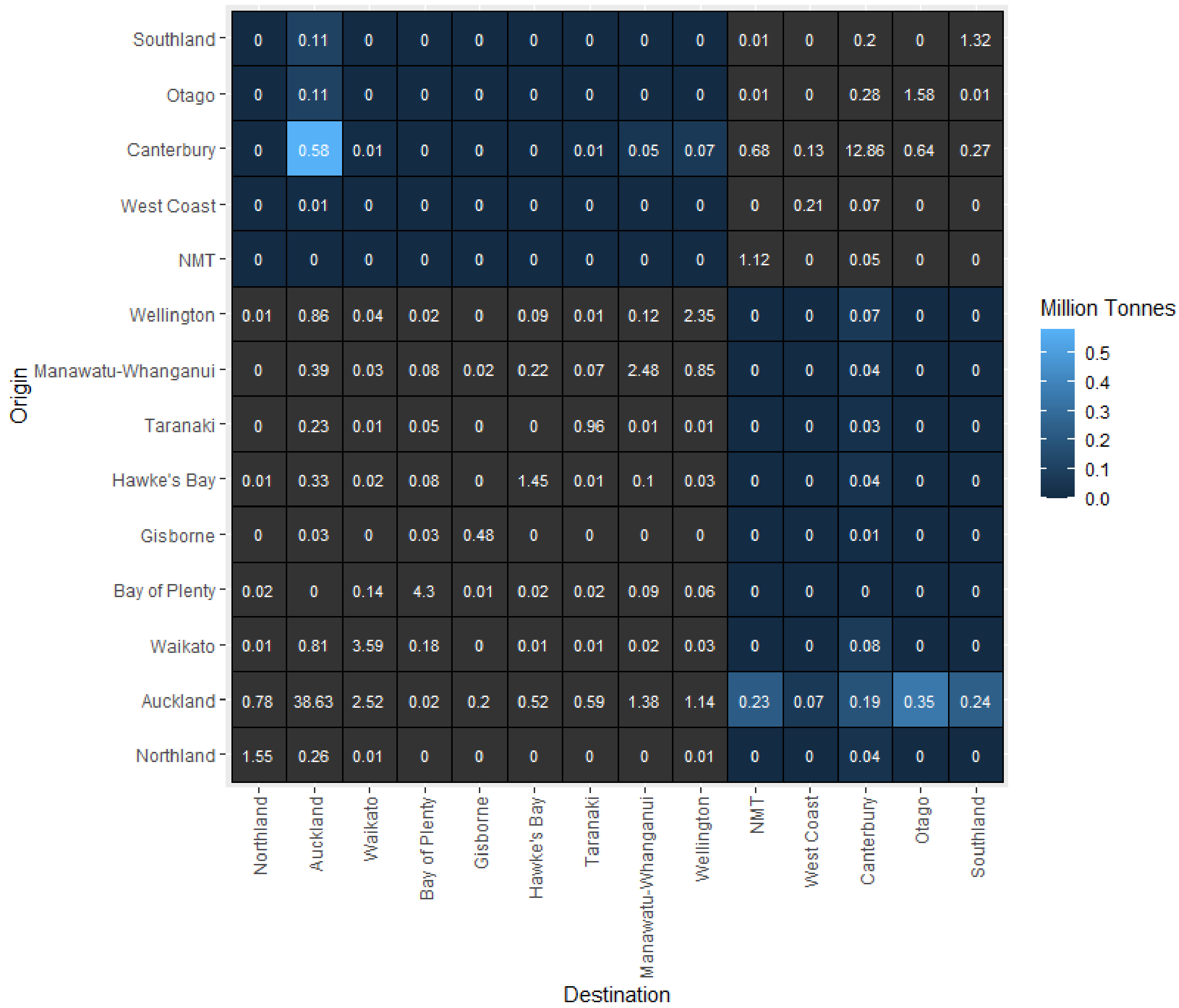


Figure 38 Inter-island road activity for manufactured and retail commodities

4.3.1 Embedded Shipping Emissions

Consistent with the road and rail analysis this section focuses on the embedded emissions of the vessels. The 'blue highway' has the advantage of no equivalent sub-surface to maintain compared to road and rail. As is recommended for road and rail, additional infrastructure and operations such as ports, docking vessels and loading and unloading of freight at the docks should be considered to provide a more complete emissions picture.

