Government of **Western Australia**
Department of **Water and Environmental Regulation**

Perth Air Emissions Study 2011–2012

Technical report 5: Off-Road Mobile Emissions

Report

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June 2018

Temporal and spatially allocated emission estimates produced for this study can be made available on request. Please contact **npi@dwer.wa.gov.au** with queries and requests for information.

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Summary

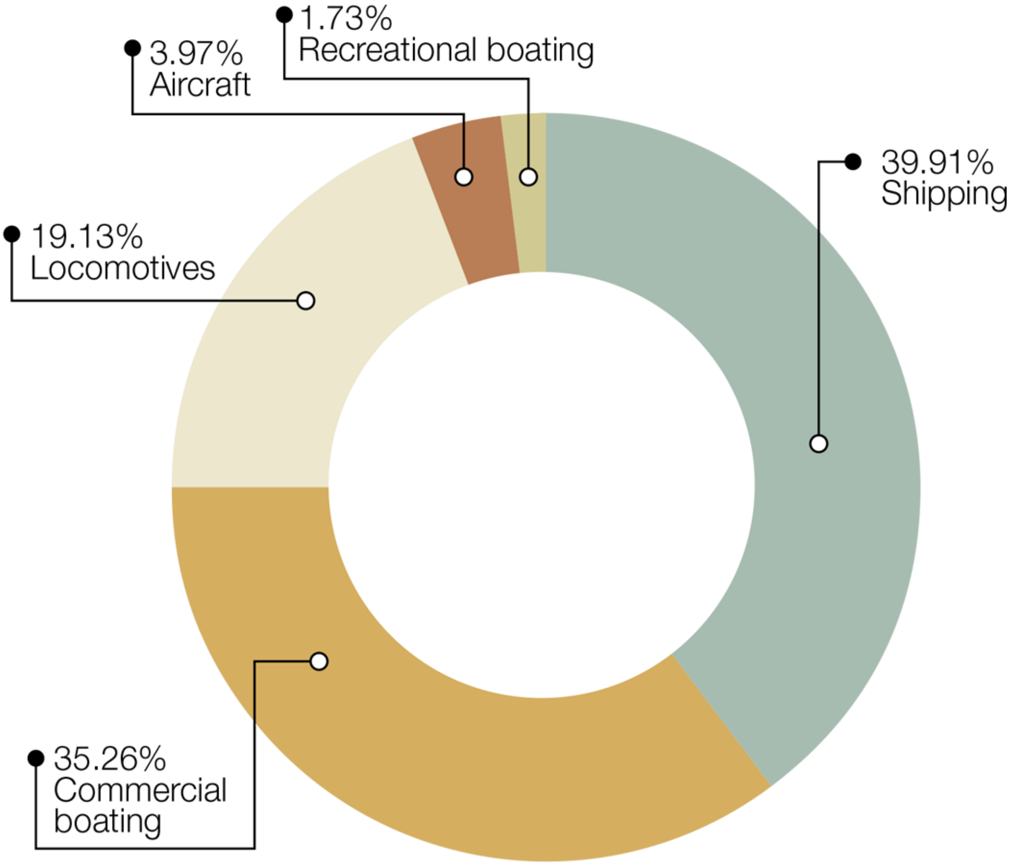
The Department of Water and Environmental Regulation (DWER) has completed an air emissions inventory of Perth for the 2011–12 financial year. The study area was generally consistent with the Australian Bureau of Statistics (ABS) Census Dataset: Greater Capital City Statistical Area – Greater Perth. The inventory estimated emissions for a variety of natural and anthropogenic emission sources.

This report summarises the estimated emissions from off-road mobile sources, including aircraft, locomotives, shipping, recreational boating and commercial boating.

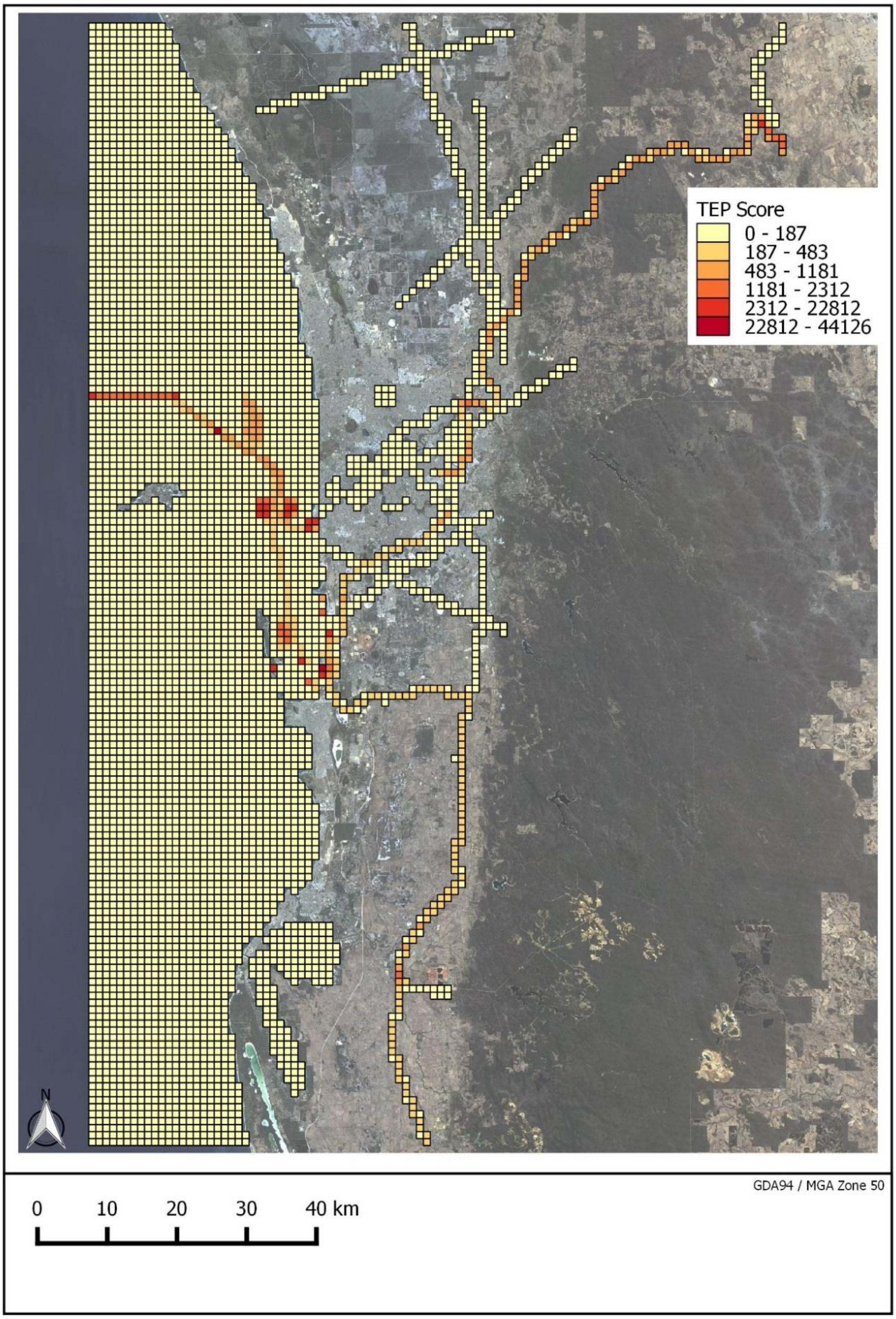
Emissions were estimated using the methodology published in the *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in New South Wales* (NSW EPA 2012). Methodologies were adapted to address the availability of local data and, in some cases, were superseded by more relevant or recently developed methods. Emissions were spatially allocated based on the activity data available for each emission source.

Based on a toxic equivalency potential (TEP) scoring system, emission estimates from off-road mobile sources showed that oxides of nitrogen (NO_X) emissions were the most significant key pollutant emitted. Total emissions of metals such as mercury, lead, cadmium, and polychlorinated dioxins and furans were comparatively small, but were found to be the highest-risk pollutants due to their toxicity.

The summary figures show the relative contribution from off-road mobile emission sources to the overall TEP score, and the spatial allocation of the TEP score. Shipping and commercial boating emissions represented 75 per cent of the emission risk from off-road mobile sources.



Summary figure – relative TEP contributions from off-road mobile sources



Summary figure – spatial allocation of off-road mobile TEP score

1 Introduction

The Department of Water and Environmental Regulation (DWER) has completed an air emissions inventory of Perth for 2011–12.

This technical report presents the emission estimate methods, calculated emissions, and spatial allocation of emissions of off-road mobile emission sources.

This technical report focuses on emissions estimated as a result of off-road mobile activities. It is one of six reports prepared for the Perth Air Emissions Study 2011–2012:

1. *Perth Air Emissions Study 2011–2012: Summary of emissions*
2. *Technical report 1: Biogenic and geogenic emissions*
3. *Technical report 2: Domestic emissions*
4. *Technical report 3: Commercial and industrial emissions*
5. *Technical report 4: On-road vehicle emissions*
6. ***Technical report 5: Off-road mobile emissions***

1.1 Inventory scope

This module is defined by the following study parameters:

Year

The data presented by this study represent emissions estimated for the 2011–12 financial year. This time period aligns with Australian Bureau of Statistics (ABS) census data and available datasets.

Where data are not available for 2011–12, data outside the study period have been used as being broadly representative of 2011–12.

Boundaries

This study includes Local Government Areas (LGAs) in the ABS *Census Dataset: Greater Capital City Statistical Area – Greater Perth* (ABS 2012). The grid covers an area of 100 kilometres west to east (Rottnest Island to Toodyay) and 160 kilometres north to south (Two Rocks to Waroona). The corner coordinates are presented in Table 1, and the study area is shown in Figure 1.

Table 1 – Study grid corner coordinates

	Easting* (m)	Northing* (m)
North-west	350000	6525000
North-east	450000	6525000
South-west	350000	6365000
South-east	450000	6365000

* Geocentric Datum of Australia 1994 (GDA94 MGA Zone 50).

Figure 1 – Perth Air Emissions Study 2011–2012 boundaries

Spatial allocation

The study used a one kilometre grid to spatially allocate emission estimates. This scale balances the resolution of fine data (roads, individual point sources etc.) and computationally demanding calculations.

Grid coordinates start at the upper left corner, as illustrated in Figure 2.

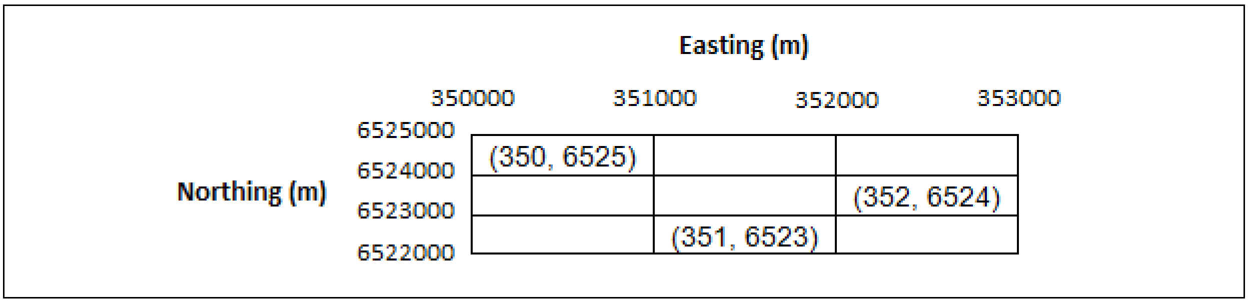


Figure 2 – Grid coordinate system

Emission substances

The substances of interest in this study module are those in the *National Environment Protection (Ambient Air Quality) Measure*. These include:

- carbon monoxide (CO);
- nitrogen dioxide (NO_2), as a subset of oxides of nitrogen (NO_X);
- particulate matter ≤ 2.5 µm ($PM_{2.5}$);
- particulate matter ≤ 10 µm (PM_{10}); and
- sulfur dioxide (SO_2).

Ozone (O_3), as a proxy for photochemical smog, is a secondary pollutant resulting from the chemical transformation of pollutants in the atmosphere over time, and was not directly considered in this study. Instead, emissions of volatile organic compounds (VOCs) were estimated because these, along with oxides of nitrogen, are considered to be precursors to smog formation.

Other emissions estimated are included in the list of substances of interest to the National Pollutant Inventory (NPI):

- ammonia;
- heavy metals, including lead, cadmium, copper, chromium, nickel, selenium and zinc; and
- organic compounds, including speciated volatiles, polycyclic aromatic hydrocarbons (B[a]Peq), and polychlorinated dioxins and furans (TEQ).

2 Study methodology

The off-road mobile emissions inventory method has two discrete stages: the estimation of total off-road mobile emissions, and the spatial allocation of those emissions. Input data were sourced from government agencies and industry organisations and emission estimation methods were developed to align with readily available data.

The off-road mobile emission sources considered in this inventory include:

- aircraft;
- boating – commercial;
- boating – recreational;
- locomotives; and
- shipping.

2.1 Aircraft

Aircraft and airport support emissions are those associated with activities such as landing, taxiing and take-off from airport and helipad facilities, ground support operations (e.g. auxiliary power, baggage loading, engine maintenance), and evaporative emissions from refuelling. Emissions estimates assess aircraft activity at public, private and military facilities.

Emissions from aircraft and support activities were estimated using the US Federal Aviation Association's Emissions and Dispersion Modeling Software (EDMS) Version 5.1.4.1. EDMS calculates annual fuel consumption and emissions by modelling input of airport and helipad locations, landing and take-off (LTO) data, and selection of ground support functions (FAA 2013).

EDMS limits estimation of aircraft emissions to those occurring below an altitude of 3,000 feet (914.4 metres). The LTO cycle is performed within this altitude and includes aircraft performing approach, taxi to and from the runway, and climb-out manoeuvres. Emission sources above the maximum altitude were considered external to the boundaries of this study, and were not included in the calculations.

