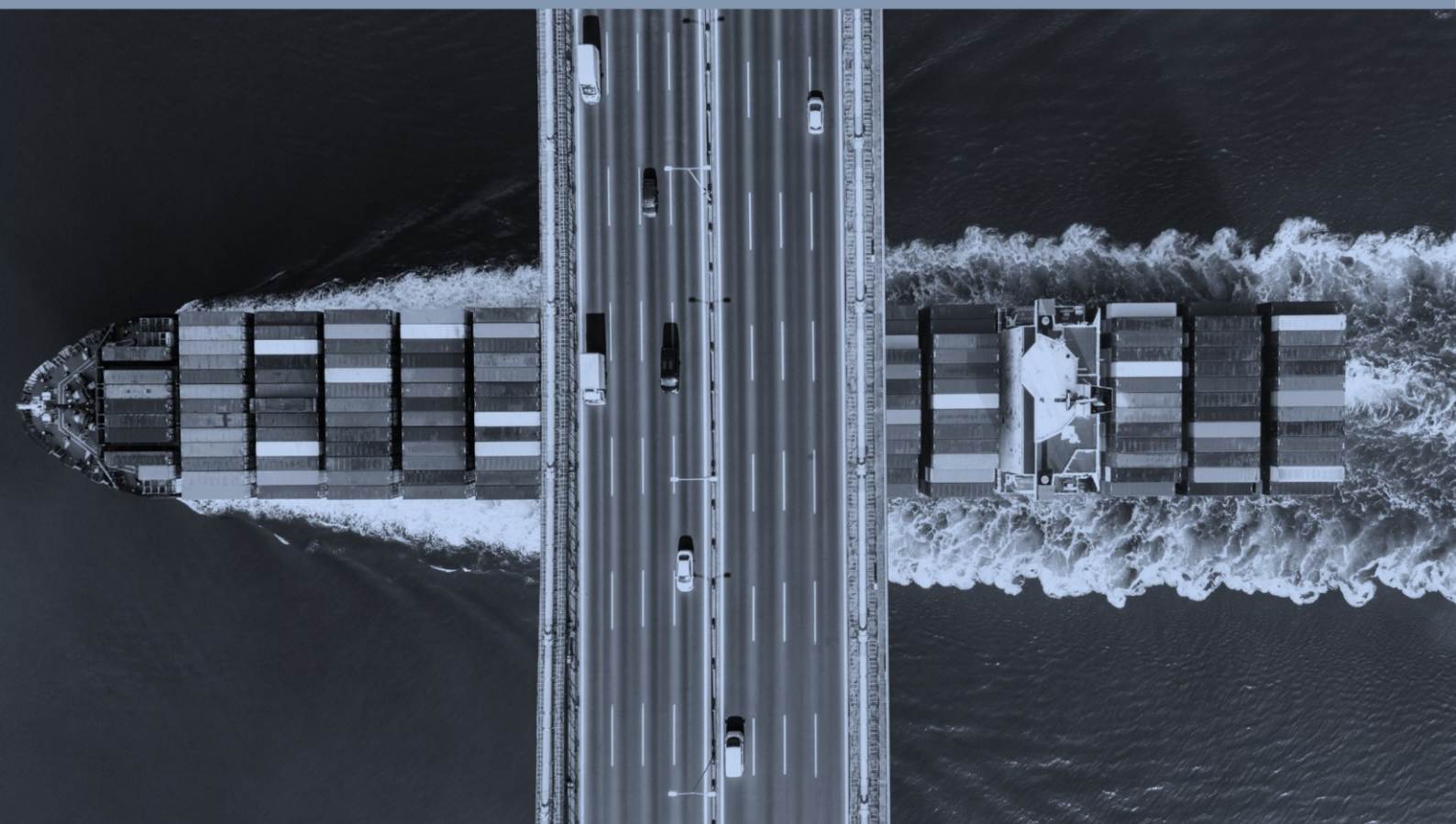




The emission reduction potential of
mode shift to maritime transport

Transport ^{Emission} Energy Research



<https://www.transport-e-research.com/>

Client: Maritime Union of Australia | Maritime Industry Australia Limited
and supported by the Energy Futures Foundation

Authors: Dr Robin Smit, Dr Paul Boulter, Ms. Ella Castillo

Date: 15 September 2026

Front cover photo: iStock

Citation: TER, 2026. *The Emission Reduction Potential of Mode Shift to Maritime Transport*,
Transport Energy/Emission Research (TER), 15 September 2026.



Table of Contents

Executive summary	1
Glossary of terms	4
1. Introduction	5
2. Emission-reduction potential of mode shift	5
3. Method and assumptions	6
3.1 Modelling approach	6
3.2 Freight routes	7
3.3 Route distances and sea currents	11
3.4 Cargo	12
3.5 Emission estimation	13
3.6 Sea freight	13
3.7 Road freight	16
3.8 Rail freight	17
4. Multi-modal emissions performance assessment	18
4.1 Container cargo	18
4.2 Bulk liquid cargo	20
4.3 Potential fuel savings through mode shift	21
5. Conclusions	23
6. References	24
7. About TER	26
Appendix A – Freight routes	27
Appendix B – Model considerations and assumptions by transport mode	31
B.1 Shipping	31
B.2 Road	31
B.3 Rail	32

Executive summary

Although shipping is a key transport mode for international trade, domestic shipping plays a relatively small role in the Australian freight task. In 2025, coastal shipping made up a little over ten percent of the total freight task and made a minor contribution to emissions nationally. This indicates that there may be significant emission-reduction potential for a shift from land-based transport to maritime transport in the Australian freight sector.

The Maritime Union of Australia (MUA), in collaboration with Maritime Industry Australia Limited (MIAL) and supported by the Energy Futures Foundation, has contracted Transport Energy/Emission Research (TER) to assess the well-to-wheel/wake (WTW) greenhouse gas emission reduction potential of shifting from land-based transport to maritime transport in the Australian freight sector in 2030, using current maritime engine technology and conventional fuels.

We find that a potential mode shift to coastal shipping can provide large reductions in both diesel fuel consumption (improving national fuel security) and greenhouse gas emissions (addressing climate change), especially on longer routes. On longer routes, we found a reduction of emissions by 60-90% per tonne of cargo per km it was carried, and a reduction in total tonnes of fuel used by 55-85%, as well as a shift away from the use of road diesel. There may also be other benefits from establishing new coastal transport options that currently do not exist such as enhancing Australia's transport resilience and strengthening supply chains.

Two common ship types – container ships and refined product tankers – were considered in this study. For container ships, two representative vessels were selected with a cargo capacity of 500 and 1000 TEU. For refined product tankers, two representative vessels were selected with a cargo capacity of 20,000 and 45,000 deadweight tonnage (DWT). For road freight transport, a representative articulated GML Tri-Axle B-double diesel truck was modelled. The representative diesel freight train consisted of 3 locomotives and 75 wagons, with a total length of almost 2 km. Furthermore, two types of cargo were considered, i.e. refined fossil fuel product (bulk liquid) and container freight.

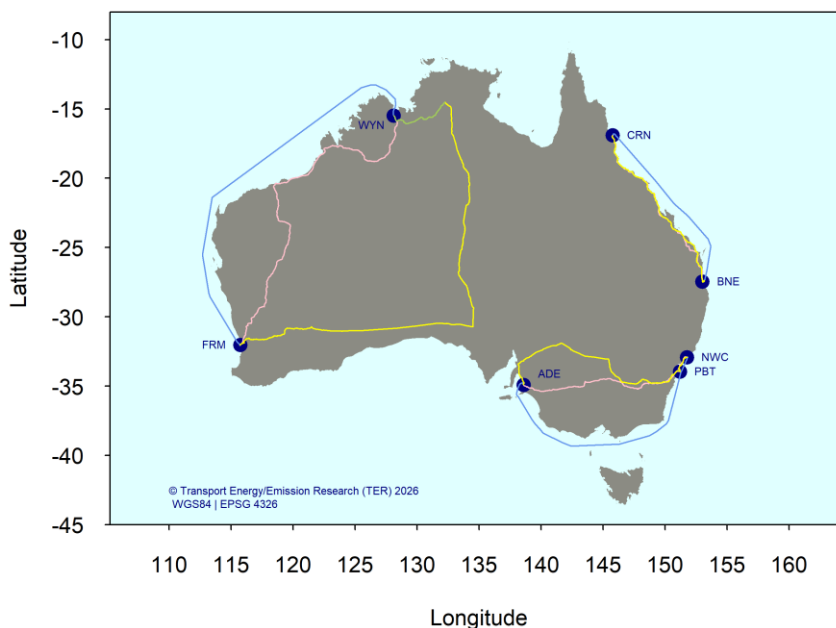


Figure ES.1 – The logistics routes considered in this study. The coloured lines represent shipping routes (blue), road routes (pink), rail routes (yellow) and connecting road routes (green).

The emission-reduction potential was assessed for four Australian freight routes for maritime vessels and then compared with the alternative rail and road options (Figure ES.1).

The study accounted for key aspects that influence the greenhouse performance and fuel consumption for each transport mode.

They include emission penalties due to unladen travel (moving without cargo freight), the impacts of varying cargo loads, the impacts of ocean currents, the mode-specific maximum cargo capacity and cargo spillover effects, and the impacts of 'connector roads', which connect port or railway station locations to the relevant origin or destination point within the city centres.

TER then used a probabilistic tool to assess the mode shift impacts on emissions and fuel consumption. A range of Australian and mode-specific emission models were used to provide the required inputs, for instance, the Maritime Transport Emission Model (MTEM), the Australian Fleet Model (AFM) and the Net Zero Vehicle Emission Model (n0vem). The simulation resulted in the creation of 1141 input and output files, with each file containing one million data points.

These data were then used to assess the mode shift impacts on the emissions performance for each transport mode, expressed as grams of carbon dioxide equivalents (CO₂-e) emitted per tonne-kilometre.

An example of an emission intensity output distribution is shown in Figure ES.2 for one route. These distributions underpin the impact assessment. They show the shape and spread of emission intensities for each transport mode on a particular route and capture the associated variability and uncertainty. Higher probability values (e.g. peaks) mean the corresponding emission intensity values are more common.

The study found that a shift of freight transport from road to coastal shipping delivered a significant to large reduction in the mean WTW greenhouse gas emission intensity and fuel consumption for road transport. This was the case for all routes and for all vessel sizes that were considered in this study.

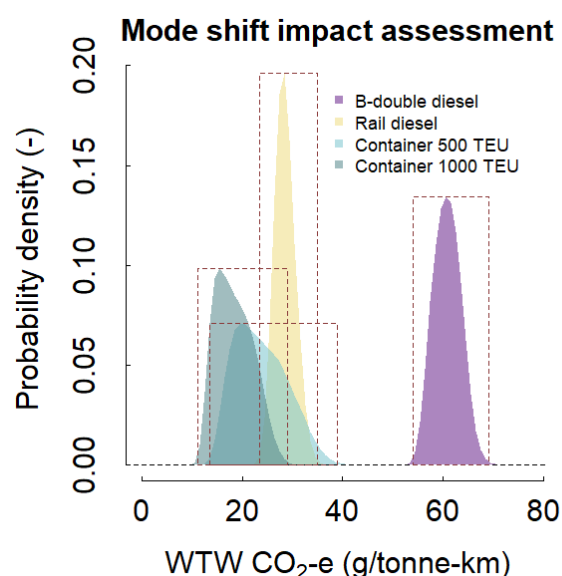


Figure ES.2 – Example of assessment results.

A summary of the results for road and maritime transport is shown in Table ES.1. The magnitude of the reduction in emissions and potential fuel savings depended on the specific route, the type of cargo, the transport mode and the vessel size.

Table ES.1 – Typical reductions in well-to-wheel/wake (WTW) GHG emissions and tank-to-wheel/wake (TTW) fuel consumption by a shift from road to maritime transport for short and longer Australian freight routes in 2030.

Route	WTW GHG emission performance – short route 170 km % reduction in g CO ₂ -e/tonne-km	WTW GHG emission performance – routes > 1400 km % reduction in g CO ₂ -e/tonne-km	TTW fuel consumption – short route 170 km % reduction in total tonne fuel used	TTW fuel consumption – routes > 1400 km % reduction in total tonne fuel used
500 TEU container ship	25%	60%	20%	55%
1000 TEU container ship	30%	70%	25%	60%
20,000 DWT bulk liquid tanker	45%	85%	45%	80%
45,000 DWT bulk liquid tanker	60%	90%	60%	85%

In terms of tank-to-wheel/wake (TTW) or operational fuel savings, this study found that a shift of freight transport from road to maritime can potentially shift significant volumes of diesel fuel currently used by road and rail transport to marine fuels. This may also result in significant to large reductions in total fuel consumption, depending on the Australian route and type of ship, as is shown in Table ES.1.

As can be seen in Table ES.1, travel distance is particularly important. For short sea routes, coastal shipping had significantly higher emissions and fuel consumption per kilometre when compared with longer routes. This is caused by a relatively high contribution of fuel consumption in stationary conditions (berth). Another notable difference was found for the type of cargo. Container trucks used the available mass capacity, resulting in fully loaded trucks. For bulk liquids, the maximum amount of cargo was limited by the maximum volume capacity. Trucks were therefore not fully loaded in terms of mass. As a consequence, the B-double tanker combination was, on average, less fuel efficient per tonne-km than container transport. This further contributed to the benefits of maritime transport.

Coastal shipping was shown to provide significant reductions in the mean WTW greenhouse gas emission intensity for rail, provided that the route was long enough and that the vessel cargo capacity was large enough. A visual summary of the study results is shown side-by-side in Figure ES.3.