The emission analysis for the ship manufacture is based on a Total Life Cycle Emission Model from Hua et al. (2019) which reported life cycle emissions based on container ships, Very Large Crude Carriers, bunker barges. The steel manufacturing emissions are based on the containers ships lightweight tonnage (LWT), the weight of the ship without any fuel cargo, provisions or passengers/crew and are based on Taiwanese manufacturer data. The reference container ships analysed have an average LWT of 32,785t, a factor of four larger than New Zealand's coastal container ship, the Moana Chief.

Emissions from steel manufacturing (2,331.2 kgCO_2e/tonne) and shipbuilding (239.6 kgCO_2e/tonne) were estimated from this study and scaled by weight and are reported in Table 13. The remaining emissions based on ship operation were deemed to be inappropriate as the container ships in Hua's study operate internationally. This is quite a different mode of operation to the Moana Chief which is operated as a coastal shipping vessel with shorter distances between ports. A 25-year lifecycle is assumed for marine vessels (Hua et al., 2019) when calculating the emissions per year.

Using this analysis, the Container ship Moana Chief, the Interislander ferries Aratere, Kairahi, Kaitaki, and the fuel tankers Matuku and Kokako were assessed and reported in Table 13. Data was not available for the New Zealand's cement tankers and barges or the private Cook Strait ferries operated by Strait Shipping or the general bulk cargo ship Anatoki. Missing from this analysis is the breakdown of emissions due to maintenance and support vessels such as tug operation which appear to be lumped in the operation. Embedded emissions from ship manufacturing work out in the order of 850-1000 kgCO_2e. A more useful metric for comparison with other transport modes is the emissions per tonne-km, these are reported in Table 14. Figures are provided for the vessels with data available, the Moana Chief and the combined KiwiRail owned interisland ferries. The embedded emissions from vessel manufacture are insignificant when compared to their operating emissions.

Table 13 Associated emissions for ship manufacture for known freight carrying marine vessels operating in NZ with known LWT (Hua et al., 2019)

Vessel Name	Description	Light Weight Tonnage (LWT) (t)	Est. Emissions (Steel & Ship building) kgCO_2e	Emissions/year (kgCO_2e)
Moana Chief (1,700 TEU)	Container cargo vessel	8766	22,537	901
Aratere	Inter-island Ferry	8128	20,895	836
Kaiarahi	Inter-island Ferry	9851	25,324	1013
Kaitaki	Inter-island Ferry	9715	24,975	999
Matuku	Fuel Tankers	11916	30,634	1225
Kokako	Fuel Tankers	11252	28,927	1157

Table 14 Equivalent emissions per tonne-km for the marine vessels with sufficient data available

Vessel	Est. Emissions per year kgCO_2e	Distance Travelled (km)	Cargo (t)	Emissions (gCO2e/tkm)
Moana Chief	901	140,978	1,164,264	0.0009
Combined KiwiRail Inter-island Ferries	2,848			0.0072[4]

[4] This is an overestimate as it doesn't account for passenger loading which includes passenger vehicles.

4.4 Accidents Attributable to Freight Transport Modes

A comparison of the number of injuries associated with road freight, rail and marine are presented in Table 15. While the data obtained is not perfectly aligned with freight in all modes, it does provide a useful guide to rates of fatal and serious injuries associated with different freight modes. NZTA's Crash Analysis system (CAS) (Waka Kotahi NZ Transport Agency, 2022a) was used to identify injuries that involved trucks. Rail injury data was taken from NZTA's Rail Safety statistics (Waka Kotahi NZ Transport Agency, 2022c). Note that rail accidents potentially include accidents from passenger services too. Coastal accident data was taken from the "Healthy and Safe People", from Transport Indicators (Te Manatū Waka Ministry of Transport, 2022). Marine accidents were split into commercial and recreational categories, however injuries from non-freight industries such as commercial fishing for example are not distinguished and could overstate injuries for this freight mode. The injury rate per tkm of freight for each mode is of the same order, with fatal injuries slightly higher for rail and serious injuries highest by proportional for coastal shipping.