Methodology

Aircraft LTO exhaust emissions were calculated in EDMS using specific model and engine type information, and LTO data. The following equation represents the calculation method completed within EDMS (NSW EPA 2012).

$$\boldsymbol{E_{i,j,k,l,m,n} = NLTO_{j,k,l,m} \times NE_{j,k} \times TIM_{j,k,n} \times FF_{j,k,n} \times EF_{i,j,k,l,m,n}}$$

Where:

$E_{i,j,k,l,m,n}$	=	Emissions of substance (i), from aircraft model (j), engine model (k), aircraft type (l), engine type (m),	(kg/yr)

		during mode of operation (n)	
$NLTO_{j,k,l,m}$	=	Landing/take-off cycles for aircraft model (j), and engine model (k), aircraft type (l), and engine type (m)	(number/yr)
$NE_{j,k}$	=	Engines for aircraft model (j), and engine model (k)	(number)
$TIM_{j,k,n}$	=	Time-in-mode for aircraft model (j) and engine model (k) during mode of operation (n)	(minutes)
$FF_{j,k,n}$	=	Fuel flow rate for aircraft model (j), and engine model (k) during mode of operation (n)	(kL/minute)
$EF_{i,j,k,l,m,n}$	=	Emission factor for substance (i), for aircraft model (j), engine model (k), aircraft type (l), and engine type (m) during mode of operation (n)	(kg/kL)
i	=	Substance	(–)
j	=	Aircraft model	(–)
k	=	Engine model	(–)
l	=	Aircraft type	(–)
m	=	Engine type	(–)
n	=	Mode of operation	(–)

Exhaust emissions from ground support equipment and auxiliary power units were estimated using default EDMS settings for each aircraft. The following equation represents the calculation method completed within EDMS (NSW EPA 2012).

$$E_{i,j,m,p,s} = P_{j,m,p} \times A_{j,m,p} \times HP_{j,m,p} \times LF_{j,m,p} \times EF_{i,j,m,p,s}/1000$$

Where:

$E_{i,j,m,p,s}$	=	Emissions of substance (i), from ground support equipment and auxiliary power unit type (j), engine type (m), engine power range (p), and source type (s)	(kg/yr)
$P_{j,m,p}$	=	Population of ground support equipment and auxiliary power unit type (j), engine type (m), and engine power range (p)	(number)
$A_{j,m,p}$	=	Activity of ground support equipment and auxiliary power unit type (j), engine type (m), and engine power range (p)	(hr/yr)
$HP_{j,m,p}$	=	Maximum rated power of ground support equipment and auxiliary power unit type (j), engine type (m), and engine power range (p)	(hp)
$LF_{j,m,p}$	=	Fractional load factor for ground support equipment and auxiliary power unit type (j), engine type (m), and engine power range (p)	(hp/hp)

$EF_{i,j,m,p,s}$	=	Emission factor for substance (i) for ground support equipment and auxiliary power unit type (j), engine type (m), engine power range (p), and source type (s)	(g/hp.h)
i	=	Substance	(–)
j	=	Ground support equipment or auxiliary power unit type	(–)
m	=	Engine type	(–)
p	=	Engine power range	(hp)
s	=	Source type	(–)
1000	=	Conversion factor	(g/kg)

VOC evaporative refuelling emissions – from the transfer of fuel to storage tanks, tankers and aircraft – were estimated using the following equation adopted from NSW EPA (2012).

$$\boldsymbol{E_{VOC,i} = EF_{VOC,i} \times A_i}$$

Where:

$E_{VOC,i}$	=	Emissions of VOC from fuel type (i)	(kg/yr)
$EF_{VOC,i}$	=	VOC emission factor for fuel type (i)	(kg/kL)
A_i	=	Amount of fuel type (i) loaded	(kL/yr)
i	=	Fuel type	(–)

VOC emission factors were sourced from USEPA (2008). Factors were converted using the equation below (NSW EPA 2012).

$$\boldsymbol{EF_{VOC,i} = 12.46 \times \frac{S_j \times P_i \times M_i}{T} \times \left(1 - \frac{eff_j}{100}\right) \times \frac{0.4536}{3.7862}}$$

Where:

$EF_{VOC,i}$	=	VOC emission factor fuel type (i)	(kg/kL)
S_j	=	Saturation factor for loading type (j) – 0.6, 0.6 and 1.45 for loading to storage tanks, loading to tankers, and refuelling aircraft respectively (Table 5.2-1 USEPA 2008)	(–)
P_i	=	True vapour pressure of fuel type (i) – 3.5 and 0.0085 for Avgas and Avtur respectively (Table 7.1-2 USEPA 2006)	(psia)

M_i	=	Molecular weight of vapour for fuel type (i) – 68 and 130 for Avgas and Avtur respectively (Table 7.1-2 USEPA 2006)	(lb/lb.mol)
T	=	Temperature of bulk liquid loaded – 520ºR (Table 7.1-2 USEPA 2006)	(ºR)
eff_j	=	Overall reduction efficiency for loading type (j) – 95.92%, 0% and 0% for loading to storage tanks, loading to tankers and refuelling aircraft respectively	
i		Fuel type	(–)
j		Loading type	(–)
0.4536		Conversion factor	(lb/kg)
3.7862		Conversion factor	(L/US gal)

Polycyclic aromatic hydrocarbon (PAH) emission factors were calculated using the following equation and VOC fractions (Pechan 2005).

$$EF_{PAH,i} = \sum EF_{VOC,i} \times PAH_{i,j} \times WHO_j$$

Where:

$EF_{PAH,i}$	=	PAH emission factor for fuel type (i)	(kg/kL)
$EF_{VOC,i}$	=	VOC emission factor for fuel type (i)	(kg/kL)
PAH_i	=	PAH speciation profile[1] for fuel type (i), and substance (j)	(%)
WHO_i	=	World Health Organization (1998)[2] relative potency for substance (j)	(lb/lb.mol)
i		Fuel type	(–)

Exhaust emission factors were sourced from EDMS and NSW EPA (2012), and are presented in Table 24 of Appendix A.

VOC emissions were speciated using the California Air Resources Board ORGPROF database (CARB 2015), and are presented in Table 31 of Appendix B. Particulate emissions were speciated using the California Air Resources Board PMSIZE database (CARB 2014a), and presented in Table 32 of Appendix B.

Activity data

Fuel consumption and emissions were estimated using EDMS and a range of input data. EDMS required the procurement and entry of information, including:

[1] Speciated PAH factors sourced from Pechan (2005), Table D2 (page D-16).

[2] PAH speciation factors weighted using relative potencies from NPI (2015), Appendix E (page 52).

- airport location;
- aircraft schedules and activity; and
- Civil Aviation Safety Authority (CASA) aircraft/engine characteristics.

International, domestic and defence airport locations were sourced from Airservices Australia Pty Ltd (ASA) and the Royal Air Force Australia (RAAF). Nine locations were considered in this study, with details provided in Table 2. Data were unavailable for a few smaller metropolitan airstrips predominantly used for skydiving, the Rottnest Island airstrip, and several seasonally utilised helicopter launch sites. Emissions have not been estimated for these locations.

Table 2 – Airport locations

Site	ICAO[3] code	Activity	Elevation (m)	Easting (m)	Northing (m)
Burswood	YBWD	Helipad	3	678,490	6,462,917
Jandakot	YPJT	Airport	29	394,308	6,448,659
Langley Park	YCHP	Airport	1.5	393,405	6,463,169
Perth airport	YPPH	Airport	20	402,384	6,465,910
RAAF Gingin	YGIG	Airport	83	392,014	6,518,303
RAAF Pearce	YPEA	Airport	36	406,626	6,495,904
Royal Perth Hospital	YXRP	Helipad	15	392,884	6,464,132
Sir Charles Gairdner Hospital	YXCG	Helipad	9.9	388,212	6,462,423
TV stations	YPTV	Helipad	65	392,059	6,472,058

LTO data were sourced from ASA and RAAF and are presented in Table 3.

Table 3 – Landing and take-off data for each airstrip

Site	LTOs
Burswood	1,053
Jandakot	60,749
Langley Park	32
Perth airport	71,727
RAAF Gingin	30,621
RAAF Pearce	67,473
Royal Perth Hospital	175
Sir Charles Gairdner Hospital	33
TV stations	943
Total	**232,806**

[3] International Civil Aviation Organisation

LTO data were filtered to remove potential errors before entry into EDMS, including:

- removal of engine-less gliders; and
- removal of entries for planes landing at helipad sites.

Data provided by ASA and RAAF included information on aircraft type for each LTO. Aircraft types were then matched with CASA registration data, which includes:

- manufacturer;
- aircraft model;
- engine model; and
- fuel type.

Matched aircraft and engine model data were then entered into EDMS for each LTO. Where engine model information did not align with the options available in EDMS, aircraft were matched to the engine of best fit based on web searches. Given the altitude cap in EDMS for fuel estimates, EDMS-estimated fuel consumption is not considered representative of total refuelling or the extent of evaporative emissions. Instead, Western Australia 2011–12 aviation fuel data were sourced from the Bureau of Resources and Energy Economics (BREE 2012). BREE data were scaled to the study area using population data for Western Australia and the study area.

Table 4 – Avgas and Avtur fuel use for study area

	Avgas fuel use (kL)	Avtur fuel use (kL)	Total (kL)
Whole of Western Australia	15,825	888,715	904,540
Study area	12,378	695,172	707,551

EDMS-calculated fuel use was apportioned to each location using LTO ratios. The Avgas and Avtur consumption ratios calculated by EDMS were then used to apportion BREE Avgas and Avtur data from Table 4. Locations operating as a helipad were assumed to not refuel Avtur, as this fuel is intended for fixed wing aircraft which do not operate at helipads. EDMS fuel consumption and estimated site refuelling data are presented in Table 5.

Table 5 – EDMS fuel consumption and total refuelling

Site	EDMS fuel consumed (kg)	% Avgas	% Avtur	Avgas refuelled (kL)	Avtur refuelled (kL)
Burswood	20,500	0.026%	–	3.25	–
Jandakot	1,466,328	1.88%	1.88%	232	13,049
Langley Park	775	0.0010%	–	0.12	–
Perth airport	52,813,966	67.6%	67.6%	8,364	469,997
RAAF Gingin	6,901,451	8.83%	8.83%	1,093	61,417

Site	EDMS fuel consumed (kg)	% Avgas	% Avtur	Avgas refuelled (kL)	Avtur refuelled (kL)
RAAF Pearce	16,935,368	21.7%	21.7%	2,682	150,710
Royal Perth Hospital	6,116	0.0078%	–	0.97	–
Sir Charles Gairdner Hospital	1,154	0.0015%	–	0.18	–
TV stations	22,327	0.029%	–	3.54	–
Total	**78,167,985**	**100%**	**100%**	**12,378**	**695,172**

Emissions estimates

Emissions estimates from aircraft activity are summarised in Table 6.

Table 6 – Aircraft total emissions by source

Pollutant	Emissions (kg/yr)				
	Aircraft LTO	Ground support operations	Auxiliary power units	Evaporative	Total
Acetaldehyde	21,248	286	52.0		21,586
Acetone	2,383		4.50		2,388
Acrolein	12,092		29.8		12,121
Benzene	8,380	317	20.5	469	9,187
1,3-Butadiene (vinyl ethylene)	8,362		20.6		8,382
Carbon monoxide	2,577,288	585,738	14,537		3,177,564
Chlorine and compounds	689				689
Chromium (total)	4.92				4.92
Cobalt and compounds	4.92				4.92
Copper and compounds	4.92				4.92
Cumene (1-methylethylbenzene)	13.9		0.037	46.1	60.1
Ethylbenzene	860	121	2.12	182	1,165
Formaldehyde (methyl aldehyde)	57,556	845	150		58,551
n-Hexane		277		388	666
Manganese and compounds	4.92				4.92
Nickel and compounds	4.92				4.92
Oxides of nitrogen	856,081	142,460	19,275		1,017,816
Particulate matter ≤ 2.5 µm	9,840	6,632	2,053		18,526

Pollutant	Emissions (kg/yr)				
	Aircraft LTO	Ground support operations	Auxiliary power units	Evaporative	Total
Particulate matter ≤ 10 µm	9,840	6,863	2,053		18,757
Phenol	3,501		8.84		3,510
Polycyclic aromatic hydrocarbons (B[a]Peq)	27.2				27.2
Styrene (ethenylbenzene)	1,549		3.76	7.08	1,560
Sulfur dioxide	91,550	1,419	2,461		95,431
Toluene (methylbenzene)	3,159	540	7.82	414	4,121
Total volatile organic compounds	509,239	25,877	1,212	19,147	555,474
Xylenes (individual or mixed isomers)	2,225	502	2.02	1,041	3,770
Zinc and compounds	4.92				4.92

Spatial allocation

Ground support, auxiliary power and evaporative emissions were allocated based on the activities conducted at each airport facility.

LTO emissions for fixed wing aircraft were allocated in a straight line from the start and end of each runway. The lengths of landing and take-off lines were determined based on the altitude restriction for calculations (see Section 2.1) and typical ascent and descent angles. Each airstrip was assumed to include flight landings from either direction. Spatial allocation applies the longer descent length beyond each strip, with emissions applied evenly. The calculated lengths are presented in Table 7.

Table 7 – LTO emission allocation distance

Angle of ascent	Angle of descent	Cut-off height (m)	Extent of allocated emissions – ascent (m)	Extent of allocated emissions – descent (m)
10	3	914	5,186	17,448

Emissions from helipads were allocated evenly over a centred nine square kilometre area, given the variability of destinations and flight altitudes.

Ground support equipment, auxiliary power units, and evaporative emission spatial allocation were assigned to the footprint of each site based on satellite imagery.

The spatial allocation of aircraft VOC emissions is presented in Figure 3.