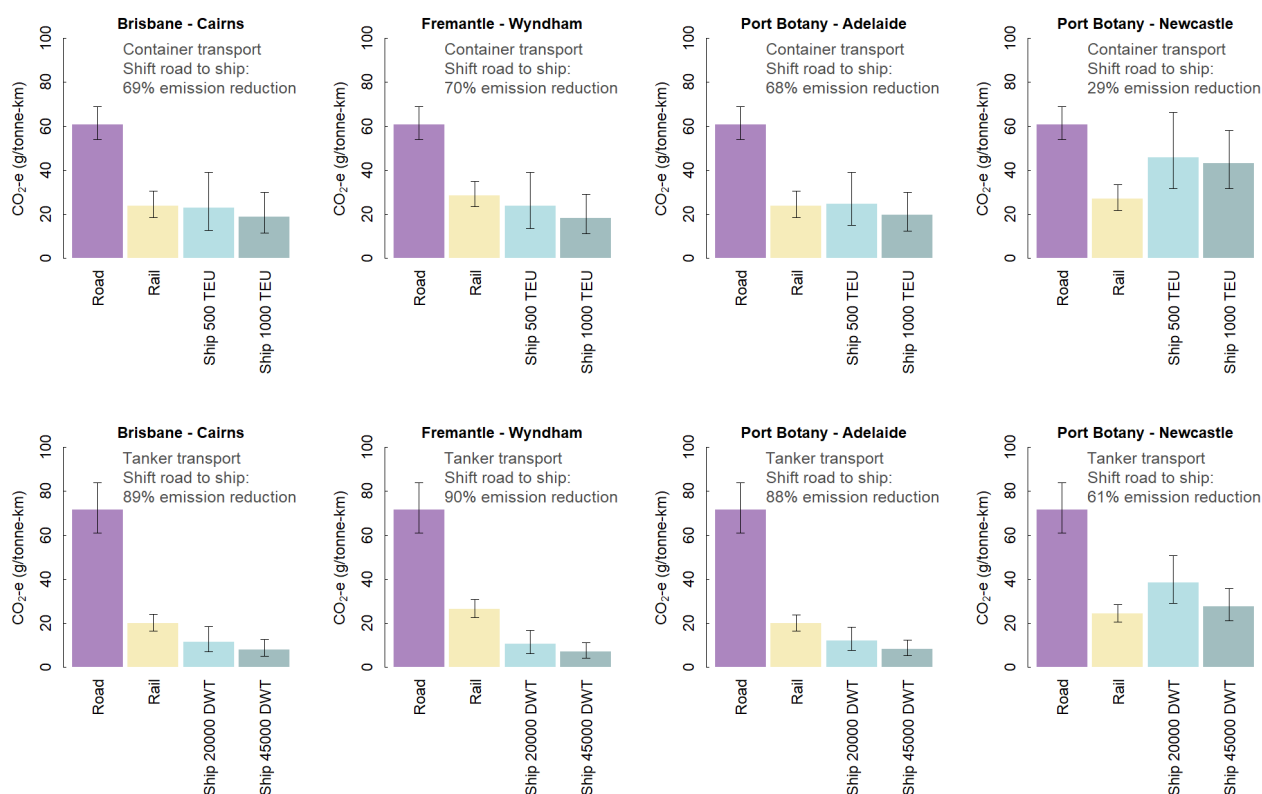


Figure ES.3 – WTW greenhouse gas emission intensities by cargo type, transport mode and route in 2030, including plausible ranges.

Finally, this study focused on conventional maritime engines and machinery that use marine fuels (e.g. HFO, IFO, VLSFO, MDO and MGO) for propulsion, on-board electricity generation and heat. Lower emission options for shipping such as low carbon liquid fuels (e.g. methanol, ammonia), battery electric ships and shore power may be assessed in a future and separate study, which would also include low and zero emission options for rail and road.

Moreover, a more comprehensive consideration of all operating modes and typical proportions of time spent in these modes (e.g. AIS data analysis), could also be included. Finally, the study could be expanded to account for other aspects such as costs and air quality impacts.

Glossary of terms

AIS	Automatic Identification System
AFM	Australian Fleet Model
AMSA	Australian Maritime Safety Authority
API	Application Programming Interface
CH ₄	methane
CO	carbon monoxide
CO ₂	carbon dioxide
CO _{2-e}	carbon dioxide equivalents
DWT	Dead Weight Tonnage
EEZ	Exclusive Economic Zone
HFO	Heavy Fuel Oil
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
kg	kilogram
kt	kilotonne
LCA	lifecycle assessment
MCR	Maximum Continuous Rating
MD	Marine Distillates (MDO/MGO)
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
m/m	mass in mass (grams of a substance in grams of product)
MMSI	Maritime Mobile Service Identity
MTEM	Maritime Transport Emission Model
nmt	nautical miles travelled
n0vem	Net Zero Vehicle Emission Model
RO	residual oil (heavy fuel oil)
RoRo	Roll-on Roll-off
t	tonne
tkm	tonne-kilometre
TTW	tank-to-wheel/wake, direct emissions from moving transport units
TER	Transport Energy/Emission Research
TEU	Twenty-foot Equivalent Unit
VKT	vehicle kilometres travelled
VLSFO	Very Low Sulphur Fuel Oil
WTW	well-to-wheel/wake, greenhouse gas emissions related to operation and upstream fuel production

1. Introduction

The Maritime Union of Australia (MUA), in collaboration with Maritime Industry Australia Limited (MIAL) and supported by the Energy Futures Foundation, has contracted Transport Energy/Emission Research (TER) to assess the well-to-wheel/wake (WTW) greenhouse gas emission-reduction potential of a shift of freight from road and rail transport to maritime transport. The study considered several pre-defined routes in Australia and assessed the effects of mode shift in 2030. This report presents the findings of the study. It starts with a brief discussion of the context (Section 2), followed by the method and assumptions (Section 3), the results (Section 4) and finally the conclusions (Section 5).

2. Emission-reduction potential of mode shift

In terms of national greenhouse gas emissions, expressed as carbon dioxide equivalents ($\text{CO}_2\text{-e}^1$), the domestic transport sector has become more important over time. The sector as a whole contributed about 10% to total emissions in 1990, but by 2024 it had more than doubled to 21%, as shown in Figure 1 (left chart). This is for personal travel and freight combined.

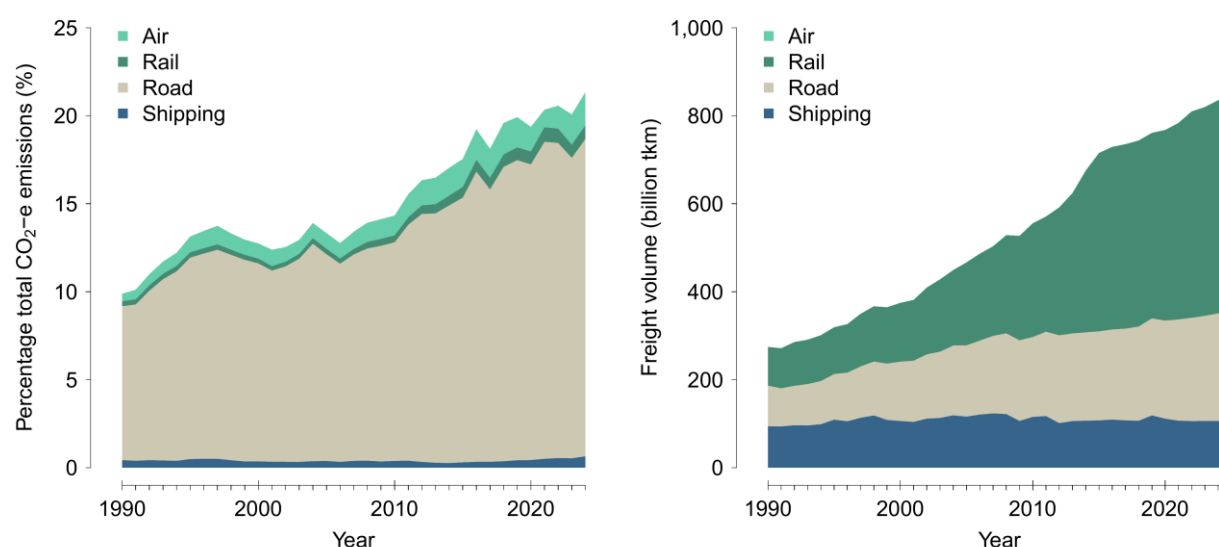


Figure 1 – **Left:** contribution of different transport modes to total greenhouse gas emissions in Australia in 1990-2024 (Source: DCCEEW, 2026), **Right:** Domestic freight task for Australia by transport mode in 1990-2025 (Source: BITRE, 2022).

Figure 1 (left chart) shows the contributions of the different transport modes to total annual greenhouse gas emission loads in Australia in the period 1990 – 2024 (DCCEEW, 2026). Whereas domestic shipping (‘domestic navigation’) has remained relatively stable over the period, increasing from 0.4% to 0.6%, the other transport modes have increased at a higher rate: 0.3% to 0.8% for rail, 0.4% to 1.9% for air and 8.7% to 18.0% for road.

In 2024, 84% of $\text{CO}_2\text{-e}$ emissions from the Australian transport sector were from road, followed by 9% from air (‘domestic aviation’), 4% from rail and 3% from shipping. Clearly, emissions are not evenly distributed across the transport modes and the relative contribution of shipping to total emissions has reduced over time. This suggests that there may, in fact, be a significant emission-reduction potential for mode shift towards the domestic shipping sector within the Australian transport sector.

¹ $\text{CO}_2\text{-e}$ emission factors are computed through multiplication of greenhouse gas emission estimates (CO_2 , CH_4 , N_2O) with 100-year GWP (global warming potential) IPCC values (6th assessment), i.e. 1.0, 29.8 (fossil origin) and 273.0, respectively.

When looking more specifically at freight (Figure 1, right chart), the Australian domestic freight task has experienced strong growth over the last 40 years, with road and rail freight now dominating domestic freight activity. The right chart in Figure 1 shows total freight volume, expressed as tonne-kilometres (tkm), for all transport modes in Australia in the same period (BITRE, 2022). The air freight task is less than 0.08% and is therefore not visible.

The right chart in Figure 1 also shows that coastal shipping has remained relatively stable increasing by 13% over the period 1990 – 2025. In contrast, the other transport modes increased at substantially higher rates, i.e. rail transport increased by a factor of 5.5 and road transport increased by a factor of 2.7. In 2025, coastal shipping made up 13% of the total freight task and recent estimates suggest it may be even lower at 11% (BITRE, 2025). This indicates that there may be significant emission-reduction potential for a shift from land-based transport to maritime transport in the Australian freight sector.

These aggregated results are more nuanced once examined in more detail. For instance, there are significant differences depending on the type of cargo. Road transport is the dominant mode for domestic freight for all but the major iron ore and coal exporting supply chains, where rail plays a major role. Moreover, road freight volumes are primarily influenced by total economic activity. It is noted that the rate of growth for road freight has slowed since the early 1990s, from an average around 6.0% per year between 1971 and 1991, to around 3.8% per year between 1991 and 2012, and around 1.8% per year since 2012.

In conclusion, national Australian emissions and freight data suggests that shipping currently plays a relatively small role in the freight task and that it has a minor contribution to total emissions. Given the relatively low emission intensities for shipping when compared to road transport in particular (Smit and Boulter, 2024b), there could be significant emission-reduction potential for a shift from land-based (road, rail) to maritime shipping.

3. Method and assumptions

This study focused on conventional maritime engines and machinery that use marine fuels (e.g. HFO, IFO, MDO, MGO) for propulsion, on-board electricity generation and heat.

Lower emission options for shipping (e.g. methanol, ammonia, battery electric) may be assessed in a future and separate study, but this would require some changes to the study scope. For instance, consideration of (battery) electric shipping and other electrification options (e.g. cold ironing and shore power), would reasonably require a similar expansion of the study for the road and rail sectors to include electric trucks and freight trains. Moreover, consideration of low carbon liquid fuels (LCLFs) would require a more detailed assessment of the impacts on both tank-to-wake and well-to-tank ship emissions, for instance in terms of fuel specifications (e.g. LHV, carbon content), impacts on specific fuel consumption (g/kWh) and upstream emissions during the production and distribution of these fuels.

3.1 Modelling approach

This study builds on previous mode shift research for the Australian situation, which was published in an open access international peer-reviewed journal in 2024 (Smit and Boulter, 2024a; 2024b).

Depending on the transport mode, well-to-wheel/wake/wing (WTW) greenhouse gas emissions include all emissions related to fuel production – often referred to as the fuel-cycle.² This can be broken down into two components: a tank-to-wheel/wake/wing (TTW) component that represents direct emissions from moving transport units, and a well-to-tank (WTT) component that includes indirect emissions associated with fuel extraction, energy production (refined fossil fuels, electricity, hydrogen, low carbon liquid fuels, etc.) and distribution.

² A life-cycle assessment (LCA) expands WTW analysis and estimates ‘cradle-to-grave’ emissions, accounting for both fuel-cycle emissions (WTW) and vehicle-cycle emissions (vehicle production as well as end of life, recycling or disposal). The scope of this study is restricted to WTW emissions. So the production, maintenance, and disposal of transport units and infrastructure are not taken into account in this study, and could be considered in a future study. Nevertheless, this analysis is expected to capture the bulk of the total GHG emissions for the different transport modes, because the fuel cycle typically dominates total emission loads.

As will be discussed later, each transport mode is characterised using a *reference transport unit*, defined as a representative vehicle in the year 2030. The general model for the analysis combines direct exhaust emissions from fossil fuel combustion with indirect emissions due to electricity and hydrogen consumption, as well as the upstream production of fossil fuels, electricity and hydrogen.

Given the complex, dynamic and location-specific nature of mode shift impacts, it is important that the uncertainty and variability in emission estimates are explicitly quantified. TER has therefore developed an innovative, fast and cost-effective WTW (or LCA) approach to explicitly quantify the uncertainty in the results (e.g. Smit and Kennedy, 2022; Smit *et al.*, 2024). This probabilistic approach explicitly quantifies uncertainty and variability in model outputs and estimates non-linear interactions. The approach has also been used in this study. A full mathematical description of the mode shift impact modelling can be found in Smit and Boulter (2024a, Tables S1-S9; 2024b, Table S1-S4).

Briefly, statistical techniques, including Monte Carlo simulation, bootstrap analysis, parametric distribution fitting, linear and non-linear regression modelling are used to develop (truncated) input distributions, representing the probabilities of all possible values in the sample space. Monte Carlo simulation is then used to propagate the uncertainty and variability in the input distributions towards the model outputs. To ensure consistency in the calculations, common input parameters and intermediate distributions are stored and retrieved when they are required as input in subsequent steps. The resulting probability density functions (PDFs) not only indicate central tendencies (mean, median), but also capture the variability and uncertainty in the output variables arising from the combination of the input distributions as prescribed by the mathematical model formulation.

The probabilistic approach estimates the plausible range³ of values for each output and their chance of occurrence. This provides useful insight into the robustness of study outcomes and supports cost-effective real-world implementation of mode shift policies and measures.

3.2 Freight routes

The routes, cargos and type of ship analysed in this report were selected by MIAL and the MUA based on their maritime industry expertise. The objective was to give a range of realistic options based on current widely available vessel and port technology and make an initial evaluation of possibilities for emissions and fuel reduction. It was beyond the scope of the study to assess the full potential for mode shift to Australian domestic shipping and this work is still to be done.

The emission-reduction potential was assessed for four selected freight routes for maritime vessels and then compared with the alternative rail and road options. The following routes were considered:

- Route A – Brisbane – Cairns (BNE – CRN)
- Route B – Fremantle – Wyndham (FRM – WYN)
- Route C – Port Botany – Adelaide (PBT – ADE)
- Route D – Port Botany – Newcastle (PBT – NWC)

As will be discussed later, different ship types and sizes were considered, i.e. 500 and 000 TEU⁴ container ships and 20,000 and 45,000 DWT⁵ refined product tankers. The seven selected Australian ports are shown in Figure 2.

For all transport routes the origin and destination points for freight transport were assumed to be located within the respective city centres. This meant that a relatively small amount of additional truck transport was required for both rail and shipping, which we will refer to as ‘connector road routes’.

³ The plausible range (truncation) is defined as the 99.7% confidence interval of the mean.

⁴ TEU (Twenty-foot Equivalent Unit) is the industry standard to measure containers, with dimensions set by the ISO (MPC, 2026).