Table 15 Reported fatal and serious injuries from accidents attributable to the different freight sections for the 2018 study year and normalised by tkms

	Number of Injuries 2018			Injuries per tkm		
	Road	Rail	Coastal	Road	Rail	Coastal
Fatal Injury	73	17	5	2.4E-9	5.3E-9	1.1E-9
Serious Injury	196	15	36.5[5]	6.6E-9	4.7E-9	8.2E-9

4.5 Summary of Results

Figure 39 presents a summary of transport activity and GHG emissions (Well-to-Wheels) across modes and commodity sectors. Activity and emissions associated with coastal shipping include interisland ferry movements. The 'General' category encompasses the movements of retail and manufactured goods and is the sector associated with the highest activity and emissions shares, 41.0% and 42.7%, respectively. In terms of activity, energy use, and emissions, road transport appears as the dominant mode in heavy freight transportation. As for coastal shipping and rail, Figure 39 shows that the shares are not consistent across activity and emissions. Coastal shipping has a modal activity (tkm) share of 11.5%, and a 2.83% share of total emissions. The contrast in activity and emissions between rail and shipping is owed to differences in activities, utilisation, and carbon intensities; the latter depends on the fuel economy of ships and trains, and on the properties of the corresponding fuels involved. The commodity-based analysis accounts for emissions of carbon dioxide, methane, and nitrous oxide, as shown in Figure 40. Emissions from these gases were converted to the equivalent amount of carbon dioxide (CO_2e) assuming a Global Warming Potential (GWP) period of 100 years.

[5] Coastal injuries were averaged from 2017/2018 and 2018/2019 data.

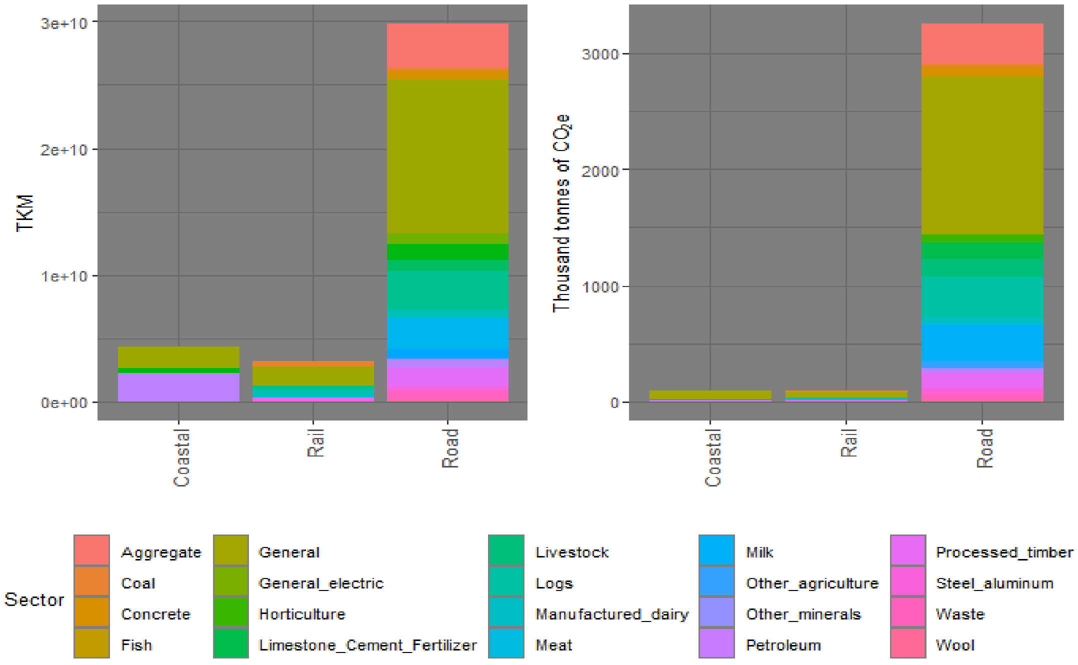


Figure 39 Activity and Total Emissions from Heavy Freight Transport in New Zealand