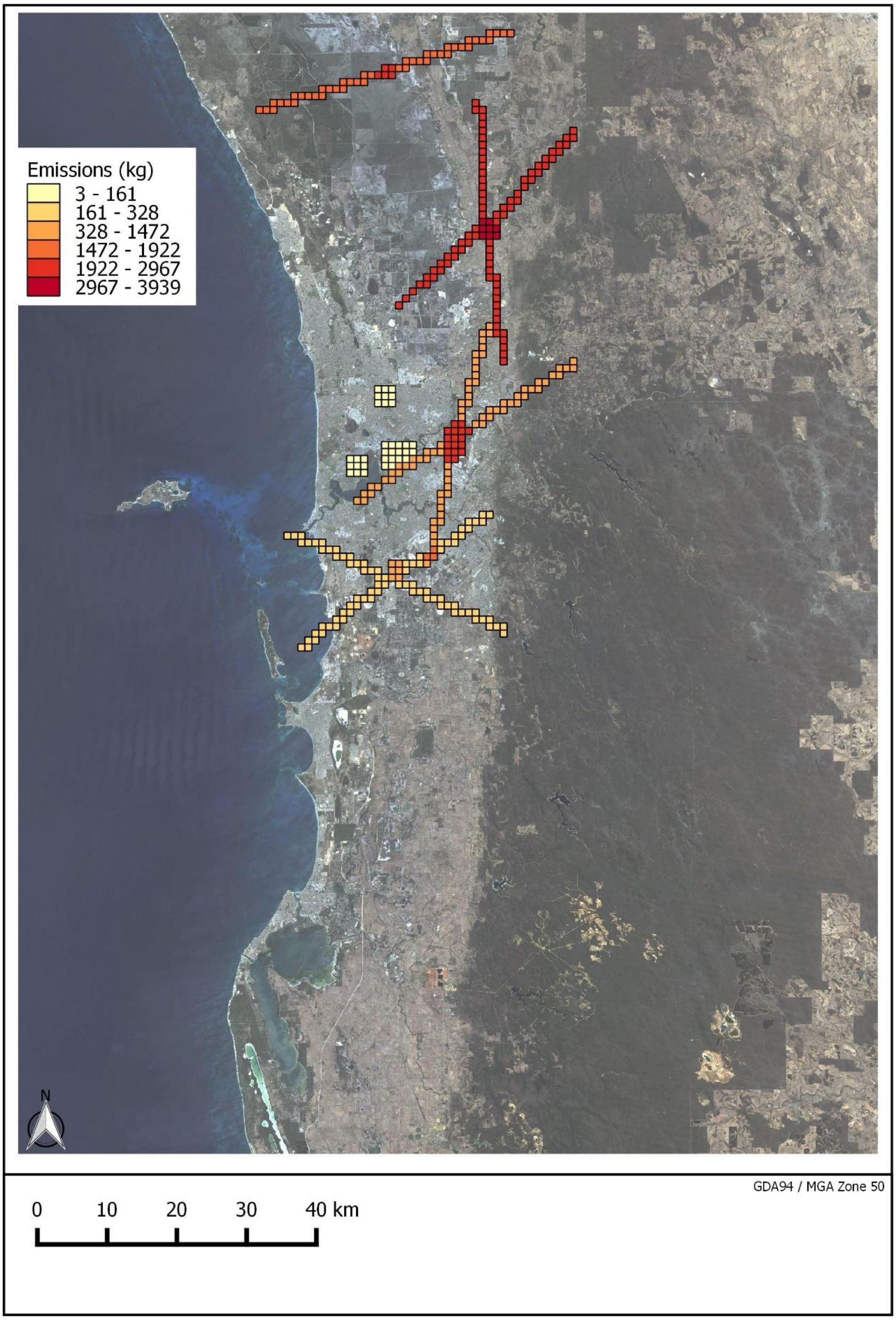


Figure 3 – Spatial allocation of aircraft VOC emissions

2.2 Commercial boating emissions

Commercial boating emissions were estimated for the study area, including activities such as commercial fishing, ferry services and support services (e.g. dredging, tugboats, coast guard). Emissions from shipping are covered in Section 2.5, while emissions from recreational boating are addressed in Section 2.3.

Commercial boating estimates address evaporative and exhaust emissions from the use of three different engine types:

- 2-stroke petrol;
- 4-stroke petrol; and
- diesel.

Methodology

Emission estimates were calculated using the following equation, which was simplified due to data availability in the study area.

$$\boldsymbol{E_i = EF_{i,p} \times A_p}$$

Where:

E_i	=	Emissions of substance (i)	(kg/yr)
$EF_{i,p}$	=	Emission factor for substance (i) from engine type (p)	(kg/kL)
A_p	=	Activity of engine type (p)	(kL/yr)
i	=	Substance	(–)
p	=	Engine type	(–)

PAH emission factors were calculated using the following equation and PM_{10} fractions (Pechan 2005).

$$\boldsymbol{EF_{PAH,i} = \sum EF_{PM10,i} \times PAH_{i,j} \times WHO_j}$$

Where:

$EF_{PAH,i}$	=	PAH emission factor for fuel type (i)	(kg/kL)
$EF_{PM10,i}$	=	PM_{10} emission factor for fuel type (i)	(kg/kL)
PAH_i	=	PAH speciation profile[4] for fuel type (i), and substance (j)	(%)

[4] Speciated PAH factors sourced from Pechan (2005), Table D2 (page D-16).

WHO_i	=	World Health Organization[5] relative potency for substance (j)	(lb/lb.mol)
i	=	Fuel type	(–)
j	=	Substance	(–)

Emission factors were sourced from NSW EPA (2012) and are presented in Table 25 of Appendix A.

Exhaust VOC emissions were speciated using profiles from Pechan (2005). Evaporative VOC emissions were speciated using profiles from DECC (2007). PM_{10} emissions were scaled to total suspended particulates (TSP) using the California Air Resources Board PMSIZE database (CARB 2014a), and then speciated to individual metals using the PMPROF database (CARB 2014b). Speciation profiles are presented in Appendix B.

Activity data

Commercial boating evaporative and exhaust emission calculations were derived using fuel consumption data. NSW EPA (2012) commercial boating operational data were used to estimate average fuel consumption per engine for each boat and fuel type. Calculated fuel use is presented in Table 8.

Table 8 – Calculated commercial boating fuel consumption per engine

Boat type	Engine type	NSW study engine population	NSW study fuel use (kL/yr)	Estimated fuel use per engine (kL/yr/engine)
Ferry	2-stroke petrol	–	–	–
	4-stroke petrol	–	–	–
	Diesel	89	24,850	279
Commercial fishing	2-stroke petrol	2,541	6,905	2.72
	4-stroke petrol	841	1,346	1.60
	Diesel	2,276	5,962	2.62
Other commercial boating	2-stroke petrol	509	18,597	37
	4-stroke petrol	174	5,724	33
	Diesel	1,317	89,368	68

The 2015–16 Western Australian commercial boating fleet population was sourced from the Department of Transport (DoT). Data for 2011–12 were unavailable, so 2015–16 data were used as a supplement. DoT advised that the commercial boating fleet population had not changed significantly between the two periods.

[5] PAH speciation factors weighted using relative potencies from NPI (2015), Appendix E (page 52).

Fleet data were filtered based on postcode of registration in the metropolitan area, assuming that activity occurs through harbours nearest to the place of registration. Fleet data were then grouped into fishing boats or ferries, with the remainder of the fleet assigned to 'other commercial boating'.

Each boat was allocated either one or two engines based on boat type and length sourced from NSW EPA (2012) and supplemented with web searches. Boat engine and fuel type data were not available for the study area. NSW EPA (2012) engine and fuel ratios were therefore used to further categorise the fleet.

Fuel use per engine (Table 8) was then applied to the fleet population to determine the total commercial boating fuel use for the study area. These data are presented in Table 9.

Table 9 – Calculated commercial boating fuel use

Boat type	Engine type	Boat population	Engine population	Calculated fuel use (kL/yr)
Ferry	2-stroke petrol	–	–	–
	4-stroke petrol	–	–	–
	Diesel	20	40	11,168
Commercial fishing	2-stroke petrol	82	163	442
	4-stroke petrol	27	54	86
	Diesel	73	146	382
Other commercial boating	2-stroke petrol	148	216	7,882
	4-stroke petrol	51	74	2,426
	Diesel	382	558	37,879
Total		783	1,250	60,265

Calculated fuel consumption was used to determine evaporative emissions.

Emission estimates

Emissions of pollutants from commercial boating in the study area are summarised in Table 10.

Table 10 – Commercial boating total emissions

Pollutant	Emissions (kg/yr)			
	2-stroke petrol	4-stroke petrol	Diesel	Total
Acetaldehyde	2,686	174	3,489	6,349
Acrolein	484	29.7	199	713
Ammonia (total)	241	72.9	1,087	1,402
Antimony and compounds	–	–	5.36	5.36
Arsenic and compounds	–	–	0.15	0.15

Pollutant	Emissions (kg/yr)			
	2-stroke petrol	4-stroke petrol	Diesel	Total
Benzene	40,748	2,265	1,337	44,351
1,3-Butadiene (vinyl ethylene)	3,463	403	122	3,989
Cadmium and compounds	–	–	2.58	2.58
Carbon monoxide	2,761,690	1,059,849	292,123	4,113,662
Chlorine and compounds	2,317	33	11	2,360
Chromium (total)	16.5	0.23	0.39	17.2
Cobalt and compounds	16.5	0.23	0.23	17.0
Copper and compounds	–	–	1.16	1.16
Cumene (1-methylethylbenzene)	–	–	74.7	74.7
Cyclohexane	9.24	2.73	–	12.0
Ethylbenzene	38,686	845	213	39,743
Formaldehyde	4,096	726	7,767	12,590
n-Hexane	22,881	432	105	23,418
Lead and compounds	–	–	1.16	1.16
Manganese and compounds	16.5	0.23	0.89	17.7
Mercury and compounds	–	–	1.00	1.00
Nickel and compounds	16.5	0.23	0.62	17.4
Oxides of nitrogen	28,718	52,433	1,714,680	1,795,831
Particulate matter ≤ 2.5 µm	29,551	427	37,071	67,049
Particulate matter ≤ 10 µm	32,131	452	38,554	71,138
Polychlorinated dioxins and furans (TEQ)	2.74×10^{-8}	8.27×10^{-9}	2.26×10^{-4}	2.26×10^{-4}
Polycyclic aromatic hydrocarbons (B[a]Peq)	1.70	0.083	0.058	1.84
Selenium and compounds	–	–	0.19	0.19
Styrene (ethenylbenzene)	2,090	32.1	39.1	2,162
Sulfur dioxide	1,240	497	4,103	5,840
Toluene (methylbenzene)	158,192	3,147	1,025	162,363
Total volatile organic compounds	1,632,441	47,811	67,223	1,747,475
Xylenes (individual or mixed isomers)	173,586	2,902	829	177,318
Zinc and compounds	–	–	15.4	15.4

Spatial allocation

Emissions from commercial boating were radially spatially allocated – assuming that traffic flowed between major activity points along the coast (i.e. large boat harbours) and ferry activity between Rottnest Island, Fremantle Port and Hillarys Boat Harbour.

The spatial allocation of commercial boating CO emissions is presented in Figure 4.

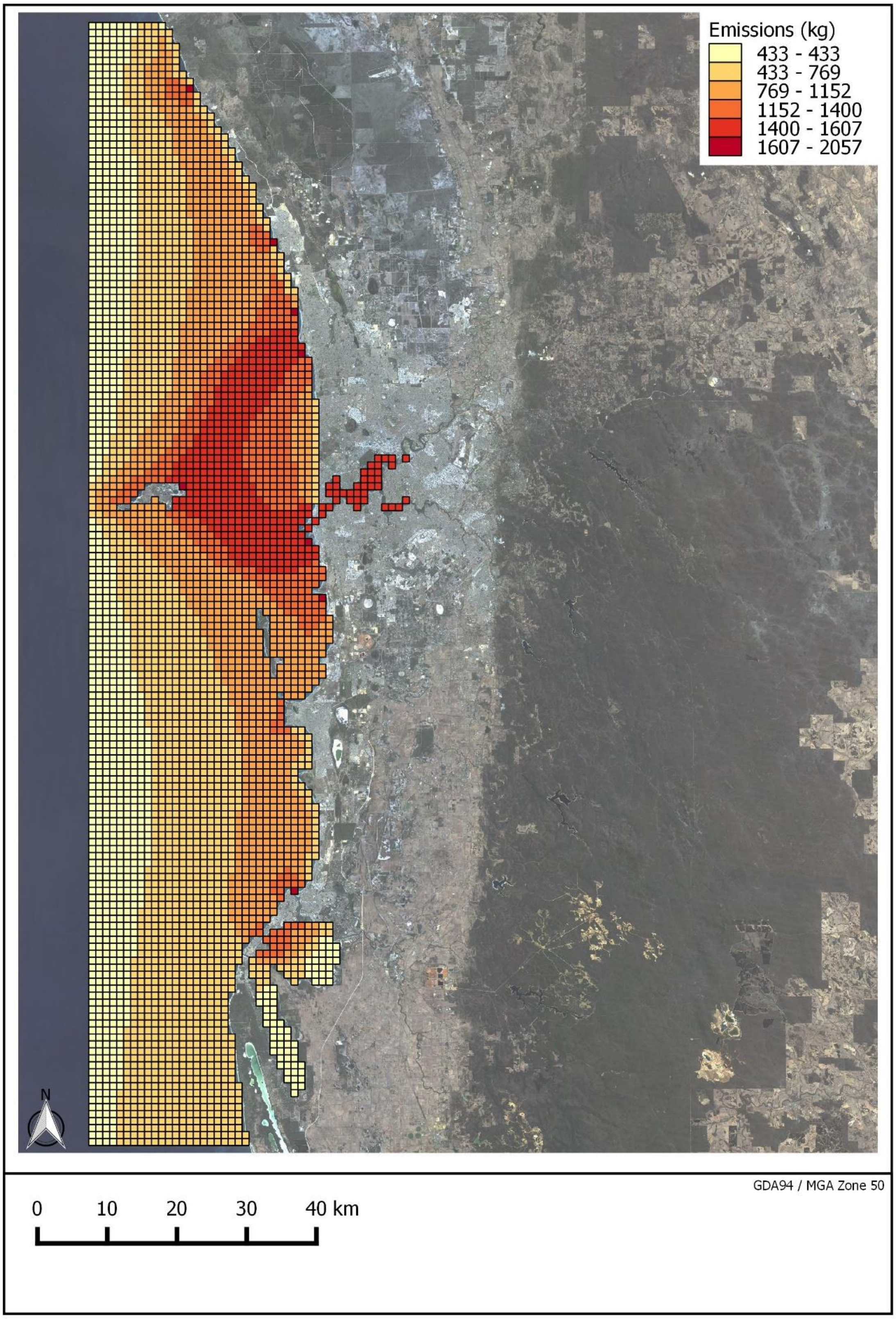


Figure 4 – Spatial allocation of commercial boating CO emissions

2.3 Recreational boating emissions

Recreational boating emissions were estimated for the study area, and include activities such as recreational fishing and aquatic leisure (jet skis). Emissions from shipping are covered specifically in Section 2.5, while emissions from commercial boating are addressed in Section 2.2.