⁵ Deadweight tonnage (DWT) refers to the amount of cargo that a ship can safely carry. Cargo also includes items like fuel, fresh water, ballast water, provisions, passengers and crew (MPC, 2026).

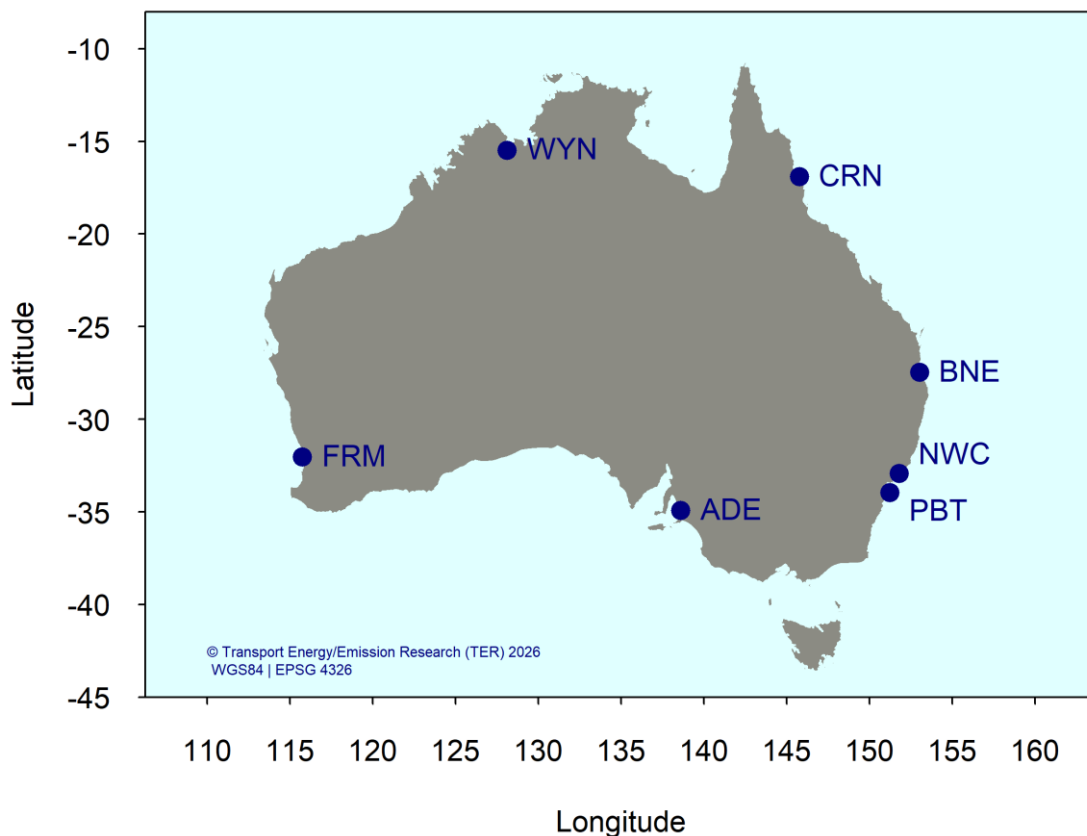


Figure 2 – The seven ports considered in this study: Fremantle, WA (FRM), Wyndham, WA (WYN), Cairns, QLD (CRN), Brisbane, QLD (BNE), Newcastle, NSW (NWC), Port Botany, NSW (PBT) and Adelaide, SA (ADE).

Routes, ships and cargos were selected on the basis of 1) common widely available cargo ship types up to 10 years old, 2) port capacity and the type and size of ships likely to service most Australian regional ports, and 3) common types of domestic freight which can easily be carried by ship and which have been carried by Australian domestic ships in recent history. This resulted in selecting relatively smaller but more versatile vessels than those operating in Australia's major international ports. Some routes reflect coastal shipping services which used to exist, or recent proposals for coastal shipping services that were close to viability but do not yet exist. They would add resiliency to current freight transport options.

- Plausible shipping routes were constructed using observed vessel traffic activity that were published by the Australian Maritime Safety Authority (AMSA, 2026). These satellite/terrestrial data on shipping movements are commonly referred to as Automatic Identification System (AIS) data. AIS is a mandatory collision avoidance system on ships generally larger than 300-500 gross tonnes.⁶ AIS data were downloaded from the AMSA website, processed and analysed to provide guardrails for the definition of plausible maritime routes. High-trafficked shipping lanes were generally visible in these data and were followed where possible. With 2.4 million ship location reports for just a single month, the AMSA data provide good coverage of shipping movement in Australian waters, as is shown in Figure 3.

⁶ AIS is included in the International Convention for the Safety of Life at Sea (SOLAS) convention for 1) vessels of 300 gross tonnage and upwards engaged on international voyages, 2) vessels of 500 gross tonnage and upwards not engaged on international voyages and 3) passenger ships irrespective of size. There are different classes of AIS systems on board vessels, which can be classified as Class A and Class B. The AIS referred to in the SOLAS convention is often defined as 'AIS Class A'. AIS Class B is intended for use on non-SOLAS vessels. These can include domestic commercial vessels and pleasure craft. Static and voyage information differ between Class A and B AIS. For global AIS, Class B vessels and small Class A vessels do not usually report voyage data.

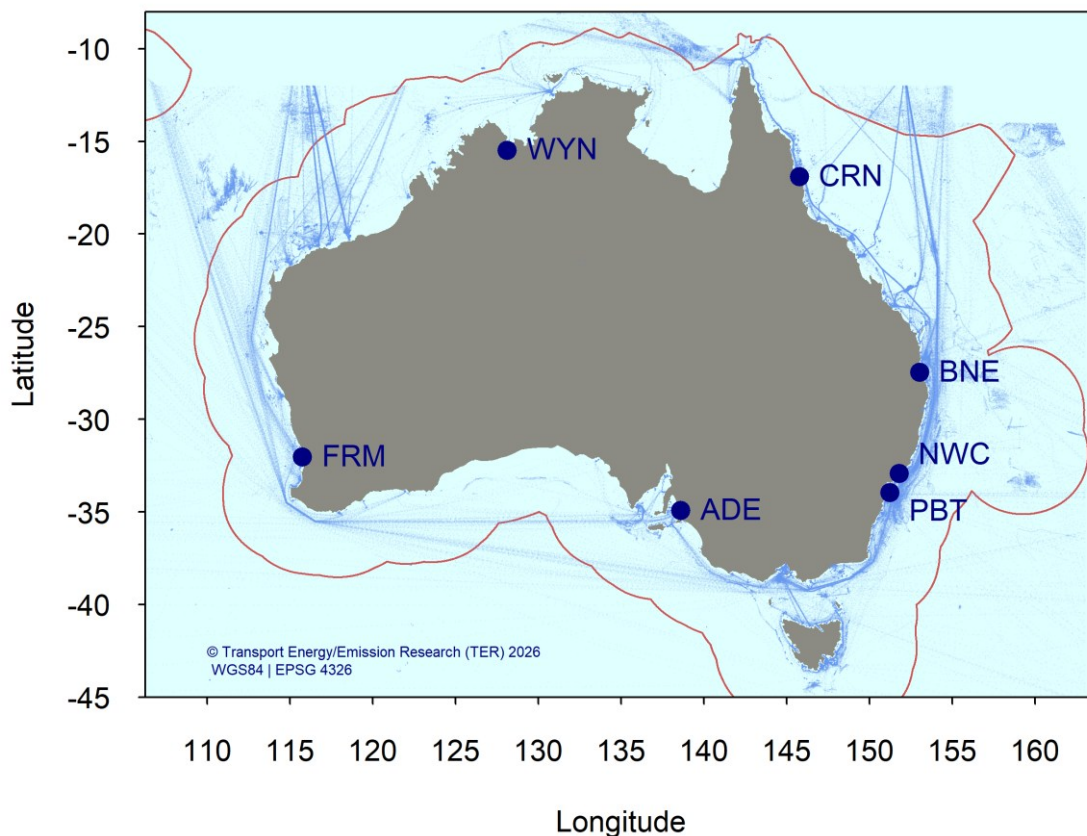


Figure 3 – Visualisation of AIS data (blue dots) to generate plausible freight routes for shipping. The Exclusive Economic Zone (EEZ) is shown as a red line.

- Plausible road transport routes were generated using a Python script that accessed the Google Maps Application Programming Interface (API) to determine the optimal routes between origin and destination points (i.e. the shortest or fastest route). These were then matched with road segments from the national digital Australian road dataset, sourced from GeoScience Australia (GA, 2024).
- Railway transport routes were based on trainline segments from the Foundation Rail Infrastructure Feature dataset (GA, 2021). The full railway dataset included extraneous line segments that connect to the full railway station network, and were not necessarily part of usual rail transport itself. These were removed to ensure the resultant transport path only included practical routes.

The resulting shipping and rail routes were supplemented by short road routes to connect port or railway station locations to the relevant origin or destination point within the city centre. Figure 4 shows the different routes that were created for this study. More detailed maps can be found in Appendix A.

It is clear that travel distances can differ significantly between routes and also between transport modes. Shipping has the shortest distance travelled (Route D, 149 km) and rail has the longest distance travelled (Route B, 4514 km). Table A.1 in Appendix A shows the route distance by transport mode including connector roads.

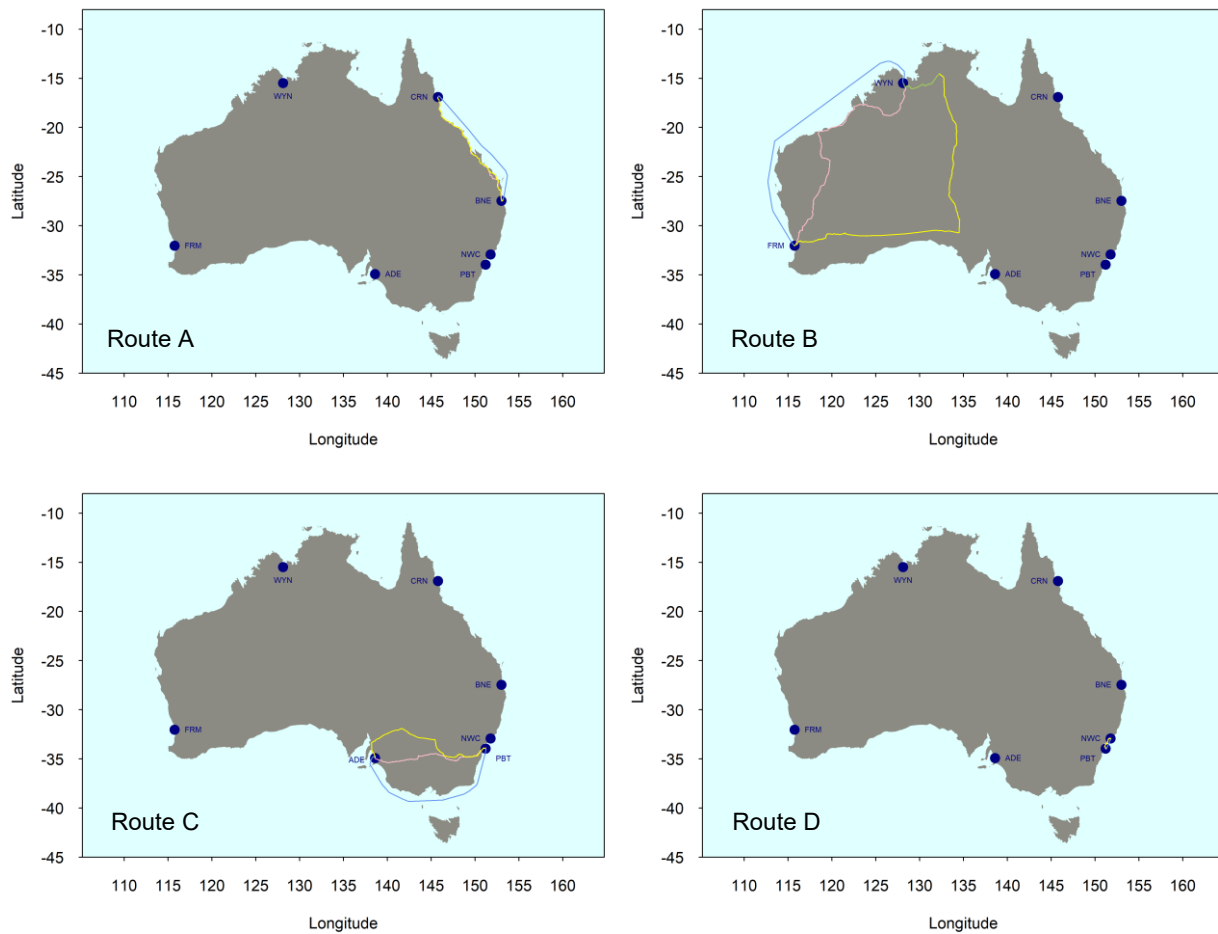


Figure 4 – The four logistics routes considered in this study (entire study area): BNE-CRN (Routes A), FRM-WYN (Route B), PBT-ADE (Route C) and PBT-NWC (Route D). The coloured lines represent shipping routes (blue), road routes (pink), rail routes (yellow) and connector road routes (green).

The variability in route distance by transport mode is a key variable in the assessment, because total emissions and fuel consumption are a direct function of total travel distance, irrespective of transport mode.

Figure 5 shows the start and end points for the routes in more detail. It shows sections of the routes within each city by transport mode, close to the origin and destination points. The connector road routes are visible in these maps (green lines). In general, these connector roads were relatively short, varying between 1 km and 24 km, with an average length of 13 km, except for one long 608 km connector road route between Katherine train depot and Wyndham CBD.