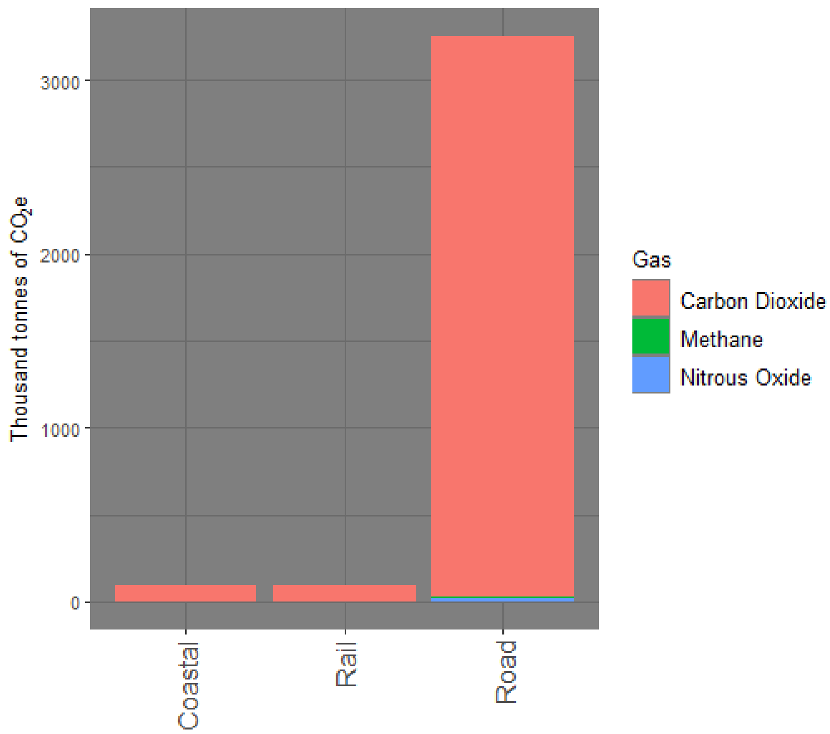


Figure 40 Total heavy freight transport GHG emissions by mode and type of gas

Moreover, the analysis has a Well-to-Wheel emissions scope, as the calculations also account for the energy losses associated with fuel extraction and refining, and electricity generation and transmission. The emissions associated with fuel transportation are included as direct emissions, as the activity is related to the movement of petroleum products one of the freight commodities of interest. Figure 41 shows direct and indirect emissions associated with each mode. Overall, indirect emissions account for approximately 8.7% of the total heavy freight transport emissions (3.44 Mt CO_2e).

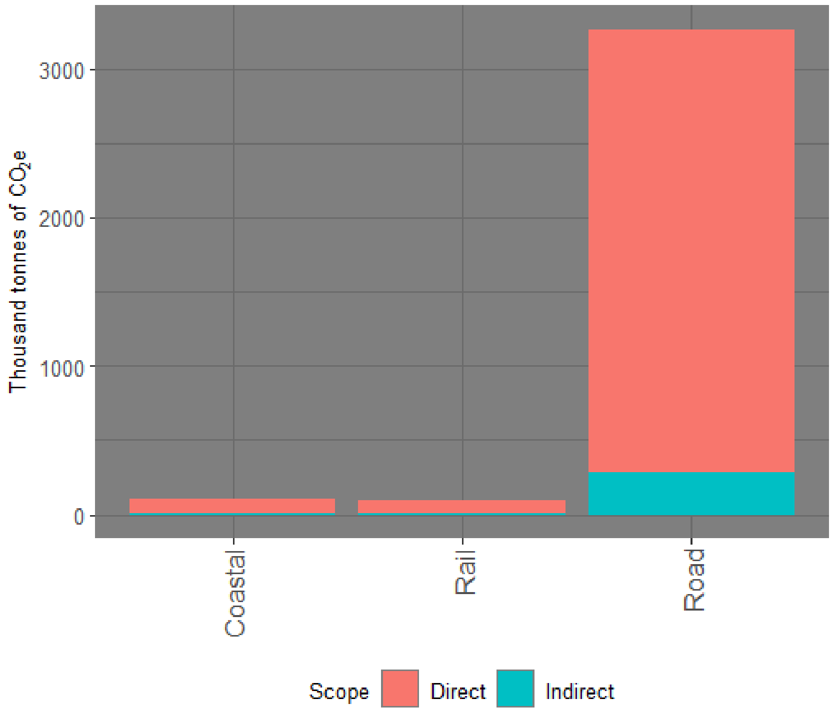


Figure 41 Total heavy freight transport GHG emissions by scope

Marsden Point oil refinery closed its operations early in 2022, meaning that the pattern of petroleum flows is evolving as processed fuels will likely be delivered directly to ports across the country from international sources. The new pattern of petroleum movements will likely lead to an apparent reduction in both direct and indirect emissions, as activity will be considered as international shipping and oil refining will be shifted overseas.