Recreational boating estimates address evaporative and exhaust emissions from the use of three different fuel types:

- 2-stroke petrol;
- 4-stroke petrol; and
- diesel.

Methodology

Emission estimates were calculated using the following equation, which was simplified due to data availability in the study area.

$$\boldsymbol{E_i = EF_{i,p} \times A_p}$$

Where:

E_i	=	Emissions of substance (i)	(kg/yr)
$EF_{i,p}$	=	Emission factor for substance (i) from engine type (p)	(kg/kL)
A_p	=	Activity of engine type (p)	(kL/yr)
i	=	Substance	(–)
p	=	Engine type	(–)

PAH emission factors were calculated using the equation below and PM_{10} fractions (Pechan 2005).

$$\boldsymbol{EF_{PAH,i} = \sum EF_{PM10,i} \times PAH_{i,j} \times WHO_j}$$

Where:

$EF_{PAH,i}$	=	PAH emission factor for fuel type (i)	(kg/kL)
$EF_{PM10,i}$	=	PM_{10} emission factor for fuel type (i)	(kg/kL)
PAH_i	=	PAH speciation profile[6] for fuel type (i), and substance (j)	(%)

[6] Speciated PAH factors sourced from Pechan (2005), Table D2 (page D-16).

WHO_i	=	World Health Organization[7] relative potency for substance (j)	(lb/lb.mol)
i	=	Fuel type	(–)
j	=	Substance	(–)

Emission factors were sourced from NSW EPA (2012) and are presented in Table 26 of Appendix A. Exhaust VOC emissions were speciated using profiles from Pechan (2005). Evaporative VOC emissions were speciated using profiles from DECC (2007). PM_{10} emissions were scaled to TSP using the California Air Resources Board PMSIZE database (CARB 2014a) and then speciated to individual metals using the PMPROF database (CARB 2014b). The speciation profiles applied are presented in Appendix B.

Activity data

Recreational boating emissions were derived using fuel consumption data. NSW EPA (2012) recreational boating operational data were used to estimate average fuel consumption per engine for each boat and fuel type. Calculated engine fuel use is presented in Table 11.

Table 11 – Calculated recreational boating fuel consumption per engine

Engine description	Fuel type	NSW engine population	NSW fuel use (kL/yr)	Estimated fuel use per engine (kL/yr/engine)
Inboard and sterndrive	2-stroke petrol	–	–	–
	4-stroke petrol	12,041	7,871	0.65
	Diesel	8,027	831	0.10
Outboard	2-stroke petrol	133,701	37,963	0.28
	4-stroke petrol	–	–	–
	Diesel	–	–	–
Personal water craft	2-stroke petrol	4,838	312	0.064
	4-stroke petrol	–	–	–
	Diesel	–	–	–

The 2011–12 Western Australian recreational boating fleet population was sourced from DoT. Fleet data were categorised to include boats registered to a postcode in the study area. Boat types unlikely to have an engine (e.g. kayaks, canoes) were excluded from estimates.

[7] PAH speciation factors weighted using relative potencies from NPI (2015), Appendix E (page 52).

Boats were assumed to only have one engine. The boating fleet was further categorised via a desktop review to group boats based on engine type (inboard, outboard) and fuel type.

Boat types with several possible engine and fuel type configurations were delineated using fleet ratios adopted from NSW EPA (2012). Boats registered as 'personal water craft' were grouped and assumed to use 2-stroke petrol engines only. All boats over 20 metres in length were assumed to be running diesel inboard/sterndrive engines.

Fuel use per engine (Table 11) was then applied to the boat engine population to determine the total fuel use. Total fuel consumption within the study area is presented in Table 12.

Table 12 – Calculated recreational boating fuel consumption

Engine description	Engine type	Engine population	Calculated fuel use (kL/yr)
Inboard and sterndrive	2-stroke petrol	–	–
	4-stroke petrol	13,854	9,056
	Diesel	2,398	248
Outboard	2-stroke petrol	49,067	13,932
	4-stroke petrol	–	–
	Diesel	–	–
Personal water craft	2-stroke petrol	4,813	310
	4-stroke petrol	–	–
	Diesel	–	–

Calculated fuel consumption was used to determine evaporative emissions.

Emission estimates

Emissions of pollutants from recreational boating in the study area are summarised in Table 13.

Table 13 – Recreational boating total emissions

Pollutant	Emissions (kg/yr)			
	2-stroke petrol	4-stroke petrol	Diesel	Total
Acetaldehyde	4,351	512	50.6	4,914
Acrolein	784	87.4	2.89	875
Ammonia (total)	413	263	5.46	681
Antimony and compounds	–	–	0.056	0.056
Arsenic and compounds	–	–	0.0016	0.0016
Benzene	68,997	8,619	19.4	77,635

Pollutant	Emissions (kg/yr)			
	2-stroke petrol	4-stroke petrol	Diesel	Total
1,3-Butadiene (vinyl ethylene)	5,611	1,189	1.77	6,801
Cadmium and compounds	–	–	0.027	0.027
Carbon monoxide	4,346,097	3,332,301	2,892	7,681,290
Chlorine and compounds	3,769	111	0.11	3,880
Chromium (total)	26.9	0.79	0.0040	27.7
Cobalt and compounds	26.9	0.79	0.0024	27.7
Copper and compounds	–	–	0.012	0.012
Cumene (1-methylethylbenzene)	–	–	1.00	1.00
Cyclohexane	206	132	–	338
Ethylbenzene	63,060	2,741	3.07	65,804
Formaldehyde	6,637	2,142	113	8,891
n-Hexane	37,912	1,822	1.52	39,736
Lead and compounds	–	–	0.012	0.012
Manganese and compounds	26.9	0.79	0.0092	27.7
Mercury and compounds	–	–	0.010	0.010
Nickel and compounds	26.9	0.79	0.0064	27.7
Oxides of nitrogen	45,291	174,426	8,412	228,129
Particulate matter ≤ 10 µm	52,270	1,540	400	54,209
Particulate matter ≤ 2.5 µm	48,140	1,449	387	49,976
Polychlorinated dioxins and furans (TEQ)	4.69×10^{-8}	2.98×10^{-8}	1.13×10^{-6}	1.21×10^{-6}
Polycyclic aromatic hydrocarbons (B[a]Peq)	2.70	0.28	0.00060	2.99
Selenium and compounds	–	–	0.0020	0.0020
Styrene (ethenylbenzene)	3,387	94.7	0.57	3,482
Sulfur dioxide	2,165	1,802	20.6	3,988
Toluene (methylbenzene)	263,552	14,007	14.8	277,574
Total volatile organic compounds	3,026,530	389,878	973	3,417,381
Xylenes (individual or mixed isomers)	283,342	9,925	11.9	293,278
Zinc and compounds	–	–	0.16	0.16

Spatial allocation

Emissions from recreational boating were spatially allocated based on the assumption of traffic flowing between key activity points along the coast (i.e. boat harbours and boat ramps), and transit to and from Rottnest Island.

The spatial allocation of recreational boating CO emissions is presented in Figure 5.

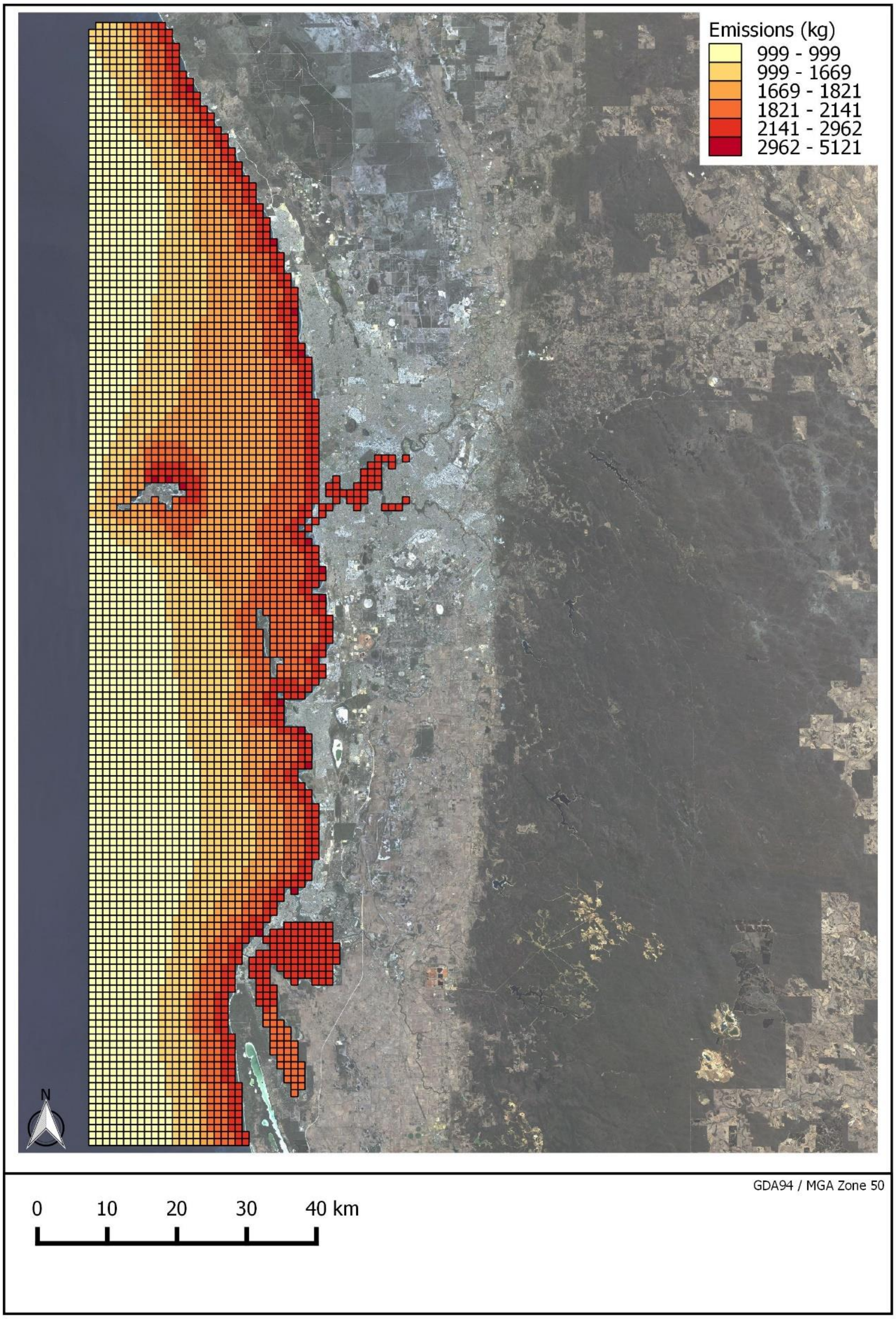


Figure 5 – Spatial allocation of recreational boating CO emissions

2.4 Locomotive emissions

Locomotive emission estimates apply to the operation of non-electric trains on the Perth rail network. Emissions calculated for locomotive activity include:

- passenger movements (Australind, AvonLink, MerredinLink and Prospector services); and
- freight haulage.

Methodology

Locomotive emissions were generated using the following equation.

$$E_i = EF_i \times A$$

Where:

E_i	=	Emissions of substance (i)	(kg/yr)
EF_i	=	Emission factor for substance (i)	(kg/kL)
A	=	Activity of locomotives	(kL/yr)
i	=	Substance	(–)

The emission factors used to simulate locomotive activities were derived from multiple sources.