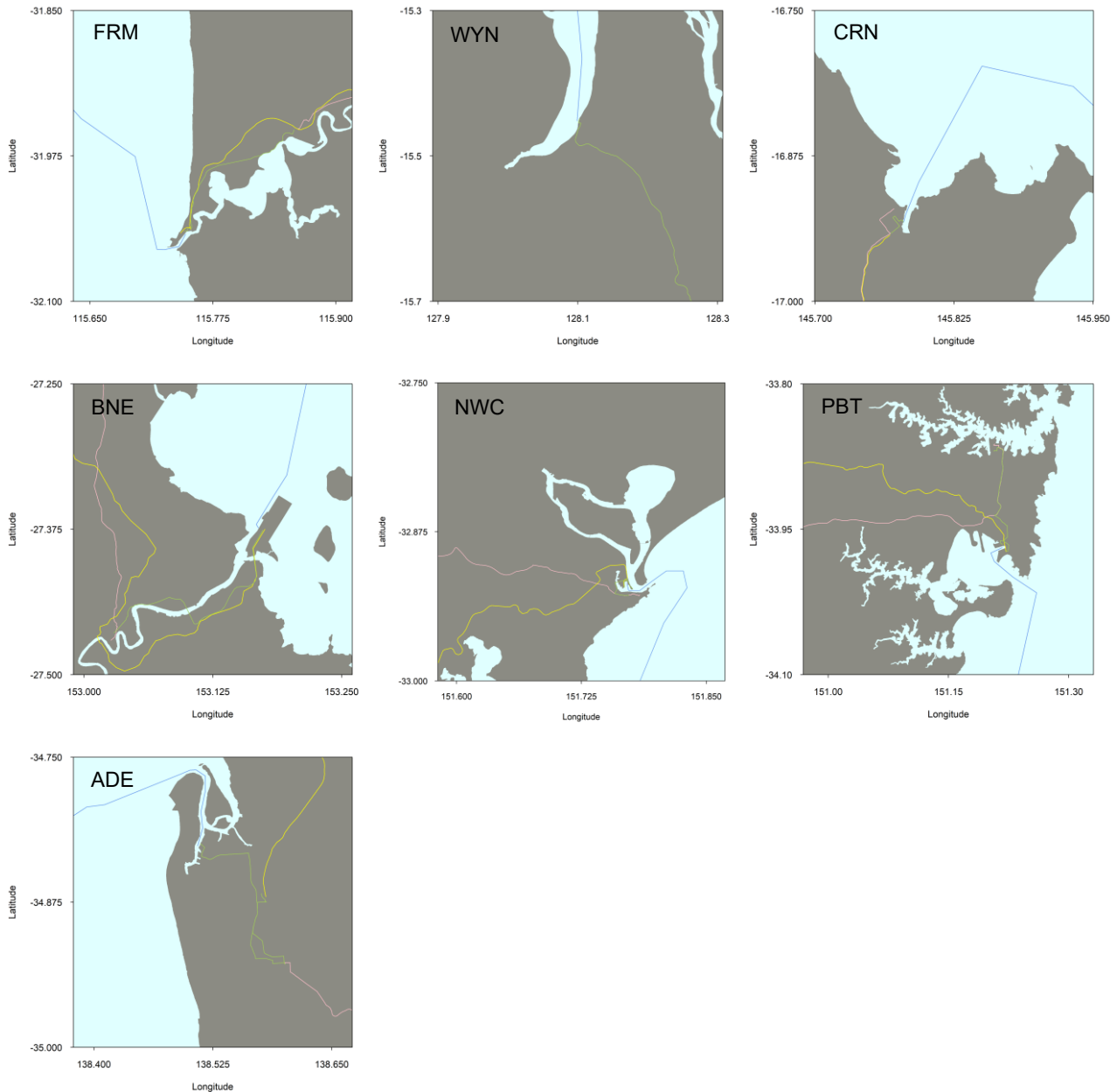


Figure 5 – The routes by transport mode close to the origin/destination points within the seven cities four logistics routes. The coloured lines show shipping routes (blue), road routes (pink), rail routes (yellow) and CBD linkage road routes (green).

3.3 Route distances and sea currents

Route distances were determined for the four selected freight routes, where $d_{i,j}$ is the total travel distance for route i and transport mode j . Since this is a probabilistic analysis, route distance is not treated as a fixed and constant value. Instead, route distance is treated as a model variable and inputs were defined as uniform distributions, with uncertainty and variability a function of transport mode, i.e.

- ($U: 0.965 d_{i,road}, 1.035 d_{i,road}$) for road transport and connector road routes.
- ($U: 0.998 d_{i,rail}, 1.002 d_{i,rail}$) for rail.
- ($U: 0.975 d_{i,shipping}, 1.025 d_{i,shipping}$) for shipping.

The study assumed that rail has the lowest level of variability in travel distance (within $\pm 0.2\%$) and road the highest level of variability (within $\pm 3.5\%$).

The impacts of ocean currents on emissions were also included in the simulation. In TER's Maritime Transport Emission Model (MTEM), which will be discussed further in Section 3.6, the speed of a vessel is defined relative to the water. An ocean current effectively increases or decreases the total distance travelled, depending on the direction of the vessel and the direction and speed of the current. The main ocean currents that were considered to be relevant to the analysis (e.g. Cresswell and Domingues, 2009; Cresswell *et al.*, 2017; Duran *et al.*, 2020) are summarised in Table 1.

Table 1 – Sea route travel distances and relevant sea currents.

Route	Total travel distance Km	Direction of travel ⁽¹⁾ -	Current -	Start -	End -	Distance weight %	Mean current speed ⁽²⁾		Route average current speed kn
							km/h	kn	
A	1,519	NB	Eastern Australia Current	Brisbane	Cairns	100%	0.0	0.0	0.0
		SB	Eastern Australia Current	Cairns	Brisbane	100%	+5.4	+2.9	+2.9
B	3,288	NB	Leeuwin Current	Fremantle	Broome	65%	-1.1	-0.6	-0.4
			Holloway Current	Broome	Wyndham	35%	-0.4	-0.2	
		SB	Holloway Current	Wyndham	Broome	37%	+0.5	+0.3	+0.7
			Leeuwin Current	Broome	Fremantle	63%	+1.8	+1.0	
C	1,848	SB	Eastern Australia Current	Port Botany	Cape Howe	24%	+3.6	+1.9	+0.4
		WB	Flinders Current	Cape Howe	Cape Otway	36%	+0.4	+0.2	
			South Australian Current	Cape Otway	Adelaide	40%	-0.7	-0.4	
		EB	South Australian Current	Adelaide	Cape Otway	40%	+0.9	+0.5	-0.1
			Flinders Current	Cape Otway	Cape Howe	36%	-0.2	-0.1	
		NB	Eastern Australia Current	Cape Howe	Port Botany	24%	-1.8	-1.0	
D	149	NB	Eastern Australia Current	Port Botany	Newcastle	100%	-1.8	-1.0	-1.0
		SB	Eastern Australia Current	Newcastle	Port Botany	100%	+5.4	+2.9	+2.9

(1) NB = northbound; SB = southbound; EB = eastbound; WB = westbound.

(2) 0 = neutral current; positive value = assisting current; negative value = opposing current.

The direction and speed of currents vary seasonally and by location. For this study, the speeds of the main currents were estimated as average values. Some downward adjustments were made to the speeds of opposing currents, given a vessel would tend to steer to weaker flows (typically inshore) in order to save fuel. For each route and direction of travel, the overall speed of the current was then determined as a distance-weighted value.

Table A.1 in Appendix A shows the route distance by transport mode including connector roads.

3.4 Cargo

Like travel distance, cargo capacity and cargo density are key variables in this study. Cargo capacity can be expressed in terms of mass or volume, whereas density is expressed using both mass and volume (kg/litre).

Together they determine the amount of cargo that can be carried on a trip by a particular transport mode. The maximum payload of a transport mode (mass or volume) is then governed by the total (allowable) mass limits and the density of the cargo being transported. Two types of cargo were considered in this study.

- Refined product (bulk liquid) were considered to be a refined fossil fuel with a density varying between 0.74 kg/l (petrol) and 0.88 kg/l (biodiesel), i.e. (U: 0.74, 0.88) (Smit *et al.*, 2021).
- Container freight were expressed as TEU (Twenty-foot Equivalent Unit), which is the industry standard. One TEU has a volume of about 33.0 m³ (MPC, 2026; Krispin, 2026), but total TEU mass varied with the type of cargo transported. The empty mass of a 20-foot container is approximately 2.2 – 2.4 t, with a maximum payload of about 28 t, so a maximum combined mass of about 30 t per TEU (CHS, 2026). In the shipping sector, homogenous capacity is defined as the number of containers that a vessel will typically be able to load, assuming an average mass of 14 tons per TEU (MPC, 2026).⁷ For the purposes of this study, the relative

⁷ Because 20-foot containers are relatively small, they are mainly used for dense and heavy cargo that breach mass limits before volume limits, improving safety, load balance and handling efficiency. TEU mass can vary significantly between say 5 t and 30 t. The cargo density for containers then varies approximately between 0.15 and 0.91 kg/l. However, the variability and uncertainty in the average load for 500 – 1000 TEUs will be substantially lower.

standard error was assumed to be about 5%, which translated to a plausible range of $\pm 15\%$. The input distribution for the average TEU, including the empty mass, was thus defined as a truncated normal distribution ($N: 14.0, 0.7$) with a plausible range of 11.9 – 16.1 tonnes. The cargo density for containers then varied between 0.36 and 0.49 kg/l, and was typically 0.42 kg/l.

The cargo capacity varies between transport modes in terms of total mass and volume limits. So, either total payload mass or total volume will limit the total amount of cargo that can be transported on a trip within a particular transport mode. This aspect was explicitly modelled. Since this is a probabilistic analysis, cargo density was not treated as a fixed and constant value. Cargo density was defined as a distribution, with the uncertainty and variability a function of the type of cargo. Cargo capacity is discussed in the following sections for each transport mode.

3.5 Emission estimation

Emissions are computed for energy cycle aspect m (tank-to-wheel, TTW, or well-to-wheel, WTW) in different steps, i.e. as total trip emissions (Equation 1) and as total trip emissions normalised for tonne-kilometres (Equation 2).

$$E_{i,j,k} = 1E^{-3}(\varepsilon_{j,m}\delta_{j,k}\theta_{j,k}d_{i,j}) + 1E^{-3}(\rho_j\varepsilon_{j,m}\delta_{j,\text{empty}}d_{i,j}) + 1E^{-3}(\varepsilon_{\text{road},m}\delta_{j,k}\theta_{j,k}d_{i,\text{road}}^*) \quad \text{Equation 1}$$

$$E_{i,j,k,(\text{tkm})} = 1E^{+3} E_{i,j,k} \div L_j (d_{i,j} + d_{i,\text{road}}^*) \quad \text{Equation 2}$$

$E_{i,j,k,m}$	total emissions for route i , transport mode j , cargo type k and energy cycle aspect m (kg CO ₂ -e)
$E_{i,j,k,m,(\text{tkm})}$	normalised total emissions for route i , transport mode j , cargo type k and energy cycle aspect m (g CO ₂ -e/tkm)
$\varepsilon_{j,m}$	emission factor for transport mode j and energy cycle aspect m (g CO ₂ -e/km)
$\delta_{j,k}$	vehicle load correction factor for transport mode j and cargo type k (-)
$\theta_{j,k}$	cargo spillover factor for transport mode j and cargo type k (-)
$d_{i,j}$	total route distance for route i and transport mode j (km)
$d_{i,\text{road}}^*$	total additional road connector route distance for route i (km) for transport mode j (i.e. rail and shipping)
ρ_j	proportion of unladen travel for transport mode j (-)
L_j	freight cargo load for a trip with transport mode j (t)

All the input variables are modelled as input distributions with one million values, rather than single values.

3.6 Sea freight

Cargo can be transported by either short-sea (coastal) or deep-sea (ocean) shipping. Domestic shipping routes for container ships and bulk liquid tankers are currently mainly delivered by large vessels on international routes that incorporate a domestic leg into their routes, which links large Australian ports like Brisbane, Sydney and Melbourne. International shipping lines are generally increasing in vessel size, although there can be practical limitations.⁸

Domestic sea freight in Australia is currently mainly involved in transporting bulk cargo, which has accounted for about 90% of total tonne-kilometres in recent years (BITRE, 2025). There is also substantial domestic shipping across the Bass Strait. In coastal shipping, relatively small vessels travel along coasts or inland waterways and they can visit smaller ports. Container vessels are typically in the range of 500 to 15,000 deadweight tonnage (DWT) or with a container capacity of less than 3,000 TEUs. They may have their own cranes or roll on-roll-off capacity to increase their versatility.

Until recently, Australia had a fleet of domestic bulk liquid tankers, which distributed refined petroleum and other bulk liquids around the coast. These ranged in size from the *Stolt Australia* (9,900 DWT) to the *British Fidelity* (46,800 DWT).⁹ International import product tankers can be as large as 80,000 DWT or larger.

⁸ For instance, Melbourne's channel depth limits their size to Panamax (Smit and Boulter, 2024b).

⁹ Information supplied by the Maritime Union of Australia: The *British Fidelity* was the last domestically-operating Australian tanker and removed from the Australian domestic trade in 2016. Other Australian tankers of a similar size included the *British Loyalty*, *Alexander Spirit*, *Hugli Spirit*, and *Tandara Spirit*. The *Stolt Australia* was mainly used for sulfuric acid (not refined petroleum). It was removed from the Australian trade in 2006.

Various methods are available for estimating fuel consumption and emissions from ships. For this study, the Maritime Transport Emission Model (MTEM), developed for the Australian ocean-going vessel fleet, was used to calculate emissions for shipping. The model is based on an extensive literature review and analysis of available data (Smit and Khan, 2019). MTEM is an energy-based ship emissions model. It requires input data for a range of ship characteristics (vessel size, speed, service speed, mix of fuel types, emission certification, maximum continuous rating, and emission control technology). MTEM firstly estimates fuel and energy use for different types of main engine (e.g., slow, medium, high-speed diesel engines and gas or steam turbines), auxiliary engines and boilers and subsequently uses fuel-based emission factors (g/kg fuel) to estimate air pollutant and greenhouse gas emissions (CO_2 , CH_4 and N_2O) (Smit *et al.*, 2022; Smit 2023).

Sea transport is characterised using reference transport units, which are defined as representative ships. As discussed before, two common ship types were considered for four routes, i.e. container vessels and refined product tankers of different size. Refined product tankers move unpacked liquid cargo in bulk. Container ships move packed cargo in standard 20-foot (or 40-foot) containers. DNV provided TER with relevant ship specifications for randomly selected ships in each category with a keel laid date of January 2015 or later. For container ships, two vessels were selected with a cargo capacity of about 500 and 1000 TEU and an example is shown in Figure 6.



Figure 6 – Example of a representative 1100 TEU container ship (Photo: © Wong-Wei-Po).

For refined product tankers, two vessels were selected with a cargo capacity of about 20,000 and 45,000 DWT and an example is shown in Figure 7.



Figure 7 – Example of a representative 48,000 DWT refined product tanker (Photo: © Wong-Wei-Po).

MTEM typically uses detailed information on ship movements from high-resolution terrestrial or satellite Automatic Identification Systems (AIS) (e.g. TER, 2025). For this analysis, the operational inputs were simplified. The ship operation profile was defined in terms of two fundamental modes of operation: (i) time at berth (the vessel is moored) for cargo loading or unloading, and (ii) in-transit cruising conditions.¹⁰

The Australian Maritime Safety Authority (AMSA) surveyed ship operations in Australian waters. Analysis of the survey data found that the average time spent at berth was 33 hours, with a 95% confidence interval of 28 – 39 hours (Smit 2023). Time spent at berth was therefore approximated using a normal distribution, truncated at 28 and 39 hours (**N**: 33, 3). For transit conditions, a plausible range of speeds was used to simplify the analysis, rather than a detailed analysis of AIS data. The service speed was taken as the maximum plausible speed.¹¹ The practice of “slow steaming” is increasingly applied in less time-sensitive shipping operations (particularly for larger vessels) to save on fuel costs. We have assumed that the lower end of plausible transit speeds is 75% of service speed. Operational speeds were therefore defined as uniform distributions, with a minimum and maximum transit speed of 75% and 100% of the vessel-specific service speeds (v_{ss}), respectively (**U**: $0.75 v_{ss}$, v_{ss}). The Bernoulli distribution was used to allocate distance-weighted current speeds (Section 3.3, Table 1) to each simulation. The ratio of the corrected (variable) speed (speed of vessel at sea minus speed of current) to the speed of vessel at sea was then used to correct the travel distance for each route.