Figure 42 shows the estimated carbon intensities across freight transport modes in New Zealand (Well-to-Wheels scope). On average, for every tonne-kilometre of freight activity, heavy truck transport produces 4.95 times more emissions than coastal shipping. However, the figures show a general overview, carbon intensities will also vary depending on the type of commodity transported, on the size of the vehicles and on their utilisation. For instance, Coastal Shipping's carbon intensity accounts for the movement of oil products and bulk products; it is likely that the average carbon intensity for the mode will be different for more recent years as oil is no longer transported by ship from Marsden Point, that is, carbon intensity for the shipping will be more influenced by bulk and container movements.

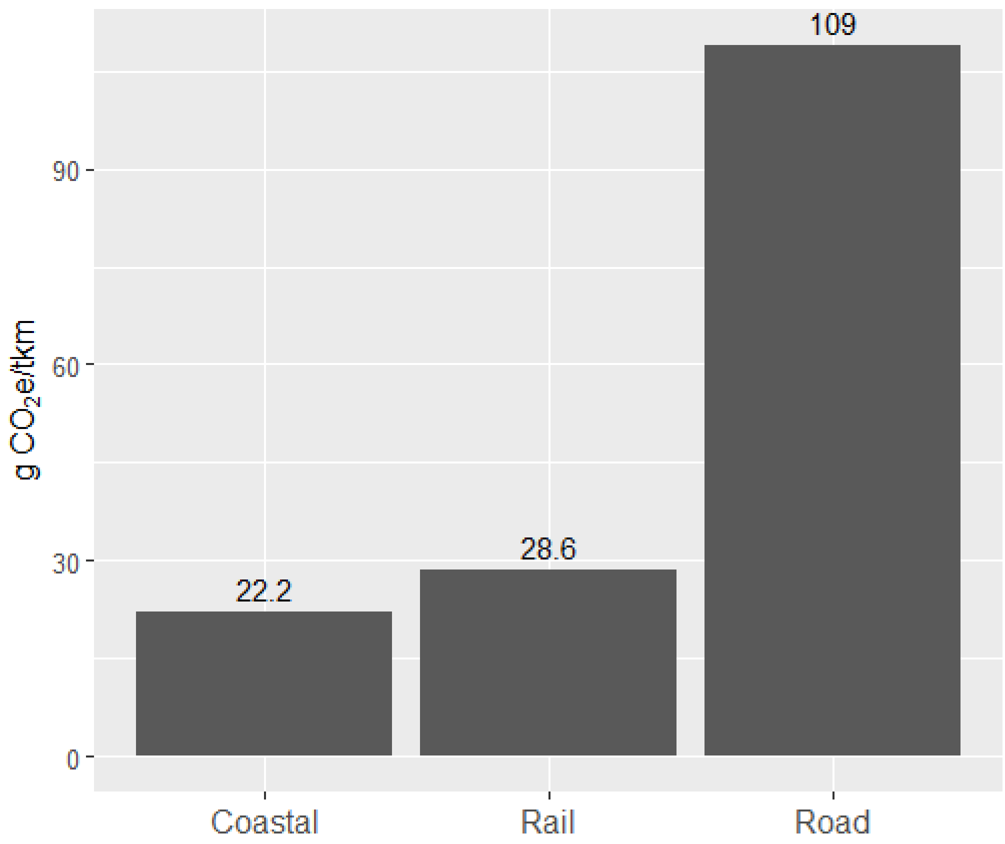


Figure 42 Carbon intensity for freight transport modes in New Zealand (Well-to-Wheel scope)

Ideally a full Life Cycle Assessment (LCA) would be undertaken to account for each of the transport sector's freight emissions to provide a comprehensive representative picture of the freight costs, not only in terms of GHG emissions but considering the full environmental impact of freight services. The scope of this study however is limited to direct GHG emissions and only considers a subset of the main emission sources due to limitations of project scope and budget.