Emissions of carbon monoxide, oxides of nitrogen, particulate matter (PM_{10} and $PM_{2.5}$) and total volatile organic compounds (TVOC) were estimated using USEPA (2009). USEPA emission factors[8] were converted to metric units using the equation below from USEPA (2009), as presented in NSW EPA (2012).

$$EF_i = \frac{EF_{US,i} \times CF}{3.7862}$$

Where:

EF_i	=	Emission factor for substance (i) – metric	(kg/kL)
$EF_{US,i}$	=	Emission factor for substance (i) – imperial	(g/bhp.h)
CF	=	Conversion factor – 20.8	(bhp.h/gal)
3.7862	=	Unit conversion factor	(litres/gal)
i	=	Substance (CO, NO_X, PM_{10}, $PM_{2.5}$, TVOC)	(–)

[8] USEPA (2009), Table 1 (page 2) – $PM_{2.5}$ is estimated as 0.97 of the PM_{10} estimates (page 4) and TVOC emission factor is 1.053 times the hydrocarbon (HC) emission factor (page 4)

Exhaust sulfur dioxide emissions were calculated using the method documented in NSW EPA (2012), as presented below.

$$EF_{SO2} = (\rho_d \times 1000 \times 0.97753 - EF_{THC}) \times 0.01 \times 0.005 \times 2$$

Where:

EF_{SO2}	=	Emission factor for SO_2	(kg/kL)
ρ_d	=	Density of diesel – 0.836	(kg/litre)
EF_{THC}	=	Emission factor for total hydrocarbons (THC) – 2.6369	(kg/kL)
3.7862	=	Conversion factor	(litres/US gal)
1000	=	Conversion factor	(litres/kL)
0.97753	=	Fractional sulfur in fuel converted to sulfur dioxide	(–)
0.01	=	Conversion factor from percent to fraction	(–)
0.005	=	Sulfur content of diesel – 50 ppm	(%)
2	=	Molecular weight of sulfur dioxide divided by molecular weight sulfur	(–)

Ammonia and metal emissions were calculated using emission factors presented in Pechan (2004) and locomotive emission estimation methods presented in Pechan (2005). Emission factors[9] were converted to metric units using the following equation.

$$EF_i = \frac{EF_{US,i} \times 0.454}{0.00379}$$

Where:

EF_i	=	Emission factor for substance (i) – metric	(kg/kL)
$EF_{US,i}$	=	Emission factor for substance (i) – imperial	(lb/gal)
0.454	=	Conversion factor	(kg/lb)
0.00379	=	Conversion factor	(kL/gal)
i	=	Substance (ammonia, beryllium, cadmium, lead)	(–)

[9] Pechan (2004), Table III-5 (page 45) and Pechan (2005), Table C-2 (page C-4)

PAH emission factors were calculated using the following equation and PM_{10} fractions from Pechan (2005).

$$EF_{PAH,i} = \sum EF_{PM10,i} \times PAH_{i,j} \times WHO_j$$

Where:

$EF_{PAH,i}$	=	PAH emission factor for fuel type (i)	(kg/kL)
$EF_{PM10,i}$	=	PM_{10} emission factor for fuel type (i)	(kg/kL)
$PAH_{i,j}$	=	PAH speciation profile[10] for fuel type (i), and substance (j)	(%)
WHO_j	=	World Health Organization (1998)[11] relative potency for substance (j)	(lb/lb.mol)
i	=	Fuel type	(–)
j	=	Substance	(–)

Emission factors are summarised in Table 27 of Appendix A. VOC emissions were speciated using profiles in Pechan (2005), and are reproduced in Table 35 of Appendix B.

Activity data

Emission estimates for locomotives were based on total fuel use. For passenger movements, fuel use data were sourced from the Public Transport Authority (PTA) for 2011–12. Fuel data for each passenger service were whole-of-route, and had to be scaled based on the proportion of the route within the study area.

For freight haulage, fuel use was estimated based on gross tonne kilometres (GTKs) using a conversion rate of 0.005 litres of fuel per GTK (Johnson et al. 2013). GTK data within the study area were sourced from Brookfield Rail.

GTK and fuel consumption by locomotives within the study area are presented in Table 14.

Table 14 – Calculated locomotive fuel consumption

Source	Gross tonne kilometres (GTK)	Fuel use (kL/yr)
Passenger movements	–	492
Freight haulage	5,356,770,493	26,784

[10] Pechan (2005)

[11] World Health Organization (1998) polycyclic aromatic hydrocarbon potencies, as published in NPI (2015)

Emission estimates

Emissions of pollutants from locomotives are summarised in Table 15.

Table 15 – Locomotive total emissions

Pollutant	Emissions (kg/yr)		
	Passenger movements	Freight haulage	Total
Acetaldehyde	72.5	3,948	4,020
Acrolein	4.14	225	229
Ammonia (total)	10.8	589	600
Benzene	27.8	1,513	1,541
Beryllium and compounds	0.025	1.35	1.37
1,3-Butadiene (vinyl ethylene)	2.54	138	141
Cadmium and compounds	0.025	1.35	1.37
Carbon monoxide	3,457	188,340	191,797
Ethylbenzene	4.23	231	235
Formaldehyde	161	8,787	8,948
n-Hexane	2.17	118	121
Lead and compounds	0.077	4.17	4.25
Oxides of nitrogen	23,227	1,265,410	1,288,638
Particulate matter ≤ 2.5 µm	838	45,672	46,511
Particulate matter ≤ 10 µm	864	47,085	47,949
Polychlorinated dioxins and furans (TEQ)	0.0000022	0.00012	0.00012
Polycyclic aromatic hydrocarbons (B[a]Peq)	0.0013	0.071	0.072
Styrene (ethenylbenzene)	0.81	44.2	45.0
Sulfur dioxide	40.5	2,206	2,246
Toluene (methylbenzene)	20.4	1,113	1,134
Total volatile organic compounds	1,365	74,371	75,736
Xylenes (individual or mixed isomers)	14.4	787	801

Spatial allocation

Emissions from locomotives were spatially allocated using imagery and spatial data supplied by Brookfield Rail. Emissions from freight haulage were allocated proportionate to GKT data. Emissions from passenger locomotives were allocated for the length of activity overlapping Brookfield Rail segments.

The spatial allocation of locomotive NO_X emissions is presented in Figure 6.

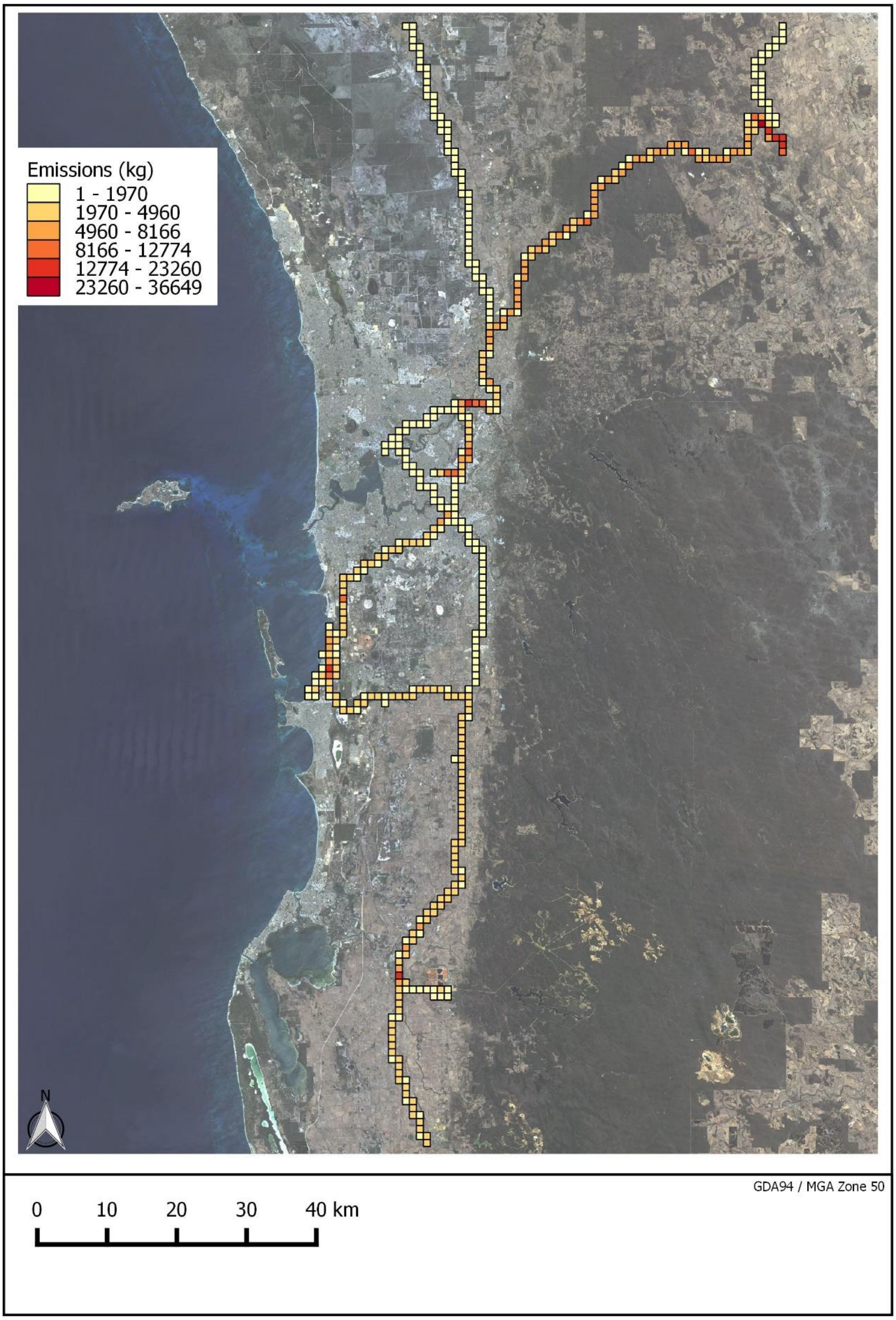


Figure 6 – Spatial allocation of locomotive NO_X emissions

2.5 Shipping emissions

Shipping emission estimates include transit, manoeuvring, berthing and anchorage activities by commercial ships. Commercial shipping within the study area is primarily conducted at the Fremantle inner harbour, bulk handling jetties in the outer harbour, and the naval base on Garden Island.

Methodology

Emissions from shipping have been estimated using data and methods consistent with the approach used by the Department of Science, Information Technology and Innovation (DSITI 2017). The equations and factors detailed below are sourced from this report.

Emissions estimated include sources from modes of shipping activity:

- transit, including open ocean and within-harbour movements;
- manoeuvring to enter/exit berth; and
- boiler and/or engine operation while at anchor or berth.

Emissions for all shipping activities were calculated using the equation below.

$$\boldsymbol{E_i = \sum \frac{EF_{i,s,a,m,f,e} \times F_a}{1000}}$$

Where:

E_i	=	Emissions of substance (i)	(kg/yr)
$EF_{i,s,a,m,f,e}$	=	Emission factor for substance (i), from ship type (s), during activity type (a), for machinery type (m), fuel type (f), and engine type (e)	(g/kg fuel use)
F_a	=	Fuel consumed for activity type (a)	(kg/yr)
i	=	Substance	(–)
s	=	Ship type	(–)
a	=	Activity (transit, manoeuvring, anchoring/berthing)	(–)
m	=	Machinery type (main engine, auxiliary engine, auxiliary boiler	(–)
f	=	Fuel type (residual oil, marine diesel)	(–)
e	=	Engine type (slow-speed diesel, medium-speed diesel, high-speed diesel, gas turbine, steam turbine)	(–)

Fuel consumption is calculated for both auxiliary and main engine activity, with auxiliary power providing support to the ship including heating of residual fuels, cargo temperature control and power for crew and passenger amenities. Fuel types covered in the study include residual oil (bunker fuel) and marine distillates.

Fuel consumption was estimated based on engine, machinery, fuel, and activity of each ship operating in the study area.

Fuel consumption for berth and anchor operations was estimated using the following equation.

$$\boldsymbol{F_{f,m} = \sum_{p=1}^{p=n} Y_s \times GT \times T \times P_{f,m}}$$

Where:

$F_{f,m}$	=	Fuel consumption for fuel type (f) and machinery type (m)	(kg/yr)
Y_s	=	Fuel consumption rate for ship type (s)	(kg/GT/hour)
GT	=	Gross tonnage of ship	(tonnes)
T	=	Time of activity	(hours)
$P_{f,m}$	=	Proportion of fuel consumed by fuel type (f) and machinery type (m)	(%)
f	=	Fuel type	(–)
m	=	Machinery type	(–)
s	=	Ship type	(–)

Fuel consumption for transit in the open ocean and along shipping channels was estimated using the following two equations for main engines and auxiliary engines respectively.

$$\boldsymbol{F_{f,m} = \sum_{p=1}^{p=n} (O_1 \times A_s \times GT^b \times D \times P_{f,m}) \left(\frac{V}{V_{ss}}\right)^3}$$

Where:

$F_{f,m}$	=	Transit main engine fuel consumption for fuel type (f) and machinery type (m)	(kg/yr)
O_1	=	Main engine power correction factor – 1.001	(–)
A_s	=	Fuel consumption rate for ship type (s)	(kg/km)
GT	=	Gross tonnage of ship	(tonnes)
b		(b) modifies fuel consumption by ship type (s)	(–)
D	=	Distance travelled during activity	(km)

$P_{f,m}$	=	Proportion of fuel consumed by fuel type (f) and machinery type (m)	(%)
V	=	Vessel speed	(km/hr)
V_{ss}	=	Maximum vessel speed under normal conditions[12]	(km/hr)
f	=	Fuel type	(–)
m	=	Machinery type	(–)
s	=	Ship type	(–)

$$F_{f,m} = \sum_{p=1}^{p=n} \left(O_2 \times A_s \times GT^b \times D \times P_{f,m}\right), when \left(\frac{V}{V_{ss}}\right)^3 > 0.20$$

Where:

$F_{f,m}$	=	Transit auxiliary engine fuel consumption for fuel type (f) and machinery type (m)	(kg/yr)
O_2	=	Auxiliary engine power correction factor – 0.084	(–)
A_s	=	Fuel consumption rate for ship type (s)	(kg/km)
GT	=	Gross tonnage of ship, where (b) modifies fuel consumption by ship type (s)	(tonnes)
b		(b) modifies fuel consumption by ship type (s)	(–)
D	=	Distance travelled during activity	(km)
$P_{f,m}$		Proportion of fuel consumed by fuel type (f) and machinery type (m)	(%)
V		Vessel speed	(km/hr)
V_{ss}		Maximum vessel speed under normal conditions[13]	(km/hr)
f	=	Fuel type	(–)
m	=	Machinery type	(–)
s	=	Ship type	(–)

The $(V/V_{ss})^3$ function of these equations calculates vessel speed against open ocean service speeds. Vessels operating with a $(V/V_{ss})^3$ function less than 0.20 were assumed to be in manoeuvring conditions.