The uncertainty (plausible range) in the tank-to-wake emission factors from MTEM was modeled as a normal distribution (**N**: 100%, 5%), truncated at 85% and 115% (Smit and Boulter, 2024b). For ships, well-to-tank emissions due to the extraction, transport, production and distribution of fuels (e.g., heavy fuel oil, marine distillate oils, and marine gas oils) were modeled as an energy or emissions penalty. The literature suggests that fossil fuel combustion typically dominates WTW emissions for ships, translating into a TTW multiplier that varies between 1.11 and 1.19. The multiplier was, therefore, defined as a uniform distribution (**U**: 1.10, 1.20) and was applied to the ship TTW emissions to estimate WTW emissions.

Figure 8 shows the variability in simulated mean fuel consumption rates (kg/km) for the four ship types as a function of average journey speed over different routes. Fuel consumption includes both stationary and moving conditions. The short sea route (Port Botany – Newcastle) has a distinct and significantly higher average fuel consumption per kilometre of travel when compared with the other longer routes, which is visible as two separate areas in Figure 8. This is caused by a relatively high contribution of fuel consumption in stationary conditions (berth). There are measures that can reduce this effect such as shore power (cold ironing), but this is outside the scope of this study.

The considerations and assumptions for other model input variables are listed in Appendix B (B.1 Shipping).

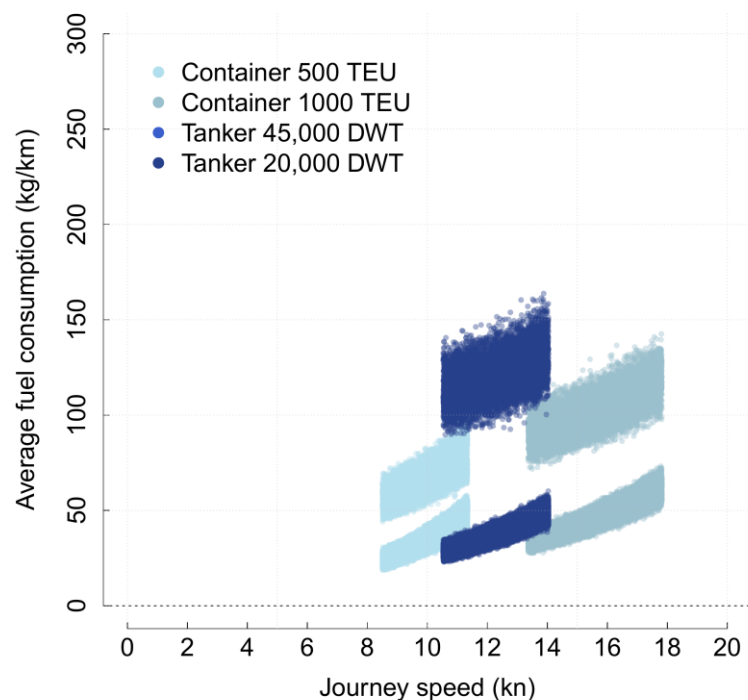


Figure 8 – Average fuel consumption for four ship types over four routes as a function of mean journey speed, including fuel consumption at berth.

¹⁰ Two other modes of operation were excluded: (i) manoeuvring, which typically occurs over short periods, and (ii) at anchor, which has similar emissions behavior to being at berth (excluding the impacts of cold ironing). In a future study, a more comprehensive consideration of all operating modes and typical proportions of time spent could be included.

¹¹ Service speed is defined as the speed a vessel can maintain at sea in normal weather conditions and at normal service draught.

3.7 Road freight

For road freight transport, the reference vehicle was an articulated GML¹² Tri-Axle B-double diesel truck with a gross combination mass limit (GCM¹³) of 63 t and a tare mass of 24 t (Figure 9).



Figure 9 – Example of a GML Tri-Axle B-Double diesel truck selected as a representative vehicle for road in this study (Photo: Icons Australia/Alamy).

Fleet-average emission factors for road freight were estimated using the Australian Fleet Model (AFM) and the Net Zero Vehicle Emission Model (n0vem). The AFM simulates future growth and turnover for the on-road fleet to 2060 and estimates the vehicle population and total travel activity (VKT).¹⁴ The AFM was used to create detailed input files for n0vem providing a breakdown of the Australian on-road fleet in 2030. In contrast to passenger vehicles, battery electric and fuel cell electric (hydrogen) trucks are expected to have an insignificant amount of travel in the freight sector in 2030 (<1%).¹⁵

The n0vem tool was released in 2022 and incorporates the established COPERT Australia software (v1.3.5) for internal combustion engine vehicle (ICEV) emission modeling. n0vem expands the emission estimation to non-ICEV technologies, namely, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel-cell electric vehicles (FCEVs). Using the results from n0vem, the fleet average tank-to-wheel greenhouse gas emission factor for the articulated GML Tri-Axle B-double diesel truck is modelled as a truncated normal distribution (N: 1620, 26), with a plausible range of 1542 – 1698 g CO₂-e/km. The simulation of variable payload changes total vehicle mass, which in turn affects energy use and emissions for trucks.

¹² GML stands for General Mass Limits or the heavy vehicle general axle mass limits prescribed in the Heavy Vehicle National Law (HVNL) that applies to public roads in Australia, unless otherwise limited by load restriction signs. Under standard Australian rules, limits vary based on the General Mass Limits (GML), Concessional Mass Limits (CML) and Higher Mass Limits (HML).

¹³ GCM is the maximum of the sum of the gross vehicle mass (GVM, total load the truck can legally carry on its own wheels) of the drawing vehicle plus the sum of the trailer axle loads that may lawfully be driven on road. So GCM is the total mass of the truck, trailer and their loads combined.

¹⁴ The model is designed to provide fleet data at the level of detail required for emission modeling, and generates estimates for 15,200 individual vehicle classes in past, current, and future years. The AFM emulates complex patterns in vehicle fleet turnover by considering on-road populations, sales data, usage profiles, growth, and scrappage.

¹⁵ It is noted that the 2024 mode shift study considered that the situation would be significantly different in 2050, when the vehicle-km travelled (VKT) share of electric trucks was forecasted to be 55%. For the year of interest in this study (2030), however, the impacts of electrification are unlikely to be of significance.

The impact of changing vehicle mass on the TTW emission factor was estimated with the nOvem estimates emissions, fuel consumption (petrol, E10, diesel, liquefied petroleum gas, and hydrogen), and energy/electricity use (kWh consumed).¹⁶ It was assumed that 5% of the trip occurred in urban driving conditions, 5% in rural driving conditions, and 90% in uncongested highway driving. nOvem load correction algorithm. A significant fraction of articulated truck kilometres (about 30%) is classified as unladen (ABS, 2020) and this was accounted for in the emissions impact assessment, assuming a proportion of unladen kilometres varying between 25% and 35% (**N**: 0.30, 0.02) and a load correction to simulate an empty B-double. The considerations and assumptions for other model input variables are listed in Appendix B (B.2 Road).

3.8 Rail freight

Diesel trains were considered for rail freight transport. Average gross train mass was calculated based on assumptions for the mass of locomotives, wagons (unladen), empty containers and freight payload, balanced according to the reference train length, and masses for inland rail (Smit and Boulter, 2024a), as shown in Figure 10. The modelled diesel freight train consisted of 3 locomotives and 75 wagons, with a total length of almost 2 km.

The average tank-to-wheel greenhouse gas emission factor for rail freight was modelled as a truncated normal distribution (**N**: 37,864, 2,000), with a plausible range of 31,865 – 43,863 g CO₂-e/km. The simulation of variable payload changed total train mass, which in turn affected energy use and emissions for rail. The impact of changing train mass on the TTW emission factor was estimated with a load correction algorithm.



Figure 10 – Example of a diesel train selected as a representative vehicle for rail this study (Photo: David Wall/Alamy).

Like road transport, a significant fraction of train kilometres was assumed to be unladen and this was accounted for in the emissions impact assessment. Similar to road transport, a proportion of unladen kilometres was assumed to vary between 25% and 35% (**N**: 0.30, 0.02) and a load correction was applied to simulate an empty train. The considerations and assumptions for other model input variables are listed in Appendix B (B.3 Rail).

¹⁶ It takes into account vehicle year of manufacture, weight and size, as well as expected emission and energy efficiency improvements out to 2060. They include vehicle speed dependencies (driving behavior and congestion level), hot running emissions, and additional emissions due to engine start, air conditioning, engine oil, and NO_x emission-control technology (e.g., selective catalytic reduction). Meteorological input data (ambient temperature and humidity) for Australia were sourced from previous research. Around two million emission factors (g/km), fuel use factors (g/km, MJ/km), and electricity/energy use factors (kWh/km) are generated, covering different operational conditions and emission types.

4. Multi-modal emissions performance assessment

The simulation for the three transport modes resulted in the creation of 1141 input and output files, with each file containing one million data points. The assessment in Section 4.1 and 4.2 compares the WTW greenhouse gas emissions performance for each transport mode, normalised for load and distance (i.e. grams of CO₂-e emitted per tkm) for the four routes in 2030. Section 4.3 estimates potential fuel savings for mode shift from road to maritime transport.

The WTW CO₂-e emissions performance has been estimated for each route and transport mode after running a probabilistic simulation, as was discussed in previous sections. Where appropriate, the modelling assumptions aligned with our previous research work (Smit and Boulter, 2024a) and were adjusted where necessary. The assessment was split into the two types of cargo (container and bulk). Along with summary statistics, graphical presentations of the emission distributions are also provided.

4.1 Container cargo

Table 2 shows the emission statistics for container transport by transport mode and for the four routes, including the plausible range.

Table 2 – Greenhouse gas performance statistics by transport mode and route for container cargo.

Transport mode	Route	Mean g CO ₂ -e emissions/tkm	Median g CO ₂ -e emissions/tkm	99.7% LCL ⁽¹⁾ g CO ₂ -e emissions/tkm	99.7% UCL ⁽¹⁾ g CO ₂ -e emissions/tkm
Road	All	61	61	54	69
Rail	Brisbane – Cairns	24	24	19	31
	Fremantle - Wyndham	29	28	23	35
	Port Botany – Adelaide	24	24	19	31
	Port Botany – Newcastle	27	27	22	34
Container ship 500 TEU	Brisbane – Cairns	23	22	13	39
	Fremantle - Wyndham	24	23	14	39
	Port Botany – Adelaide	25	24	15	39
	Port Botany – Newcastle	46	45	32	66
Container ship 1000 TEU	Brisbane – Cairns	19	19	11	30
	Fremantle - Wyndham	18	18	11	29
	Port Botany – Adelaide	20	19	13	30
	Port Botany – Newcastle	43	43	32	58

(1) LCL: Lower confidence limit; UCL: Upper confidence limit.

The emission intensities in Table 2 accounted for various aspects of cargo transport that affect the greenhouse performance for each transport mode. As discussed previously, they included the emission penalties due to unladen travel, the impacts of varying cargo loads on emissions per kilometer, the impacts of sea currents on travel distance, the mode-specific maximum cargo capacity in terms of volume and mass (spillover effects) and the impacts of connector roads (rail and shipping only).

Table 2 shows that shipping delivers a substantial reduction (25 – 70%) in the average emission intensity when compared with road transport in all cases.

When compared with rail, more mixed results are found. The actual route significantly affected the emissions performance of sea transport, and this was particularly clear for the short sea route PBT – NWC where rail had the best emissions performance with an emission intensity reduction of about 40% when compared with coastal shipping.

For the other routes, the difference between shipping and rail depended on vessel size. The smaller container ship (500 TEU) performed better than rail on the BNE – CRN and FRM – WYN routes with an emission reduction of 4% and 17%, respectively. On the PBT – ADE route, rail performed slightly better with an emission reduction of 4%. For the larger container ship (1000 TEU), however, shipping consistently provided an emission intensity reduction of about 15 – 35%.

Figure 11 and 12 (next page) visualise the results. Figure 11 presents the results (Table 2) in bar plots side-by-side, including the plausible range (99.7% confidence intervals). Figure 12 shows the emission intensity probability distributions for each route and transport mode.¹⁷ These distributions are the main outputs from this study and they underpin the impact assessment. They show the shape and spread of emission intensities for each transport mode on a particular route and capture the associated variability and uncertainty. Higher probability values (e.g. peaks) mean the corresponding emission intensity values are more common.

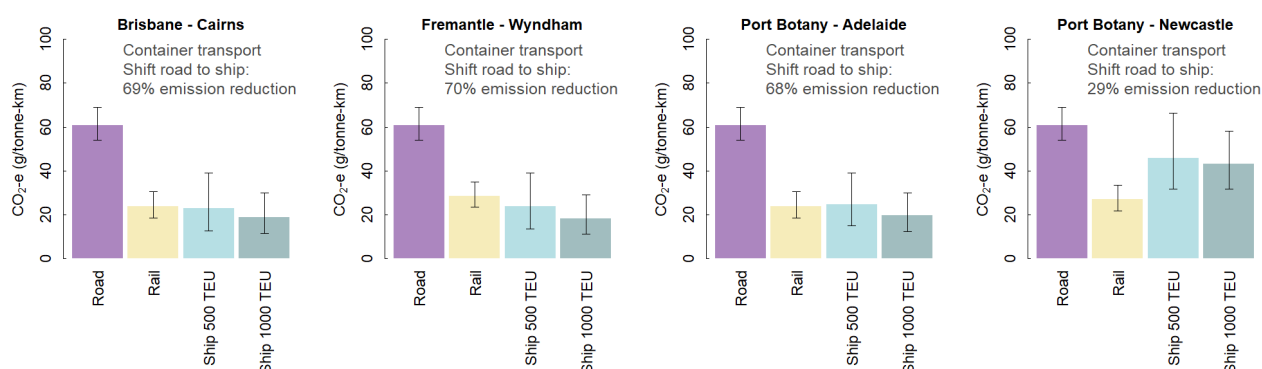


Figure 11 – WTW greenhouse gas emission intensities for container transport by mode and route in 2030, including plausible ranges.