Section 4 presented a brief analysis of the scope 3 emissions which are embedded in freight carriers i.e. trucks, rolling stock and marine vessels, as well as the main associated infrastructure such as roads and rail tracks. This is in addition to the direct combustion-based emissions that dominate emissions for the transport sector (Scope 1) and the scope 3 emissions related to fuel production and transport considered earlier in this report. Emission factors are taken from government reports, research reports and articles, and where possible, adapted for the NZ situation. Emissions related to administration aspects of businesses are specific to individual companies and are considered peripheral to the freight core business so are omitted from this analysis.

Table 16 summarises the direct combustion based emissions, along with the indirect WTP emissions and embedded vehicular and infrastructure based emissions described in Sections 4.1.1, 4.2.1, and 4.3.1. Direct emissions from the combustion of fossil fuels in the PTW are the major component which justifies the focus on direct emissions. The main takeaway shows that road emissions are between 2.4 and 2.7 times higher than rail, and between 5 and 5.6 times larger than coastal shipping emissions.

Table 16 Summary of carbon intensity figures for different emission calculation scope. Units in gCO_2e/tkm.

Scope	Road	Rail	Coastal	Observations
Well to Pump	9.46	2.28	1.85	For fuels produced in NZ
Pump to Wheel	99.54	26.31	20.32	Includes movements of petroleum products
Embedded Vehicular	3.00 - 15.70	3.08	0.01	Range owed to differences between rigid and articulated trucks
Infrastructure	0.24	15.40	-	Refers to roads, railway tracks and sleepers; does not include port infrastructure
Total	112.24 - 124.94	47.06	22.18	

5 Conclusions

This report summarised the findings from the project titled: “Evaluating the opportunity in the heavy domestic freight sector to contribute to the decarbonisation of the transport task in New Zealand - Phase 1: Baseline of direct tank-to-wheel transport Greenhouse Gas emissions for key commodities”. The assessment was based on data obtained from multiple sources including Ministry of Transport, Land Information New Zealand, Land Resource Information Systems Portal, Waka Kotahi NZ Transport Agency, Statistics NZ, Pacifica Shipping, and KiwiRail. Datasets were gathered, formatted, and integrated in order to facilitate the estimation of energy demand and emissions across transport modes, vehicle types, and commodity sectors.

Road transport emissions were evaluated from two perspectives, by commodity sector and vehicle fleet. Safety inspection records from NZTA supported the quantification of transport activity for different vehicle categories. Different sources of uncertainty have been identified, including assumptions behind the estimation of VKTs, driving regimes (i.e. urban vs. highway), load/utilisation, and road slope. A commodity-based approach was also implemented to study the relationship between commodity types, load utilisation, empty trips, and energy intensity. The contrast between both approaches provided a level of validation and visualisation of the variability of energy use, specifically, denoting how consolidation strategies and improvements in capacity utilisation can potentially lead to reductions in GHG emissions. Transport activity for the commodity based-approach was obtained through implementation of network analysis, which assumes that vehicles follow the routes with the shortest travel times. Further analysis could be complemented by the use of GPS fleet tracking records that include time series of routes, fuel consumption, and vehicle utilisation.

A freight transport model was calibrated with the aim to improve the resolution of freight distribution from a region-to-region approach to a district-to-district basis. The model was validated by successfully reproducing the results of a study that reported a calibration exercise using a sample dataset (Högberg, 1976, Gallardo et al., 2022b). The model was then executed, using freight production, attraction, and cost attributes using New Zealand as a case study. The pattern of traffic predicted upon by the model is consistent with that of the observed traffic counts, yet, the model is not accurate enough to predict freight flows and corresponding emissions. Therefore, energy and emission estimates reported in this study were obtained through the implementation of network analysis using region-to-region OD matrices. It is recommended for future work to focus on testing alternative model formulations to account for the effects of contiguity between neighbouring zones/areas/districts. Moreover, model upgrades could adopt a complementary mathematical expression for empty trips. The development of an accurate freight distribution model would be important to support the study of scenarios that reflect future changes in the freight task and the associated impacts.