Auxiliary boiler and auxiliary engine activity varies under slow speed and heavy loads, with the use of thrusters and short high-revolution main engine bursts prevalent when approaching or departing a dock.

[12] NSW EPA (2012), Table 3-161 (p363)

[13] NSW EPA (2012), Table 3-161 (p363)

Fuel consumption for ships completing manoeuvring activities was estimated using the following equation.

$$F_{f,m} = \sum_{p=1}^{p=n} \left(O_3 \times Y_s \times GT \times T \times P_{f,m}\right), when \left(\frac{V}{V_{ss}}\right)^3 \leq 0.20$$

Where:

$F_{f,m}$	=	Manoeuvring auxiliary engine fuel consumption for fuel type (f) and machinery type (m)	(kg/yr)
O_3	=	Power correction factor: Variable for auxiliary engines, fixed when calculating for auxiliary boilers – 1.000	(–)
Y_s		Fuel consumption rate for ship type (s)	(kg/GT/hour)
GT	=	Gross tonnage of ship	(tonnes)
T		Time of activity	(hours)
$P_{f,m}$		Proportion of fuel consumed by fuel type (f) and machinery type (m)	(%)
V		Vessel speed	(km/hr)
V_{ss}		Maximum vessel speed under normal conditions[14]	(km/hr)
f	=	Fuel type	(–)
m	=	Machinery type	(–)
s	=	Ship type	(–)

Fuel consumption for both auxiliary engines and auxiliary boilers was calculated using the same equation. The main engine transit equation was used to calculate main engine fuel consumption under manoeuvring conditions.

Factors utilised in the equations are detailed in Table 16, and parameters applied in the equations are detailed in Table 17: both are sourced from DSITI (2017).

[14] NSW EPA (2012), Table 3-161 (p363)

Table 16 – Shipping parameters by ship type

Ship type (s)	Fuel consumption rate in transit – A (kg/km)	b variable (–)	Fuel consumption rate at berth/anchor and manoeuvring – Y (kg/GT/h)	Power correction factor – O_3
Bulk carrier	0.31	0.52	0.0024	2.05
Container	0.05	0.74	0.0050	2.78
Cruise	0.17	0.61	0.0069 [15]	1.00
Ferry	1.23	0.40	0.0069	2.05
General cargo	0.16	0.60	0.0054	2.05
Reefer	0.23	0.56	0.0246	1.41
Ro-Ro	1.23	0.40	0.0069	1.50
Oil tanker	0.23	0.56	0.0193	1.27
Tanker	0.23	0.56	0.0193	1.27
Vehicle carrier	0.16	0.60	0.0092	1.73
Other	0.16	0.60	0.0092	2.05

Table 17 – Auxiliary engine type ratios (P) by engine and ship type

Ship type (s)	Stationary			Moving	
	AE-MD[16]	AE-RO[17]	AB-RO[18]	AE-MD[19]	AE-RO[20]
Bulk carrier	23%	48%	29%	32%	68%
Container	12%	46%	42%	21%	79%
Cruise	0%	81%	19%	0%	100%
General cargo	17%	48%	35%	27%	73%
Reefer	12%	46%	42%	21%	79%
Ro-Ro	13%	79%	8%	14%	86%
Oil tanker	9%	30%	60%	24%	76%
Tanker	9%	30%	60%	24%	76%
Vehicle carrier	21%	46%	32%	32%	68%
Other	10%	30%	60%	24%	76%

[15] Ferry ratio adopted in absence of cruise ship value

[16] Auxiliary engine using marine distillate fuel

[17] Auxiliary engine using residual oil fuel

[18] Auxiliary boiler using residual oil fuel

[19] Auxiliary engine using marine distillate

[20] Auxiliary engine using residual oil

Emission factors for key pollutants and polycyclic aromatic hydrocarbons were sourced from Goldsworthy and Goldsworthy (2015). Emission factors for metals were sourced from Cooper and Gustafsson (2004). Emission factors are summarised in Appendix A.

Particulate emissions from manoeuvring activities were speciated using the USEPA PMPROF database (CARB 2014b) and are presented in Table 36 of Appendix B. VOC emissions were speciated using the USEPA ORGPROF database (CARB 2015) and are presented in Table 37 of Appendix B.

Activity data

Shipping activities for 2011–12 were provided by Fremantle Ports. The number of visits to locations within the study area is detailed in Table 18. These movements (shifts) include activities within port waters (i.e. location to location). In total, 2,159 ships visited Fremantle Port waters in 2011–12.

Ships that did not combust fuel were removed from the dataset (e.g. non-propelled barges, sailing ships). The dataset was cleaned before calculations were completed, including removal of negative time values and reconfiguration of speeds exceeding maximum speed for the ship type.

Table 18 – Shipping movements by location

Location	Number of shifts
Cockburn Sound anchorage	616
General anchorage	237
Inner harbour jetties	1,260
Outer harbour jetties	1,355
Beyond port limits	2,191
Ship yards	1,112

The number of shifts by ship type and time spent in each mode of transport is presented in Table 19.

Table 19 – Shipping movements and total time in mode by ship type

Ship type	# shifts	Total hours			
		Transit[21]	Manoeuvring	Berth	Anchor
Barge carrier	170	315	67	21,399	1,605
Bitumen tanker	33	45	10.0	283	468
Bulk carrier	1,365	2,662	444	25,214	27,235
Buoy/lighthouse vessel	13	18.0	4.50	371	429
Chemical tanker	4	8.69	1.00	38	–

[21] Includes transit and reduced speed zone modes

Ship type	# shifts	Total hours			
		Transit[21]	Manoeuvring	Berth	Anchor
Chemical/oil products tanker	271	474	90	3,312	3,375
Container ship	1,076	1,637	298	18,355	3,044
Crude oil tanker	324	601	131	3,966	15,531
General cargo	631	1,004	207	19,825	7,733
Heavy load carrier	97	131	39	6,409	1,259
Icebreaker	6	6.94	2.00	137	138
Landing craft	3	5.66	1.00	63	–
Livestock carrier	146	208	46	3,168	2,074
LPG tanker	26	48	8.50	492	594
Miscellaneous	36	56	12.0	0.73	–
Motor hopper	18	20	8.50	1,219	29
Naval/naval auxiliary	68	109	22	2,895	481
Non-merchant	8	7.52	1.50	21	–
Offshore support vessel	23	28	8.00	820	444
Offshore tug/supply ship	750	1,285	304	25,426	13,312
Oil products tanker	337	493	102	7,968	8,028
Ore carrier	2	5.16	0.50	32	–
Other bulk dry	47	80	19.0	4,257	45
Other dry cargo	38	55	15.5	1,876	206
Other offshore	33	40	14.5	3,639	–
Passenger ship	91	125	24	837	688
Pipe layer	5	10.9	2.00	116	45
Platform supply ship	21	47	7.50	753	351
Pontoon	5	14.5	2.00	17.6	21
Research vessel	12	17.2	3.50	568	25
Ro-Ro cargo ship	32	52	13	1,757	1,116
Tankers	3	5.56	1.00	92	38
Towing/pushing	20	41	8.50	119	2,765
Tug	139	250	54	21,568	1,045
Utility vessel	29	51	12.5	2,539	293
Vehicles carrier	487	776	131	4,796	1,124

To support the equations from Section 2.5 and data provided by Fremantle Port, the following assumptions were applied when completing calculations:

- ships with a gross tonnage greater than 2,500 used slow-speed main engines, with vessels below this value assigned medium-speed main engines;
- all auxiliary engines were medium speed;

- the distance travelled during manoeuvring activities was 200 metres;
- manoeuvring was assumed to take 30 minutes per shift, irrespective of ship type or size;
- auxiliary engines were switched off when time at berth was greater than 10 days;
- ships docking at a ship yard for maintenance were limited to two days of auxiliary engine activity, to account for testing;
- main engines were switched off when at berth or anchor;
- auxiliary boilers were switched off during transit operations;
- all main engines used residual oil fuel only; and
- auxiliary boilers used residual oil fuel only.

Generation of manoeuvring activity data relied solely on these assumptions, with the method differing to that applied in DSITI (2017).

Fuel consumption for the study area is presented by fuel and engine type in Table 20.

Table 20 – Shipping fuel consumption

Source	Total fuel (kg)			
	Anchor/ berth	Manoeuvring	Transit	Total
Main engine – residual oil	–	0.13	5,006,759	5,006,759
Auxiliary engine – residual oil	16,736,242	275,461	1,124,362	18,136,066
Auxiliary engine – marine distillate	5,606,048	93,145	364,141	6,063,334
Auxiliary boiler – residual oil	25,592,844	211,166	550,189	26,354,198

Emissions estimates

Emissions of pollutants from shipping are summarised in Table 21.

Table 21 – Shipping total emissions

Pollutant	Emissions (kg/yr)			
	Anchor/berth	Manoeuvring	Transit	Total
Ammonia (total)	550	7.01	152	710
Antimony and compounds	0.30	0.0049	0.028	0.33
Arsenic and compounds	31.7	0.41	9.68	41.8
Benzene	1,041	15.7	339	1,396
Cadmium and compounds	0.49	0.0067	0.13	0.63

Pollutant	Emissions (kg/yr)			
	Anchor/berth	Manoeuvring	Transit	Total
Carbon monoxide	126,301	1,945	30,715	158,961
Chlorine and compounds	2.84	0.047	0.26	3.15
Chromium (total)	47.6	0.60	10.6	58.8
Cobalt and compounds	115	1.38	34.4	151
Copper and compounds	80.5	1.11	20.0	102
Ethylbenzene	34	0.51	11.0	45
Formaldehyde (methyl aldehyde)	48	0.73	15.7	65
n-Hexane	767	11.5	249	1,028
Lead and compounds	5.50	0.09	1.52	7.12
Manganese and compounds	115	1.39	34.4	151
Mercury and compounds	0.11	0.0014	0.029	0.14
Nickel and compounds	1,219	16.2	326	1,561
Oxides of nitrogen	1,619,111	25,259	851,653	2,496,023
Particulate matter ≤ 2.5 µm	218,093	2,661	64,135	284,889
Particulate matter ≤ 10 µm	237,784	2,903	69,607	310,294
Polychlorinated dioxins and furans (TEQ)	0.00018	0.0000023	0.000051	0.00024
Polycyclic aromatic hydrocarbons (B[a]Peq)	758	9.46	219	986
Selenium and compounds	0.72	0.010	0.19	0.92
Sulfur dioxide	2,290,471	26,619	525,428	2,842,517
Toluene (methylbenzene)	1,037	15.6	337	1,390
Total volatile organic compounds	48,216	726	15,690	64,632
Xylenes (individual or mixed isomers)	530	7.99	173	711
Zinc and compounds	52.5	0.71	15.0	68.1

Spatial allocation

Emissions were spatially allocated using locational coordinates and spatial maps provided by Fremantle Port. Emissions from anchor, berth and manoeuvring were allocated to the point of activity. Transit emissions within port waters were assigned to each respective channel, and are unique to each shift. Open ocean emissions were allocated on a path directly west of port waters, based on advice that ships travel west beyond Rottnest Island before setting a bearing for the next port.

The spatial allocation of sulfur dioxide emissions from shipping activities is presented in Figure 7.

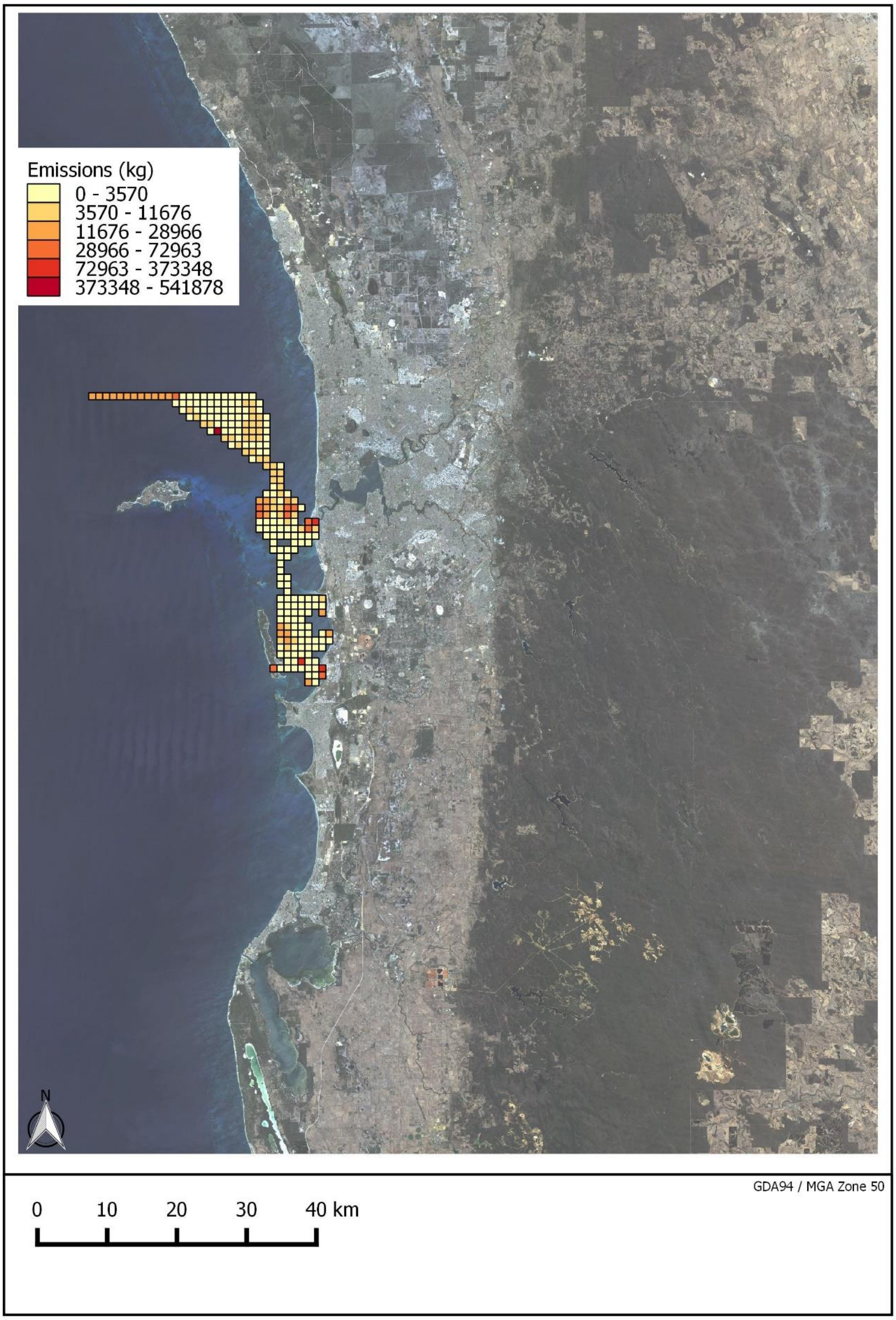


Figure 7 – Spatial allocation of shipping SO_2 emissions

3 Total emission estimates

This section presents cumulative and comparative estimates for off-road mobile emissions.