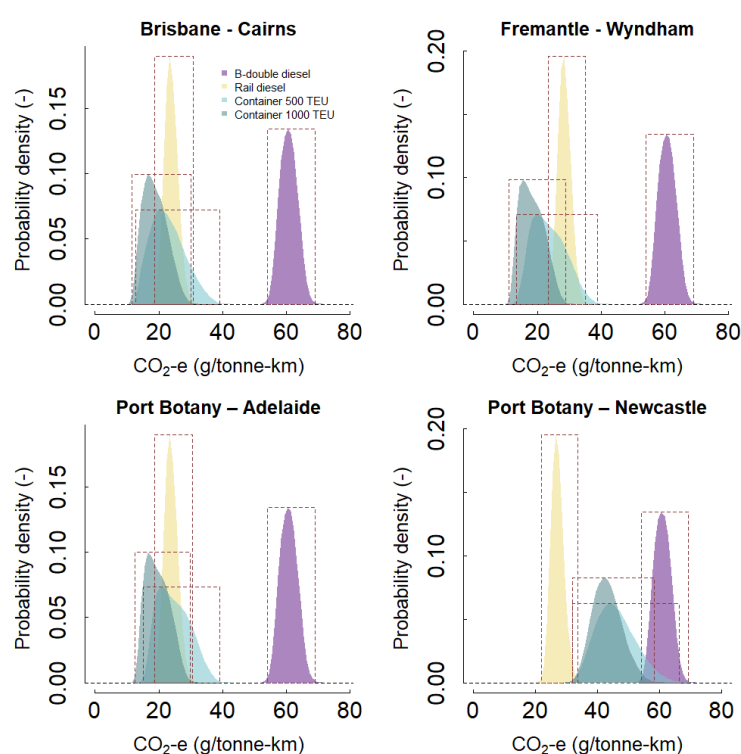


Figure 12 – WTW greenhouse gas emission intensity probability distributions for different container transport modes and different routes in 2030. The boxes with dotted lines outline the areas that define the 99.7% confidence intervals (x-axis) and the maximum probability (y-axis) for each distribution.

¹⁷ These distributions do not only indicate central tendencies, but also capture the variability and uncertainty arising from the variations in the various input variables. The probability density plot thus shows the shape and spread of the outputs using a smooth curve instead of discrete bars. The x-axis displays the scale and range of the emission intensities. The y-axis height represents the probability density of data points, where higher density values mean the corresponding emission intensity values are more common. The total area under the curve always equals 100%.

4.2 Bulk liquid cargo

Table 3 shows the emission statistics for bulk liquid cargo transport by transport mode and for the four routes, including the plausible range. Figure 13 and 14 (next page) visualise the results. Figure 13 presents the results (Table 3) in bar plots side-by-side, including the plausible range (99.7% confidence intervals). Figure 14 shows the emission intensity distributions for each route and transport mode.

Table 3 – Greenhouse gas performance statistics by transport mode and route for bulk liquid cargo.

Transport mode	Route	Mean g CO ₂ -e emissions/tkm	Median g CO ₂ -e emissions/tkm	99.7% LCL ⁽¹⁾ g CO ₂ -e emissions/tkm	99.7% UCL ⁽¹⁾ g CO ₂ -e emissions/tkm
Road	All	72	71	61	84
Rail	Brisbane – Cairns	20	20	17	24
	Fremantle - Wyndham	27	27	23	31
	Port Botany – Adelaide	20	20	17	24
	Port Botany – Newcastle	24	24	21	29
Tanker 20,000 DWT	Brisbane – Cairns	12	11	7	19
	Fremantle - Wyndham	11	10	6	17
	Port Botany – Adelaide	12	12	8	18
	Port Botany – Newcastle	38	38	29	51
Tanker 45,000 DWT	Brisbane – Cairns	8	8	5	13
	Fremantle - Wyndham	7	7	4	11
	Port Botany – Adelaide	8	8	5	13
	Port Botany – Newcastle	28	27	21	36

(1) LCL: Lower confidence limit; UCL: Upper confidence limit.

Shipping of bulk liquid cargo delivered large reductions in the average emission intensity when compared with road transport in all cases, varying from about 45 – 90%, which was larger than the emission reductions for container ships discussed in Section 4.1.

When compared with rail, mixed results are again found. For the short sea route PBT – NWC rail again had the best emissions performance, with an emission intensity reduction of about 10 – 35% when compared with coastal shipping. For the other routes, however, shipping provided an emission intensity reduction of about 40 – 75%, with the largest reductions found for the larger 45,000 DWT tanker.

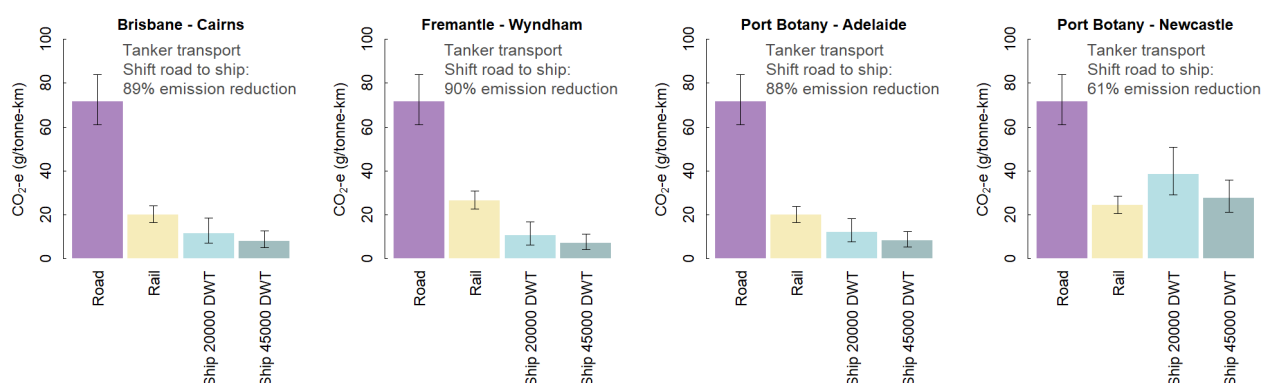


Figure 13 – WTW greenhouse gas emission intensities for bulk liquid transport by mode and route in 2030, including plausible ranges.

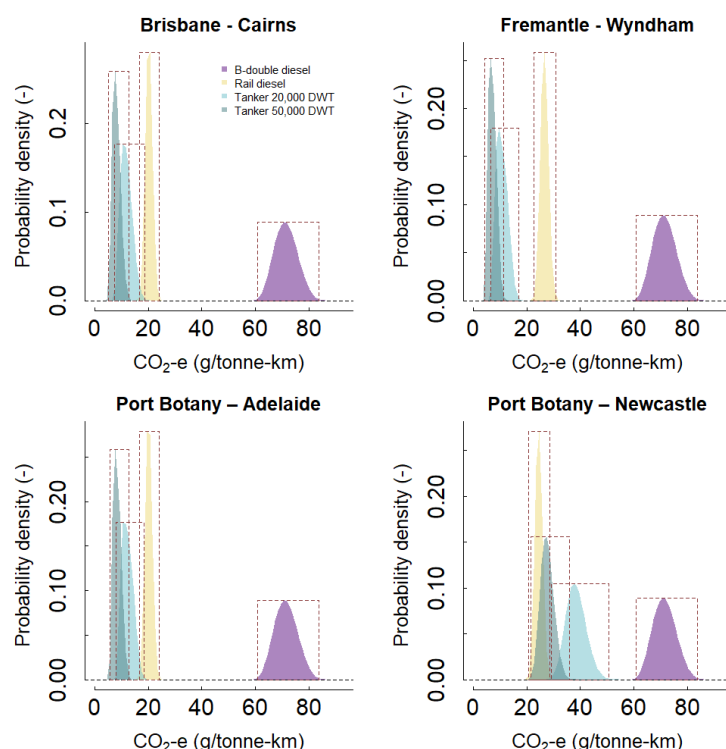


Figure 14 – WTW greenhouse gas emission intensity probability distributions for different bulk liquid transport modes and different routes in 2030. The boxes with dotted lines outline the areas that define the 99.7% confidence intervals (x-axis) and the maximum probability (y-axis) for each distribution.

4.3 Potential fuel savings through mode shift

The simulation results for GHG emissions were used to estimate potential fuel savings that could be achieved with mode shift from road to shipping. The mean WTW GHG emissions performance (g CO₂-e/tkm) discussed in the previous sections was converted into average TTW fuel consumption factors (g fuel/tkm), assuming the use of ultra-low sulphur diesel for road and rail transport¹⁸ and marine fuels for shipping (e.g. HFO, IFO, MDO, MGO, IFO, VLSFO). The fuel consumption factors were then multiplied with a hypothetical amount of cargo that would be transported on the different routes:

- 1000 TEUs representing a single trip with the largest container vessel considered in this study
- 38,250 t of bulk liquids representing a single trip with the largest product tanker considered in this study.¹⁹

The results are shown in Table 4 and 5.

Table 4 – Average TTW fuel savings by mode shift of 1000 TEUs from road to shipping for different routes.

Route	Road distance km	Sea distance km	Road * t diesel fuel	Ship 1000 TEU t marine fuel	Fuel saving	
					t fuel	%
Brisbane – Cairns	1,694	1,544	376	113	263	70%
Fremantle - Wyndham	3,207	3,311	712	236	476	67%
Port Botany – Adelaide	1,375	1,882	305	143	162	53%
Port Botany – Newcastle	168	168	37	28	9	25%

* As discussed in Appendix B.2, the articulated GML Tri-Axle B-double diesel truck transports 3 TEUs per laden trip.

¹⁸ Diesel which is refined to the specifications set out in the *Australian Fuel Quality Standards Act*, and meets Australian emissions and taxation requirements to be used for road transport.

¹⁹ i.e. 85% of 45,000 DWT for the largest bulk liquid tanker considered in this study.

Table 5 – Average TTW fuel savings by mode shift of 38,250 t bulk liquids from road to shipping for different routes.

Route	Road distance km	Sea distance km	Road t diesel fuel	Ship 45,000 DWT t marine fuel	Fuel saving	
					t fuel	%
Brisbane – Cairns	1,694	1,544	1,208	130	1,078	89%
Fremantle - Wyndham	3,207	3,311	2,287	246	2,041	89%
Port Botany – Adelaide	1,375	1,882	981	165	816	83%
Port Botany – Newcastle	168	168	120	49	71	59%

Mode shift from road to coastal shipping means a shift from the use of road diesel (available at e.g. service stations) to marine fuels. Marine fuels are not covered by the Australian *Fuel Quality Standards Act*, and ships over 400 GT operating domestically can buy bunker fuel without fuel excise. Standards for marine fuels are regulated by *MARPOL Annex VI*, implemented domestically through the *Protection of the Sea (Prevention of Pollution from Ships) Act 1983* and *Marine Order 97* and administered by the Australian Maritime Safety Authority (AMSA). This means that marine fuels cannot be used on Australian roads.

The tables show that a shift from road to sea transport can also deliver significant savings in total fuel consumption for both types of cargo of about 25% to 90%, depending on the route. In addition to these savings almost all road diesel would be ‘saved’ through mode shift to ships, as it is replaced with heavier types of marine fuels. Because marine fuels are produced to different refinery requirements than road diesel, they are also part of different supply chains and subject to different supply pressures.

These results generally aligned well with the greenhouse gas emission reductions discussed in Section 4.1 and 4.2. The only exceptions were the fuel savings in tonnes that were estimated for the Port Botany to Adelaide route, where the fuel savings were 53% (containers) and 83% (bulk liquids). These were lower than the greenhouse gas emission savings per tonne-km discussed in the previous sections, i.e. 68% and 88%, respectively.

The fuel estimates required travel distance as an input, which meant that the difference in travel distance between road and sea transport affected the results. Sea transport required a significantly longer trip for the Port Botany to Adelaide route of almost 40%, as is shown in table 4 and 5. This reduced the beneficial effect of a shift from road to maritime transport on fuel savings to some extent, but significantly less than the substantially longer route would have suggested.

Another notable difference was found for the type of cargo where container trucks used the available mass capacity, resulting in fully loaded trucks. For bulk liquids, the maximum amount of cargo was limited by the maximum volume capacity. They were therefore not fully loaded in terms of mass. As a consequence, the B-double road tanker combinations were, on average, less fuel efficient per tonne-km than container transport. This further contributed to the benefits of maritime transport.

A overview of typical emission and fuel consumption results for all ship types and sizes is shown in Table 6. In terms of TTW fuel savings, this study found that a shift of freight transport from road to maritime can potentially shift significant volumes of diesel fuel currently used by road transport to marine fuels. This would also result in significant to large reductions in total fuel consumption, depending on the Australian route and type of ship.

Table 6 – Typical reductions in WTW GHG emissions and TTW fuel consumption by a shift from road to maritime transport for short and longer Australian freight routes in 2030.

Route	WTW GHG emission performance – short route 170 km % reduction in g CO ₂ -e/tonne-km	WTW GHG emission performance – routes > 1400 km % reduction in g CO ₂ -e/tonne-km	TTW fuel consumption – short route 170 km % reduction in total tonne fuel used	TTW fuel consumption – routes > 1400 km % reduction in total tonne fuel used
500 TEU container ship	25%	60%	20%	55%
1000 TEU container ship	30%	70%	25%	60%
20,000 DWT bulk liquid tanker	45%	85%	45%	80%
45,000 DWT bulk liquid tanker	60%	90%	60%	85%

5. Conclusions

The domestic transport sector has become a more important source of greenhouse gas emissions over time. The sector as a whole contributed about 10% to total emissions in 1990, but by 2024 it had more than doubled to 21%. When looking more specifically at freight, the Australian domestic freight task has experienced strong growth, with road and rail freight now dominating domestic freight activity. In 2025, coastal shipping made up a little over ten percent of the total freight task. This confirms that there may be significant emission-reduction potential for a shift from land-based transport to maritime transport in the Australian freight sector.

The Maritime Union of Australia (MUA), in collaboration with Maritime Industry Australia Limited (MIAL) and supported by the Energy Futures Foundation, has contracted Transport Energy/Emission Research (TER) to assess the greenhouse gas emission-reduction potential of a shift of freight from road and rail transport to maritime transport in 2030. This study considers all emissions related to fuel production and use, referred to as well-to-wheel/wake (WTW) emissions. Given the complex, dynamic and location-specific nature of mode shift impacts, it is important that the uncertainty and variability in emission estimates were explicitly quantified. TER has developed an innovative, fast and cost-effective WTW assessment tool to do this. All the input variables are modelled as input distributions with one million values, rather than single values.

The probabilistic approach estimates the plausible range in emissions performance and their chance of occurrence. This provides useful insight into the robustness of study outcomes and supports cost-effective real-world implementation of mode shift policies and measures.

The emission-reduction potential was assessed for four specific freight routes for maritime vessels in Australia and then compared with the alternative road and rail options. The shipping and rail routes were supplemented with connector road routes to link port or railway station locations to the generic origin or destination point within the city centre. The impacts of ocean currents on emissions were also included in the simulation.

Two types of cargo were considered, i.e. refined fossil fuel product (bulk liquid) and container freight. The cargo capacity varies between transport modes in terms of total mass and volume limits. So, either total payload mass or total volume will limit the total amount of cargo that can be transported on a trip with a particular transport mode. This aspect was explicitly modelled.

Two common ship types were considered. For container ships, two vessels were selected with a cargo capacity of about 500 and 1000 TEU. For refined product tankers, two vessels were selected with a cargo capacity of about 20,000 and 45,000 DWT. For road freight transport, the reference vehicle was an articulated GML Tri-Axle B-double diesel truck. The modelled diesel freight train consisted of 3 locomotives and 75 wagons, with a total length of almost 2 km.