The adoption of network analysis was also relevant when assessing inter-regional railway flows. Region-to-region OD matrices were allocated across the railway network, where origins and destinations corresponded to representative train terminals within every region. The assessment of intra-regional flows and routed distances were evaluated more specifically on a case-by-case basis, following the description of logistics operations reported in sector-specific reports. For future studies, our analysis can be complemented with railway manifest records for freight shipments across New Zealand, with information about origins, destinations, distances, along with fuel consumption. The complementary use of manifest records, along with fuel records, can permit investigation of the impact of capacity utilisation. For instance, Pacifica Shipping provided detailed information on every transport leg associated with the operation of a vessel, allowing evaluation of ship performance, and hence, identifying immediate feasible actions (i.e. consolidation strategies, modal shift, higher utilisation) that could potentially lead to a 5% reduction in emissions from the freight sector. Further analysis is required to verify the feasibility of a substantial shift to alternative modes (i.e. rail or shipping), as it is likely that upgrades in capacity, resources, and infrastructure will be required. Moreover, further analysis is required to understand potential trade-offs between emissions and transport costs (i.e. travel time).

An energy model was developed to support the analysis of emissions across different modes and commodity sectors. The structure of the model is based on the ASIF approach, that is, every sector was characterised in terms of activity (tkm), energy intensity, and fuel used. The model is an important component that could be further exploited to quantify the emissions associated to alternative scenarios that contemplate changes in modal share, vehicle types, and fuels. Specifically, the model that supports this study has the potential to investigate scenarios that account for the interaction between power generation mix and transport electrification options.

6 Future Work

Phase 1 of the project focused on Step 2 of the InTIME© methodology[6] (Krumdieck, 2019). The work delivered a quantitative understanding of New Zealand's freight task, along with the corresponding energy demand and emissions. The models and outputs from Phase I provide the foundations for work to be delivered in Phase 2, which is situated within the innovation region of InTIME (Steps 3 and 4, see Figure 43).

Phase 2 will focus on exploring different development directions (Step 3 of InTIME) and the 100-year concept generation (Step 4 of InTIME). The scope will be aligned with the strategic priorities addressed in the latest Government Policy Statement on Land Transport (New Zealand Government, 2021):

- providing transportation options,
- developing a low carbon transport system while improving safety and accessibility, and,
- improving freight connections for economic development.

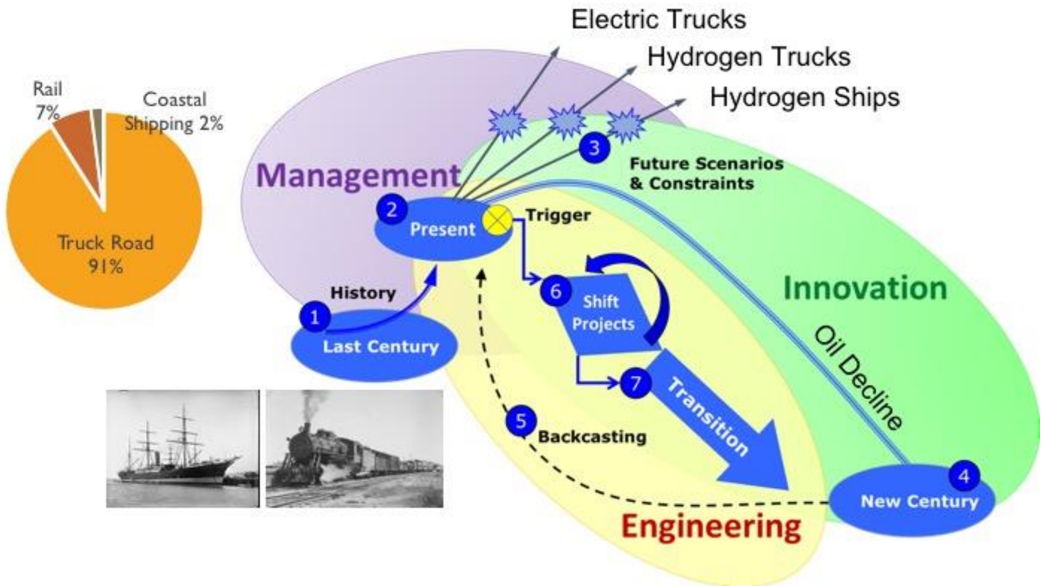


Figure 43 Transition Engineering Methodology (InTIME©)

Phase 2 aims to investigate different pathways including business-as-usual trends, changes in resource conversion technologies, and behaviour concepts (modal shifts). Scenarios will be evaluated in terms of energy use, GHG emissions, and costs over a specific timeframe.

From a methodological point of view, work in Phase 2 includes a Development Vector Analysis (DVA) and a Complex Systems Strategic Analysis (CSSA).