To assess the relative risk for all emission estimates, toxic equivalency potential (TEP) scores were calculated. TEP is a technique increasingly being used by Australian and international environment agencies for comparing substances that have varying toxicities. TEP provides a screening-level evaluation of substances according to their effect on human health, and can be calculated in two ways. The ‘non-cancer risk’ score converts emissions to toluene-equivalents and is an assessment of the potential impact of toxins on general human health. The ‘cancer risk’ score converts emissions to benzene-equivalents and is an assessment of the potential impact of carcinogenic toxins (Scorecard 2015)[22].

This study assessed TEP using the non-cancer risk score to indicate the general health risk. TEP is calculated by multiplying the emission estimates for substances by their corresponding non-cancer risk score. A list of NPI substances and their associated risk scores is included in Appendix C.

3.1 Total off-road mobile emissions

Emission estimates and TEP scores for all off-road mobile sources are presented in Table 22.

Table 22 – Off-road mobile total emissions estimates

Substance	Emissions (tonnes/year)	Toxic equivalency potential (TEP) score
Key pollutants		
Oxides of nitrogen	6,826	15,018
Sulfur dioxide	2,949	9,143
Particulate matter ≤ 2.5 µm	467	7,938
Total volatile organic compounds	5,861	5,861
Carbon monoxide	15,323	2,145
Particulate matter ≤ 10 µm	502	754
Other NPI-listed pollutants		
Polychlorinated dioxins and furans (TEQ)	0.00000059	517,663
Acrolein	13.9	22,302
Cadmium and compounds	0.0046	8,759
Lead and compounds	0.013	7,269
Cobalt and compounds	0.20	6,209
Mercury and compounds	0.0012	5,769
Nickel and compounds	1.61	5,155

[22] Further information on how TEP is calculated can be found on the Scorecard website at: http://scorecard.goodguide.com/env-releases/def/tep_caltox.html

Substance	Emissions (tonnes/year)	Toxic equivalency potential (TEP) score
Arsenic and compounds	0.042	3,524
Formaldehyde (methyl aldehyde)	89.0	1,425
Copper and compounds	0.11	1,401
Benzene	134	1,086
Toluene (methylbenzene)	447	447
Acetaldehyde	36.9	343
Chromium (total)	0.11	337
Manganese and compounds	0.20	157
Xylenes (individual or mixed isomers)	476	128
Antimony and compounds	0.0057	46.5
1,3-Butadiene (vinyl ethylene)	19.3	42.5
Beryllium and compounds	0.0014	32.9
Zinc and compounds	0.089	16.8
Ethylbenzene	107	15.0
Ammonia (total)	3.39	12.9
Selenium and compounds	0.0011	2.67
Phenol	3.51	1.33
Styrene (ethenylbenzene)	7.20	0.58
Acetone	2.39	0.12
Cumene (1-methylethylbenzene)	0.14	0.056
Cyclohexane	0.35	0.0070
n-Hexane	65.0	N/A
Chlorine and compounds	6.95	N/A
Polycyclic aromatic hydrocarbons (B[a]Peq)	0.77	N/A

The relative contributions of all off-road mobile emission sources to key pollutants are summarised in Figure 8 and Table 23. The relative contributions of off-road mobile emission sources to the overall TEP score are shown in Figure 9.

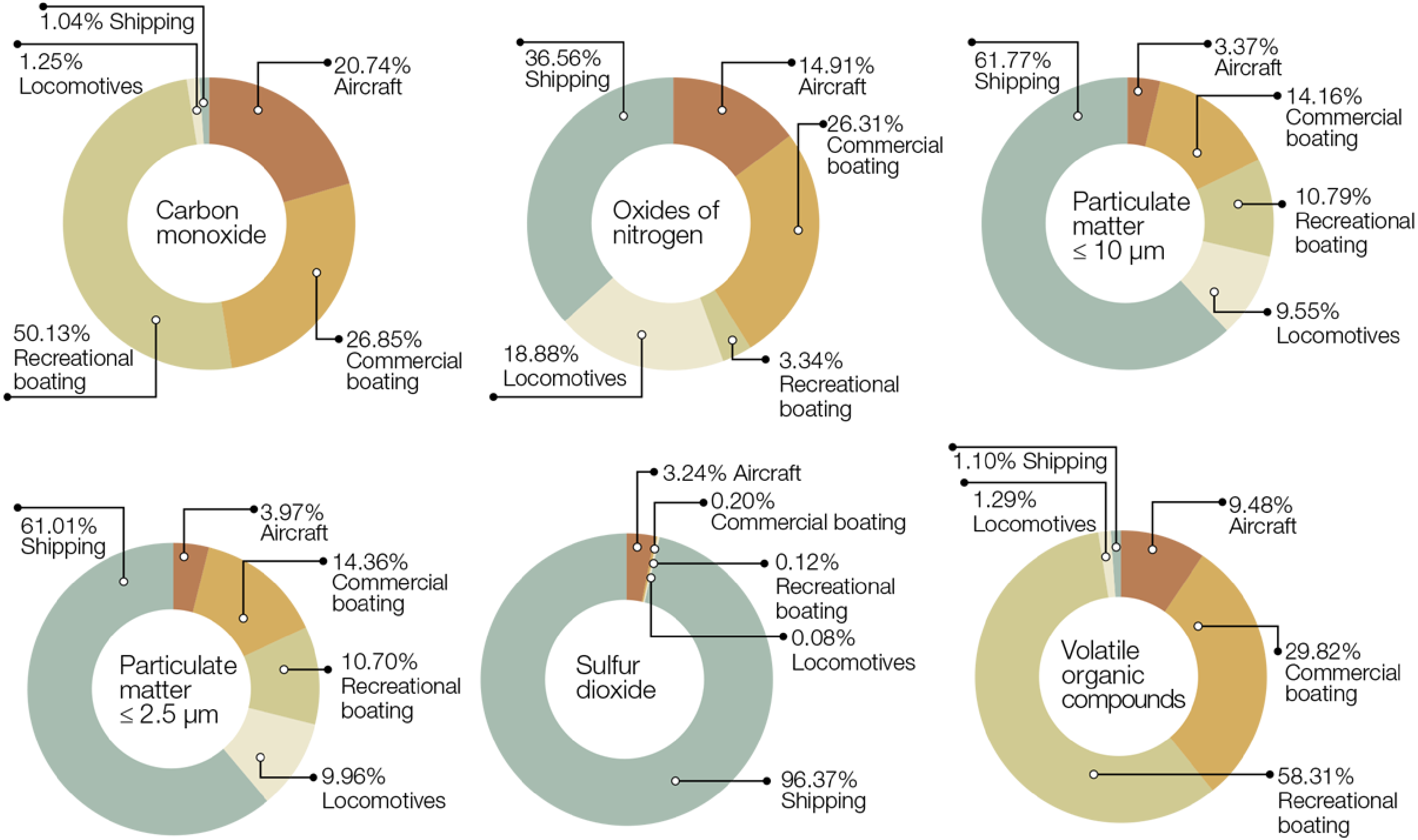


Figure 8 – Off-road mobile emission estimates: source contributions by mass

Table 23 – Off-road mobile emissions estimates by source

Substance	Emissions (tonnes/year)					Emissions (tonnes/ year)
	Aircraft	Commercial boating	Recreational boating	Locomotives	Shipping	
Key pollutants						
Carbon monoxide	3,178	4,114	7,681	192	159	15,323
Oxides of nitrogen	1,018	1,796	228	1,289	2,496	6,826
Particulate matter ≤ 2.5 µm	18.5	67.0	50.0	46.5	285	467
Particulate matter ≤ 10 µm	18.8	71.1	54.2	47.9	310	502
Sulfur dioxide	95.4	5.84	3.48	2.25	2,842	2,947
Total volatile organic compounds	555	1,747	3,417	75.7	64.6	5,861
Other NPI-listed pollutants						
Acetaldehyde	21.6	6.35	4.91	4.02	–	36.9
Acetone	2.39	–	–	–	–	2.39
Acrolein	12.1	0.71	0.87	0.23	–	13.9
Ammonia (total)	–	1.40	0.68	0.60	0.71	3.39
Antimony and compounds	–	0.0054	0.000056	–	0.00033	0.0057
Arsenic and compounds	–	0.00015	0.0000016	–	0.042	0.042
Benzene	9.19	44.4	77.6	1.54	1.40	134
Beryllium and compounds	–	–	–	0.0014	–	0.0014
1,3-Butadiene (vinyl ethylene)	8.38	3.99	6.80	0.14	–	19.3
Cadmium and compounds	–	0.0026	0.000027	0.0014	0.00063	0.0046
Chlorine and compounds	0.67	23.6	39.7	0.12	1.03	6.95
Chromium (total)	0.0049	0.017	0.028	–	0.059	0.11
Cobalt and compounds	0.0049	0.017	0.028	–	0.15	0.20

Substance	Emissions (tonnes/year)					Emissions (tonnes/ year)
	Aircraft	Commercial boating	Recreational boating	Locomotives	Shipping	
Copper and compounds	0.0049	0.0012	0.000012	–	0.10	0.11
Cumene (1-methylethylbenzene)	0.060	0.075	0.0010	–	–	0.14
Cyclohexane	–	0.012	0.34	–	–	0.35
Ethylbenzene	1.17	39.7	65.8	0.23	0.045	107
Formaldehyde (methyl aldehyde)	58.6	12.6	8.89	8.95	0.065	89.0
n-Hexane	0.69	2.36	3.88	–	0.0032	65.0
Lead and compounds	–	0.0012	0.000012	0.0042	0.0071	0.013
Manganese and compounds	0.0049	0.018	0.028	–	0.15	0.20
Mercury and compounds	–	0.0010	0.000010	–	0.00014	0.0012
Nickel and compounds	0.0049	0.017	0.028	–	1.56	1.61
Phenol	3.51	–	–	–	–	3.51
Polychlorinated dioxins and furans (TEQ)	–	0.00000023	0.0000000012	0.00000012	0.00000024	0.00000059
Polycyclic aromatic hydrocarbons (B[a]Peq)	0.027	0.0018	0.0030	0.000072	0.73	0.77
Selenium and compounds	–	0.00019	0.0000020	–	0.00092	0.0011
Styrene (ethenylbenzene)	1.56	2.16	3.48	–	–	7.20
Toluene (methylbenzene)	4.12	162	278	1.13	1.39	447
Xylenes (individual or mixed isomers)	3.77	177	293	0.80	0.71	476
Zinc and compounds	0.0049	0.015	0.00016	–	0.068	0.089
Total TEP for each source	**24,762**	**219,659**	**10,769**	**119,168**	**248,647**	**623,005**

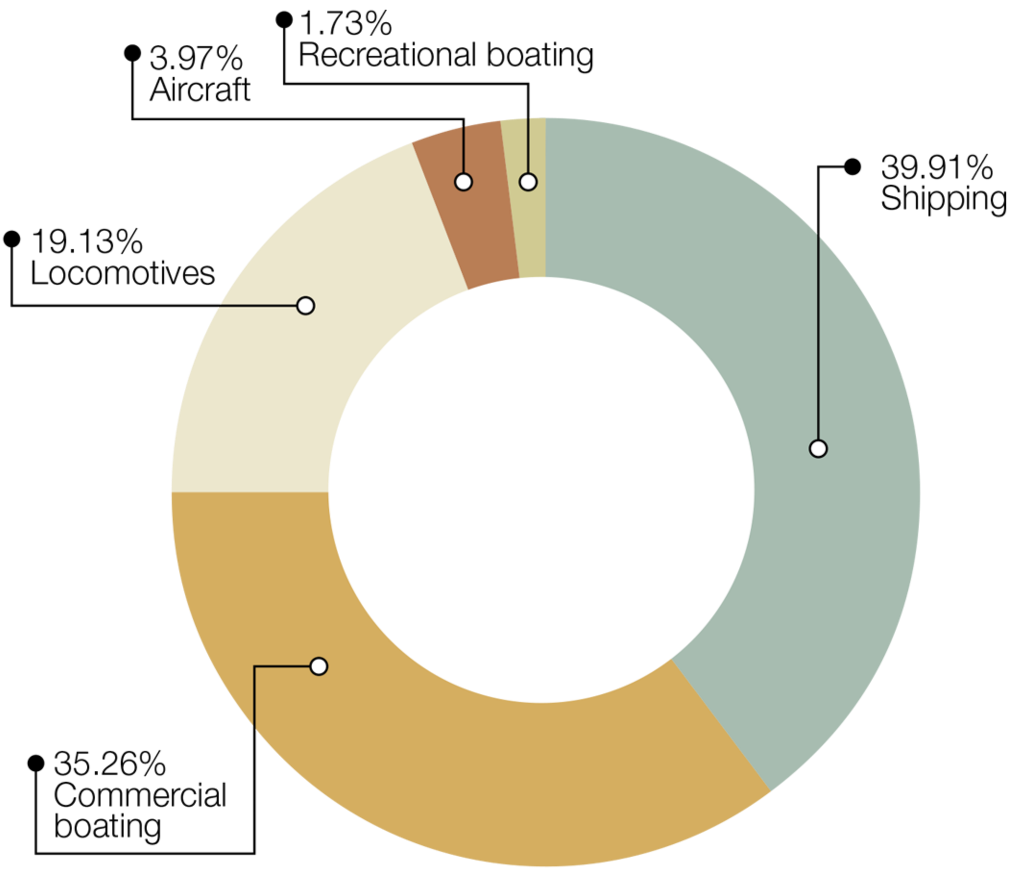


Figure 9 – Relative TEP contributions from off-road mobile sources

Carbon monoxide was the largest substance emitted by mass. NO_X emissions represented the greatest risk from the key pollutants list. Emissions of polychlorinated dioxins and furans (TEQ) were substantially smaller compared with key pollutant emissions, but represented a greater risk due to their high toxicity.