The Maritime Transport Emission Model (MTEM), developed for the Australian ocean-going vessel fleet, was used to calculate emissions for shipping. Emissions for road freight were estimated using the Australian Fleet Model (AFM) and the Net Zero Vehicle Emission Model (n0vem). Emissions for rail were based on previous research work conducted by the authors.

The simulation for the three transport modes resulted in the creation of 1141 input and output files, each containing one million data points. These data were then used to assess the mode shift impacts on the well-to-wheel/wake greenhouse gas emissions performance for each transport mode, normalised for load and distance (i.e. grams of CO₂-e emitted per tkm). The results showed that the mode shift impacts depend on the specific route, the type of cargo, the transport mode and the vessel size.

- Container transport – Shipping delivered substantial reductions when compared with road transport on all routes, varying from about 25 – 70%. Rail had the best emissions performance for the shortest route with an emission intensity reduction of about 40% when compared with coastal shipping. For the smaller container ship (500 TEU), shipping provides an emission intensity reduction or increase between -17% to +4%, depending on the actual route. For the larger container ship (1000 TEU), shipping provides an emission intensity reduction for all routes of about 15 – 35%.

- Bulk liquid transport – Shipping of bulk liquid cargo delivers large reductions in the average emission intensity when compared with road transport in all cases, varying from about 45 – 90%. For the shortest sea route, rail had again the best emissions performance with an emission intensity reduction of 10 – 35% when compared with coastal shipping. For the other routes, however, shipping provides an emission intensity reduction of about 40 – 75%, with the largest reductions found for the larger tanker.
- In terms of TTW fuel savings, this study also found that a shift of freight transport from road to maritime can potentially shift significant volumes of diesel fuel currently used by road and rail to marine fuels. This may also result in reductions in total fuel use from 25% to 90%, depending on the Australian route.

The results of this study accounted for various aspects of cargo transport that affect the greenhouse performance and fuel consumption for each transport mode. They include the emission penalties due to unladen travel, the impacts of varying cargo loads (mass) on emissions per kilometer, the impacts of ocean currents on travel distance, the mode-specific maximum cargo capacity in terms of volume and mass (freight cargo spillover effects) and the impacts of connector roads (rail and shipping only).

This study found that a potential shift to coastal shipping can deliver a significant to large reduction in the mean WTW greenhouse gas emission intensity and fuel consumption for road transport, on all routes and for all vessel sizes that were considered in this study. For rail transport the results were more mixed. Coastal shipping could provide significant reductions in the mean WTW greenhouse gas emission intensity for rail on the conditions that both the route was long enough and the vessel cargo capacity was large enough.

The Federal government's *Transport and Infrastructure Net Zero Roadmap and Action Plan* (DITRDSCA, 2025) refers to mode shift of freight to rail to reduce emissions and includes a section on shipping and ports (Section 3.4) that focuses on low and zero emission fuels, electrification and operational measures. This study finds that current maritime transport technology can offer similar or in several cases probably greater reductions in greenhouse gas emissions than rail when conventional fuels (ultra-low sulphur diesel for road and rail and marine fuels for shipping) are considered. There may also be other benefits from establishing new coastal transport options that currently do not exist, such as enhancing Australia's transport resilience and strengthening supply chains (e.g. CoA, 2023).

Finally, this study focused on conventional maritime engines and machinery that use marine fuels (e.g. HFO, IFO, MDO, MGO) for propulsion, on-board electricity generation and heat. Lower emission options for shipping such as low carbon liquid fuels (e.g. methanol, ammonia), battery electric ships and shore power may be assessed in a future and separate study, which would also include low and zero emission options for rail and road.

Moreover, a more comprehensive consideration of all operating modes and typical proportions of time spent in these modes (e.g. AIS data analysis), could also be included. Finally, the study could be expanded to account for other aspects such as costs and air quality impacts.

6. References

- ABS, 2020. *Survey of Motor Vehicle Use*, Australian Bureau of Statistics (ABS), www.abs.gov.au.
- AMSA, 2026. *Vessel Traffic Data 2026*, Australian Maritime Safety Authority, <https://www.operations.amsa.gov.au/spatial/DataServices/DigitalData>.
- BITRE, 2022. *Australian Aggregate Freight Forecasts – 2022 Update*, Bureau of Infrastructure and Transport Research Economics (BITRE), Research Report 154, November 2022, ISBN 978 1 922521 80 4.
- BITRE, 2025. *Australian Infrastructure and Transport Statistics - Yearbook 2025*. Bureau of Infrastructure and Transport Research Economics (BITRE), <https://www.bitre.gov.au/publications/2025/australian-infrastructure-and-transport-statistics-yearbook-2025>.
- CHS, 2026. *Weight of Containers – Empty Weight, Payload and Total Weight Explained Simply*, <https://chs-containergroup.com/de/en/shipping-container-weights/>.
- CoA, 2023. *Strategic Fleet Taskforce*, Commonwealth of Australia, INFRASTRUCTURE 6080, November 2023, ISBN 978-1-922879-09-7, <https://www.infrastructure.gov.au/sites/default/files/documents/strategic-fleet-taskforce-final-report.pdf>.
- Cresswell, G., Domingues, C.M., 2009, *Leeuwin Current*, Encyclopedia of Ocean Sciences (2nd Edition), 444-454, Academic Press.

- Cresswell, G.R., Peterson, J.L., Pender, L.F., 2017. The East Australian Current, upwellings and downwellings off eastern-most Australia in summer, *Mar. Freshwater Res.*, 68 (7): 1208–1223.
- DCCEEW, 2026. *Australia's National Greenhouse Accounts*, Australian Government, Department of Climate Change, Energy, the Environment and Water, <https://www.greenhouseaccounts.climatechange.gov.au/>.
- DITRDCA, 2025. *Transport and Infrastructure Net Zero Roadmap and Action Plan, Transport Sector Plan*, Department of Infrastructure, Transport, Regional Development, Communications, Sport and the Arts (DITRDCA), September 2025, <https://www.infrastructure.gov.au/department/media/news/transport-and-infrastructure-net-zero-roadmap-and-action-plan-released>.
- Duran, E.R., Phillips, H.E., Furue, R., Spence, P., Bindoff, N.L., 2020, Southern Australia Current System based on a gridded hydrography and a high-resolution model, *Progress in Oceanography*, 181, February 2020, 102254.
- GA, 2021. Foundation Rail Infrastructure, GeoScience Australia, https://services.ga.gov.au/gis/rest/services/Foundation_Rail_Infrastructure/MapServer.
- GA, 2024. National Roads MetaData statement, GeoScience Australia, <https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/147684>.
- Krispin, B., 2026. *TEU vs FEU: choosing the right container unit for freight planning*, 16 February 2026, <https://wisor.ai/teu-vs-feu/>.
- MPC, 2026. *MPC Container Ships Industry terms*, <https://www.mpc-container.com/about-us/industry-terms/>.
- Smit R., Khan F., 2019. Shipping fuel consumption and emissions modelling in fourteen port areas, 23rd *Transport and Air Pollution Conference*, Thessaloniki, Greece.
- Smit, R., Mellios, G., Paisiou, G., 2021. *The Impact of Australia's New Fuel Quality Standards on Australian Vehicle Emission Factors*, Brisbane: Department of Environment and Science, Queensland Government.
- Smit, R., Chu-Van, T., Suara, K., Brown, R.J., 2022. Comparing an energy-based ship emissions model with AIS and on-board emissions testing, *Atmosph Environ X*, 16:1-13.
- Smit, R., 2023. An analysis of an AMSA ship survey and comparison with the Maritime Transport Emission Model (MTEM), *Atmosph Environ X*, 17:100203.
- Smit, R., Kennedy, D.W. (2022) Greenhouse gas emissions performance of electric and fossil-fueled passenger vehicles with uncertainty estimates using a probabilistic life-cycle assessment, *Sustainability*, 14 (6), 3444, 1-29, <https://doi.org/10.3390/su14063444>, <https://www.mdpi.com/2071-1050/14/6/3444>.
- Smit, R. Helmers, E., Schwingshackl, M., Opetnik, M., Kennedy, D., 2024 Greenhouse gas emissions performance of electric, hydrogen and fossil-fuelled freight trucks with uncertainty estimates using a probabilistic life-cycle assessment (pLCA), *Sustainability*, 16 (2), 762, <https://www.mdpi.com/2071-1050/16/2/762>.
- Smit, R., Boulter, P., 2024a. Impacts of mode shift on well-to-wheel emissions from inter-capital land transport in Australia - Part I: Road and rail transport, *Explora Environ Resour.*, 1 (1), 3470, [doi: 10.36922/eer.3470](https://doi.org/10.36922/eer.3470).
- Smit, R., Boulter, P., 2024b. Impacts of mode shift on well-to-wheel emissions from inter-capital land transport in Australia - Part II: Sea and air transport, *Explora Environ Resour.*, 1 (1), 3471, [doi: 10.36922/eer.3471](https://doi.org/10.36922/eer.3471).
- TER, 2025. *Ship emissions inventory for NSW - Base year 2023*, Transport Energy/Emission Research (TER), Prepared by Robin Smit, Ella Castillo, Daniel Kennedy, 25 February 2025.

7. About TER

Transport Energy/Emission Research (TER) is an Australia-based independent research consultancy that supports government, NGOs and the transport sector in the transition to smart, clean, zero emissions transport.

TER was founded in 2019 and provides a range of services (<https://www.transport-e-research.com/services>), which includes high quality and impartial expert advice, in-depth data analysis and customised tools to quantify fuel consumption, energy use and emissions from the transport sector (road, rail, air and sea).

TER is a networked company and has agreements in place with highly qualified, respected and well-known experts in Australia, Europe, the UK and the United States (<https://www.transport-e-research.com/about-us>). TER projects typically involve a tailored team of national and international experts.

TER also collaborates with a network of global experts, university researchers, consultants and statisticians. This has included work for the Intergovernmental Panel on Climate Change (IPCC), the International Electric Vehicle Technology Collaboration Programme under the International Energy Agency (IEA) framework, the European Research Group on Mobile Emission Sources (ERMES) and EU's Joint Research Centre (JRC).

TER uses a portion of its revenue to fund new and forward-looking research. This includes regular publications in international peer-reviewed scientific journals, making information freely available to anyone with an interest in transport emissions.

From the founder Dr Robin Smit:

We are not your typical engineering or consultancy company. We love numbers and the story they tell. We take pleasure in presenting information clearly and in an insightful way. We are driven by a passion to provide high quality, sound, impartial, independent and evidence-based advice to our clients. We are forward looking and we operate with integrity, do not over-promise and maintain a strong focus on quality, efficiency and attractive pricing.

Appendix A – Freight routes

Table A.1 – Route distance by transport mode including connector roads.

Route	Road distance km	Rail distance km	Sea distance km
BNE – CRN	1,694	1,697	1,544
FRM – WYN	3,207	4,514	3,311
PBT – ADE	1,375	1,807	1,882
PBT – NWC	168	194	168

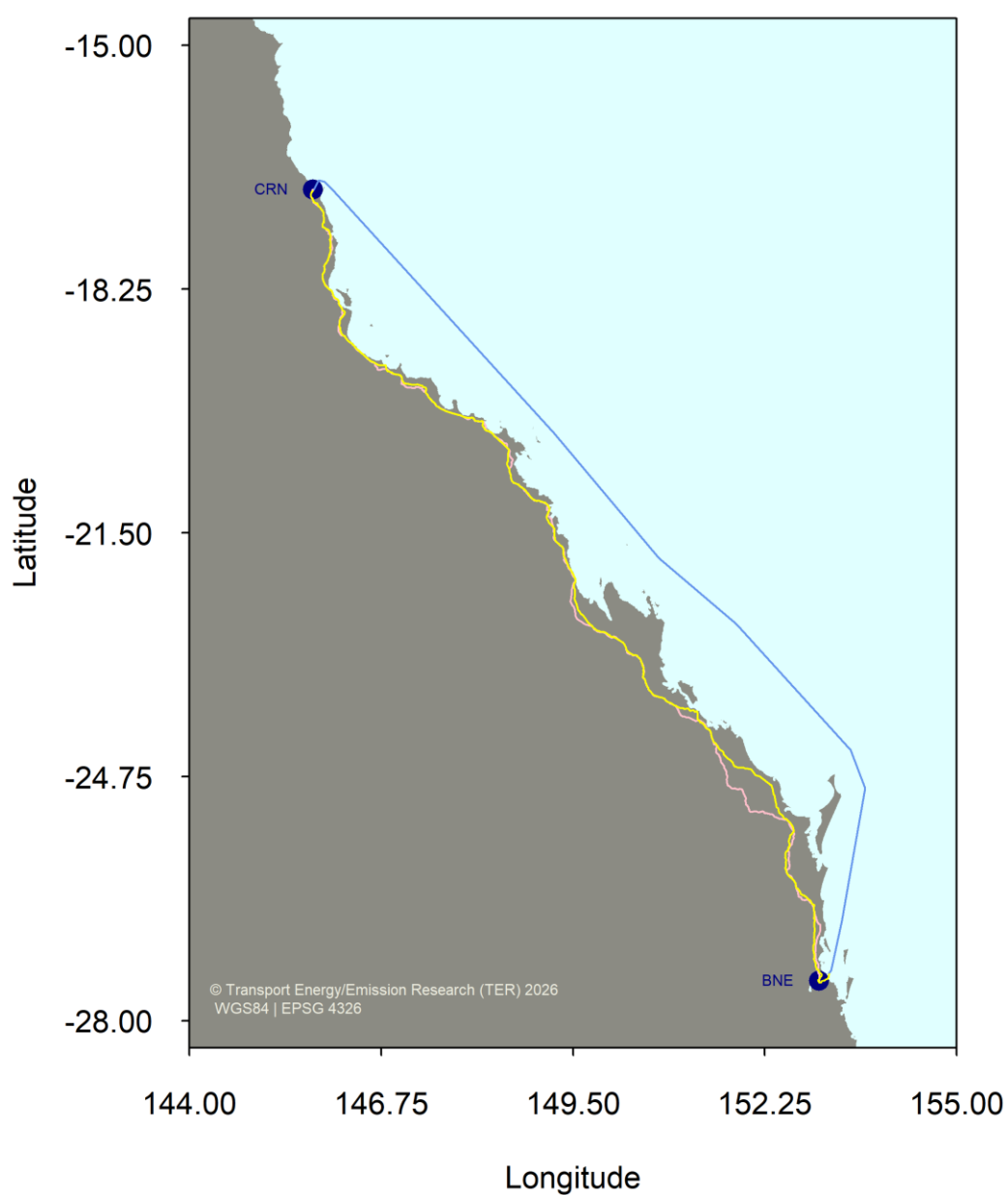


Figure A.1 – The BNE-CRN freight route by transport mode (Routes A). The coloured lines represent shipping routes (blue), road routes (pink), rail routes (yellow) and CBD linkage road routes (green).