[6] The InTIME© process was developed by Professor Susan Krumdieck and published in her book "Transition Engineering: Building a Sustainable Future" (2019).

6.1 Development Vector Analysis (DVA)

DVA aims to support strategies specific to the Coastal Shipping, mainly associated to future propulsion solutions. The aim is to map different feasibility hurdles (i.e. technical challenges, material needs and processing, system architecture and system integration) that must be overcome along the development pathways for different technologies.

The analysis will be supported by energy systems and emissions modelling and lifecycle analysis databases. Moreover, work will be supported by a scientific literature review on the state-of-the-art for different propulsion fuels and technologies.

6.2 Complex Systems Strategic Analysis (CCSA)

CSSA is a new tool in Transition Engineering that has proven very useful in interdisciplinary multi-criteria decision support. Phase 2 would adopt the implementation of CSSA as part of the Scenario Analysis (Step 3 in InTIME) and the 100-year concept generation processes (Step 4 in InTIME). The CSSA allows consideration of multiple lines of options in multiple categories of infrastructure, technology, service and operations, policy and demand behavior. The CSSA has a wider scope as it investigates scenarios applicable to the whole freight sector.

An opportunity space will be defined by cross-linking possible technology and infrastructure options. The analysis will be supported by spreadsheet modelling with environmental planning and lifecycle analysis software, databases, and relevant scientific literature. Every scenario will be evaluated in terms of energy consumption, GHG emissions, and costs. Furthermore, modelling will be supported by the background work and data from Phase 1 and through the development of multimodal transport modelling. The implementation of CSSA will lead to the identification of the most feasible infrastructure and technology options, and consequently enable delivery of a long term conceptual design for the freight system.

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Appendix A COPERT Environmental Information setup for New Zealand

Month	Min Temperature [°C]	Max Temperature [°C]	Humidity [%]
January	12.2	22	77.3%
February	12.3	22	81%
March	10.6	20.3	81.2%
April	8.2	17.6	82.9%
May	6.1	14.8	85.2%
June	3.9	12.2	86.3%
July	3.1	11.5	86.1%
August	4	12.7	84%
September	5.7	14.7	79%
October	7.4	16.4	77.8%
November	9	18.2	75.6%
December	11	20.3	76.5%

Appendix B COPERT Fuel specifications

Primary Fuel	Energy Content [MJ/kg]	Density [kg/m3]
Petrol Grade 1	43.8	750.0
Petrol Grade 2	43.8	750.0
Diesel Grade 1	42.7	840.0
Diesel Grade 2	42.7	840.0
LPG Grade 1	46.6	520.0
LPG Grade 2	46.6	520.0
CNG	48.0	175.0
Biodiesel	37.3	890.0
Bioethanol	28.8	794.0

Appendix C COPERT Implied emission factors

Category	CO_2[g/km]	CH_4[g/km]	N_2O[g/km]
Rigid <=7,5 t	365.1909	0.04675	0.03
Rigid 7,5 - 12 t	500.8492	0.04675	0.03
Rigid 12 - 14 t	534.7489	0.04675	0.03
Rigid 14 - 20 t	668.5274	0.1145	0.03
Rigid 20 - 26 t	784.5553	0.1145	0.03
Rigid 26 - 28 t	827.514	0.1145	0.03
Rigid 28 - 32 t	934.0266	0.1145	0.03
Rigid >32 t	927.4238	0.1145	0.03
Articulated 20 - 28 t	823.1767	0.09975	0.03
Articulated 28 - 34 t	863.8437	0.09975	0.03
Articulated 34 - 40 t	987.9996	0.09975	0.03
Articulated 40 - 50 t	1,095.7673	0.09975	0.03
Articulated 50 - 60 t	1,315.9101	0.09975	0.03

Appendix D LEAP Tier 2 emission factors for different combustion technologies

	Loading [kg/TJ consumed]		
Effect	Diesel Truck	Diesel Engine Railways	Ocean Ship Residual Fuel Oil
Carbon Dioxide	73,275.496	73,275.50	76,540.25
Carbon Monoxide	319.00	250.00	46.00
Methane	4.00	4.00	NA
Non-Methane Volatile Organic Compunds	107.00	110.00	NA
Nitrogen Oxides	677.00	900.00	2,100.00
Nitrous Oxide	2.00	30.00	2.00