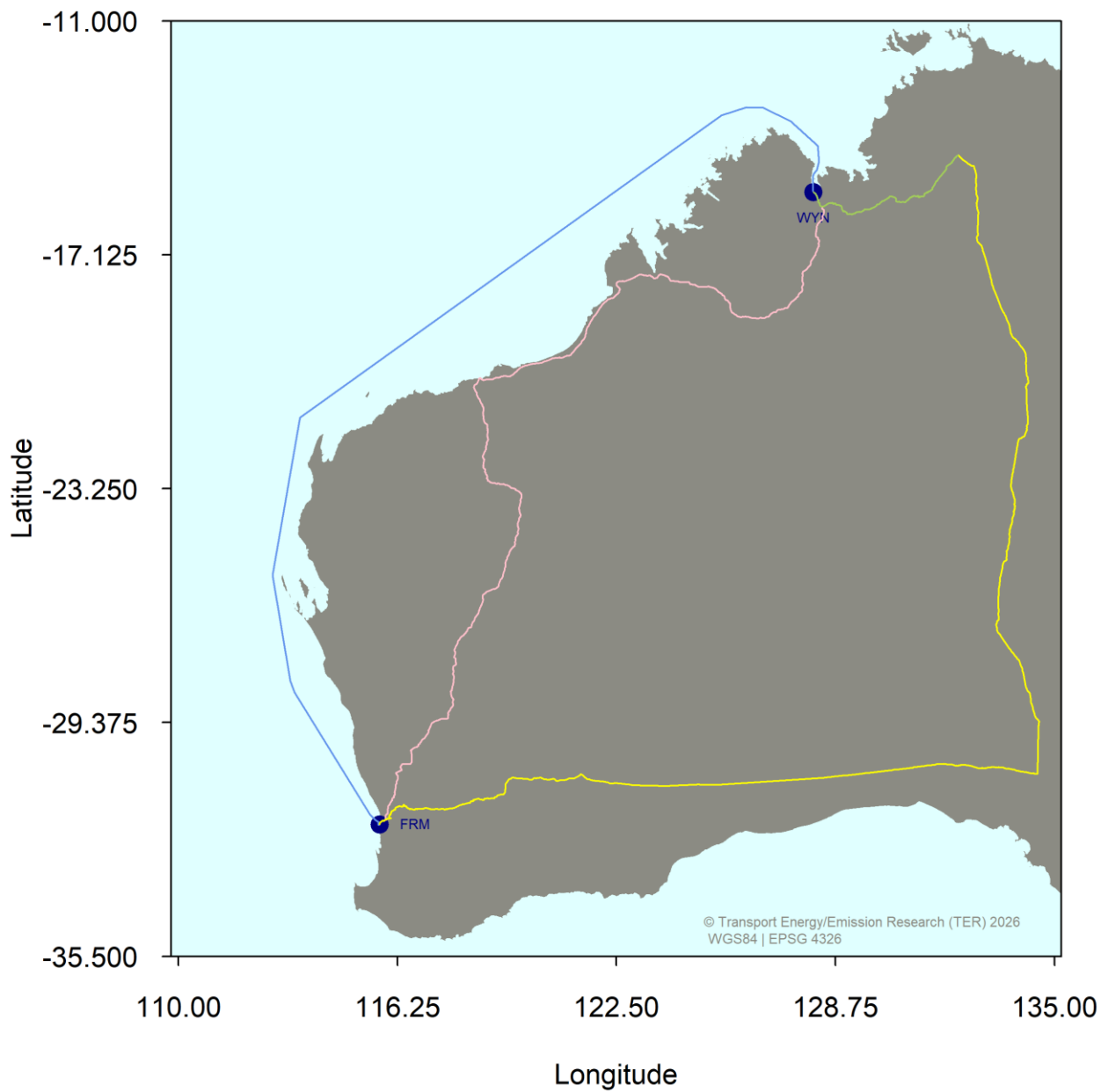


Figure A.2 – The FRM-WYN freight route by transport mode (Route B). The coloured lines represent shipping routes (blue), road routes (pink), rail routes (yellow) and CBD linkage road routes (green).

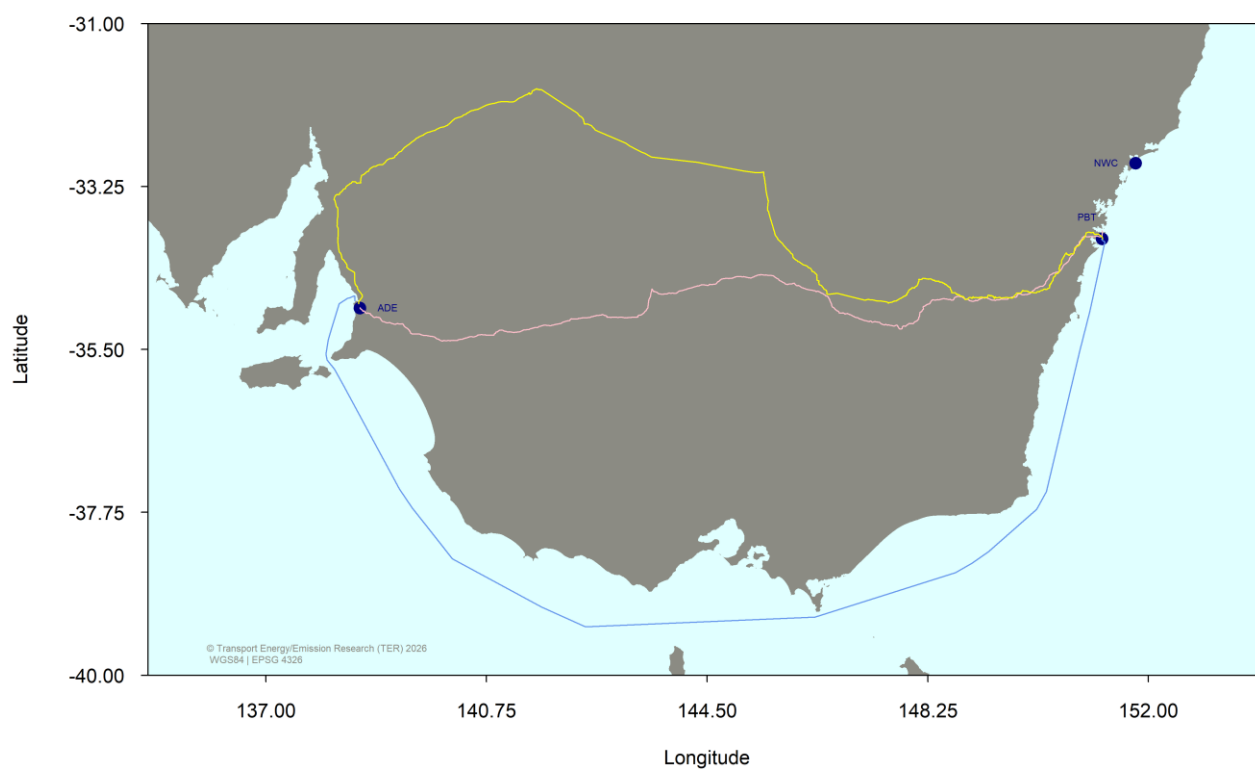


Figure A.3 – The PBT-ADE freight route by transport mode (Route C). The coloured lines represent shipping routes (blue), road routes (pink), rail routes (yellow) and CBD linkage road routes (green).

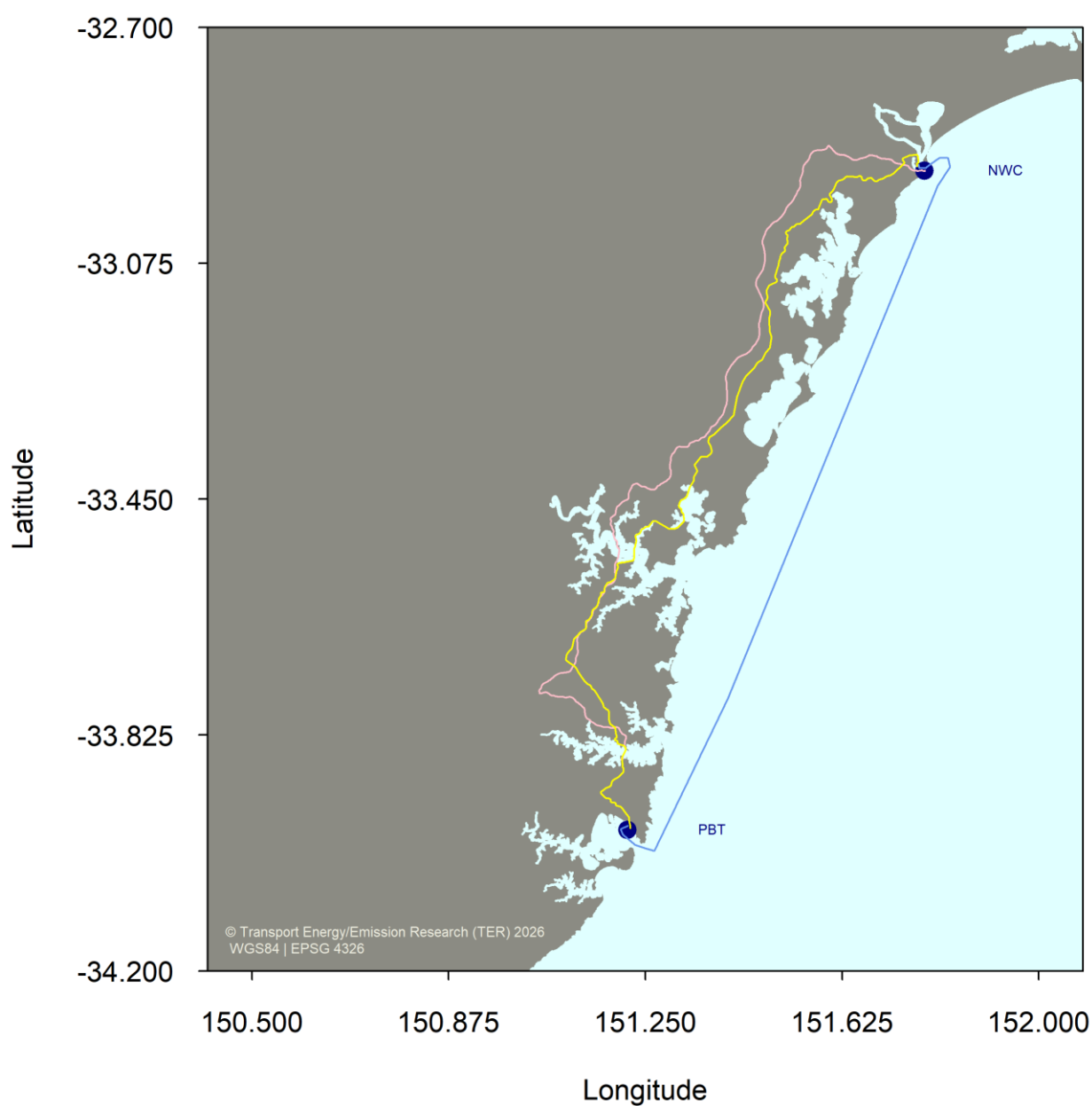


Figure A.4 – The PBT-NWC freight route by transport mode (Route D). The coloured lines represent shipping routes (blue), road routes (pink), rail routes (yellow) and CBD linkage road routes (green).

Appendix B – Model considerations and assumptions by transport mode

B.1 Shipping

- The maximum mass-based cargo-carrying capacity (t) for maritime vessels was estimated to be 80-90% of DWT (Smit and Boulter, 2024b; MPC, 2026).
- The corresponding maximum volume-based cargo capacity for ships is estimated as 1.3 to $1.5 \times$ mass based cargo-carrying capacity for tankers (**U**: 1.30, 1.50). For container vessels, the specified cargo capacity in terms of TEU was considered to be the maximum volume-based cargo capacity.
- The effective payload capacity (t) was assumed to vary between 50% and 80% of maximum capacity, given that tankers can have empty backhauls (**U**: 0.50, 0.80).²⁰ For container ships, a higher cargo utilisation rate was assumed (Smit and Boulter, 2024b), with the average payload varying between 60% and 90% of maximum capacity (**U**: 0.60, 0.90).

B.2 Road

- B-double mass limits refer to the maximum allowable mass for a heavy vehicle combination consisting of a prime mover towing two semi-trailers.
- In practice, the payload for a GML B-double truck can vary between 0 tonne (empty) and about 39 tonnes (maximum payload).²¹
- Containers:
 - The cargo capacity is assumed to be equivalent to 3 TEUs for container transport, so about 100 m^3 .
 - For an average TEU mass of 14 t, the GCM limit can thus be exceeded, which means that the full 3 TEU load cannot always be transported in a single trip by road.
 - A freight cargo *spillover ratio* (θ) is computed by dividing total vehicle mass by the GCM limit of 63 t.
 - Any θ values less than unity are set to 1 and any values above unity become an emission multiplier, effectively assuming that the leftover portion of the total load will be transported on the next road trip with the same vehicle, following the same route. In the simulation, θ varies between 1.00 and 1.15.
- Bulk liquids:
 - a B-double road tanker combination has been assumed to hold 38 to 43 m^3 (**U**: 38, 43).
 - In this case, the GCM limit is never exceeded, even for bulk liquids with the highest density, so θ has a value of 1.00 in all cases (no cargo spillover).
- For diesel trucks, upstream well-to-tank emissions were modeled as an energy and emissions penalty, reflecting the portion of energy in the diesel fuel that was consumed within the fuel chain (**U**: 0.14, 0.28). This distribution was combined with the distribution for TTW emission factors to estimate a distribution of WTW emission factors for road freight transport.
- Indirect emissions due to electricity generation and consumption and hydrogen production and use (including all losses) are normally estimated in the probabilistic method (Smit and Boulter, 2024a), but they are not relevant for road freight transport in 2030 and have been ignored.

²⁰ When a transport mode is not hauling cargo during a trip, it is considered an empty backhaul. Because bulk liquid vessels are specialised, and because of other factors such as one-directional flows of commodities and product cross-contamination risks, returning empty may be a common and expensive reality in the logistics and maritime industry.

²¹ The maximum payload is the difference between Gross Combination Mass (GCM) and the combination's tare mass.

B.3 Rail

- The maximum cargo-carrying capacity (tonne) was estimated to typically be 210 TEUs, assuming 40% double-stacking, but varying between 150 TEU (single stacking only) and 300 TEU (double stacking only), so as a triangular distribution (**T**: 150, 300, 210).
- For bulk liquids, a tank wagon has been assumed to hold 75 to 90 m³ (**U**: 75, 90). The total volume capacity for a train was then estimated to vary between 5625 and 6750 m³ for bulk liquids.
- The train mass limit of 7900 t is never exceeded for rail, even for bulk liquids with the highest density, so θ has a value of 1.00 in all cases (no cargo spillover).
- For diesel-fueled trains, upstream emissions were modeled with an energy and emissions penalty (**U**: 0.14, 0.28). In the WTW simulation, this distribution was combined with the distributions for TTW emissions.
- Indirect emissions due to electricity generation and consumption (including all losses) for electric freight trains are estimated in the probabilistic method (Smit and Boulter, 2024a), but they are ignored in this study.