Shipping was the primary source of off-road particulate and SO_2 emissions. Exhaust emissions from 2-stroke petrol engines used in commercial and recreational boating contributed 16.6 per cent of $PM_{2.5}$ and 16.8 per cent of PM_{10} emissions.

The main source of off-road NO_X emissions was shipping, accounting for 36.6 per cent of emissions. Other large sources of NO_X emissions were diesel exhaust emissions from commercial boating (25.1 per cent) and locomotives (18.9 per cent).

Recreational boating was the primary source of off-road CO and VOCs. Exhaust emissions from 2-stroke petrol engines used in commercial and recreational boating accounted for 46.4 per cent of CO emissions and 79.5 per cent of VOC emissions.

3.2 Spatial allocation summary

Spatial allocation of key pollutant emissions from all off-road mobile sources is presented in Figure 10 through to Figure 15. Shipping emissions were the most significant source of emissions for most key pollutants. Airport activity was a notable source of NO_X, VOC and CO emissions, while VOC emissions from boating activity were large relative to other off-road VOC emission sources.

Spatial allocation of the TEP score for all off-road mobile sources is presented in Figure 16. Shipping and locomotive emissions had the highest emission risk per grid cell as these emissions were concentrated along relatively narrow transit routes.

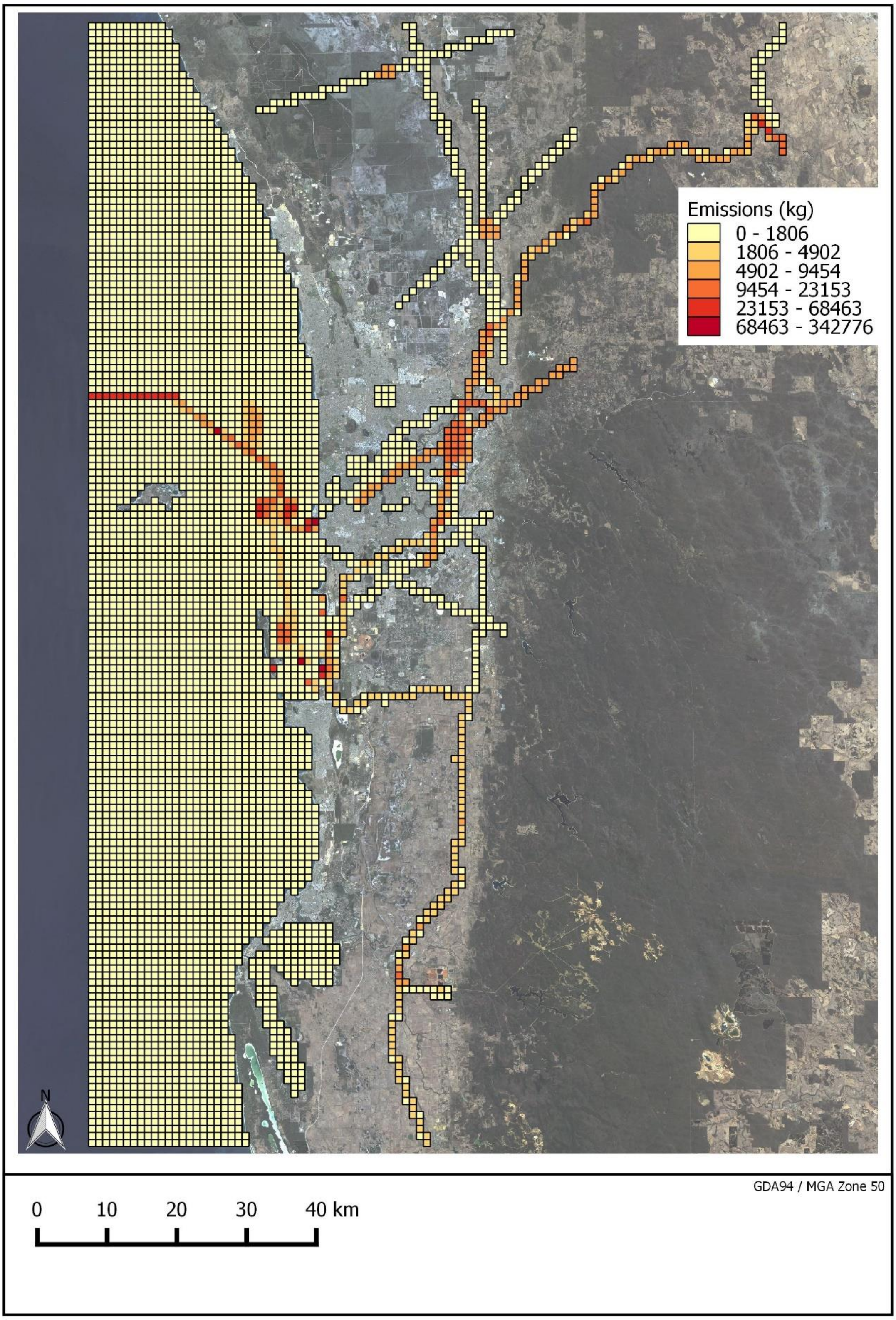


Figure 10 – Spatial allocation of off-road mobile NO_X emissions

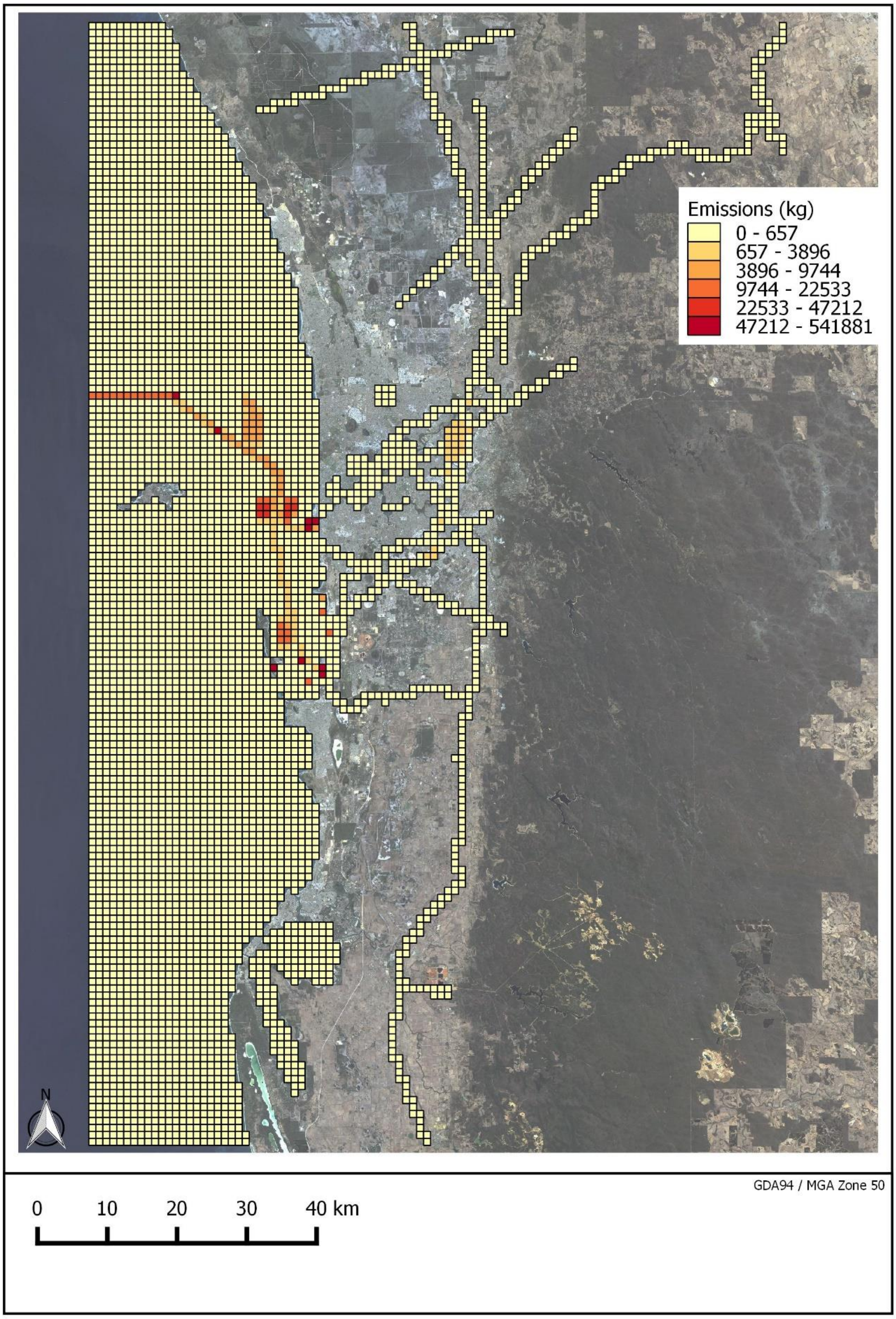


Figure 11 – Spatial allocation of off-road mobile SO_2 emissions

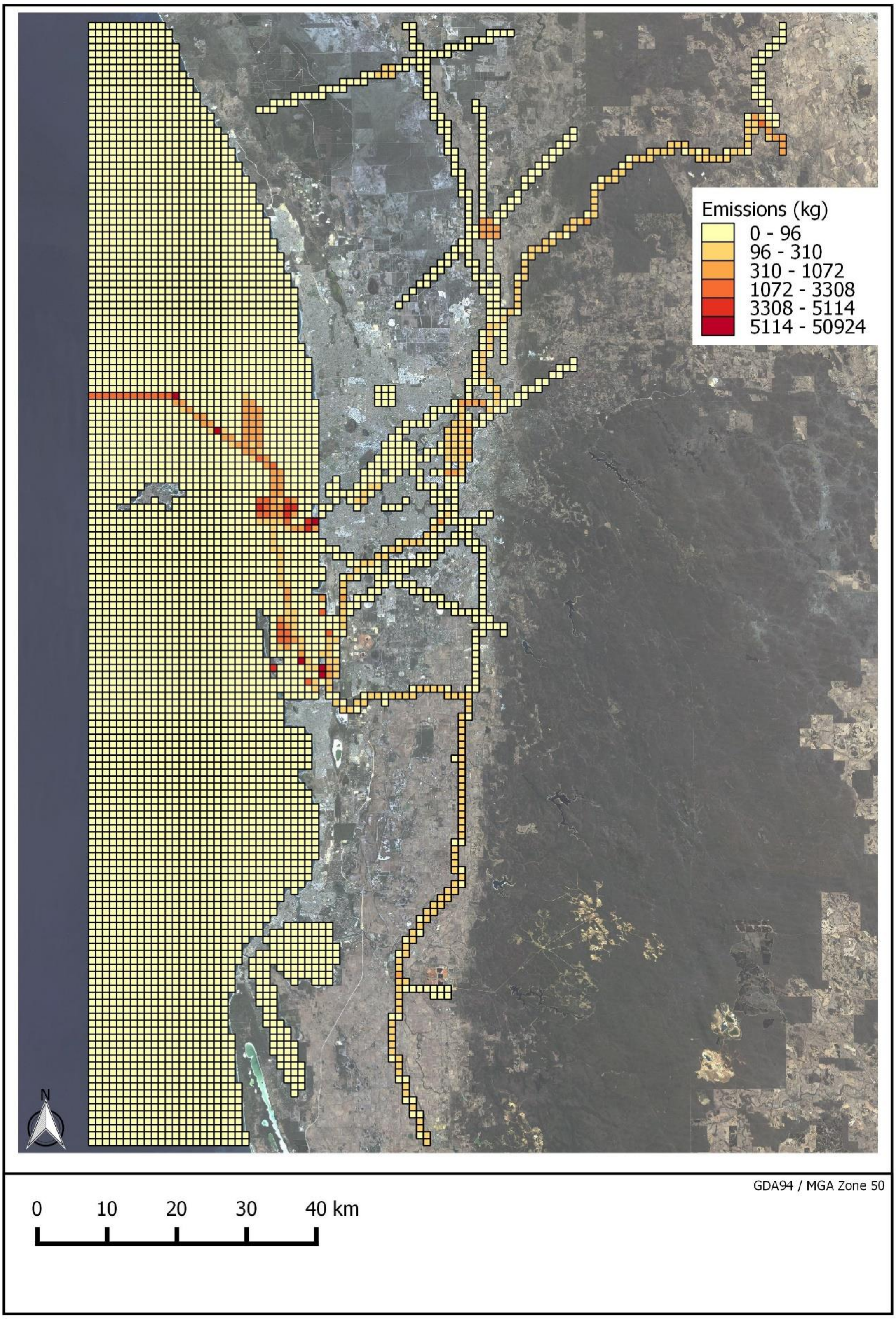


Figure 12 – Spatial allocation of off-road mobile $PM_{2.5}$ emissions

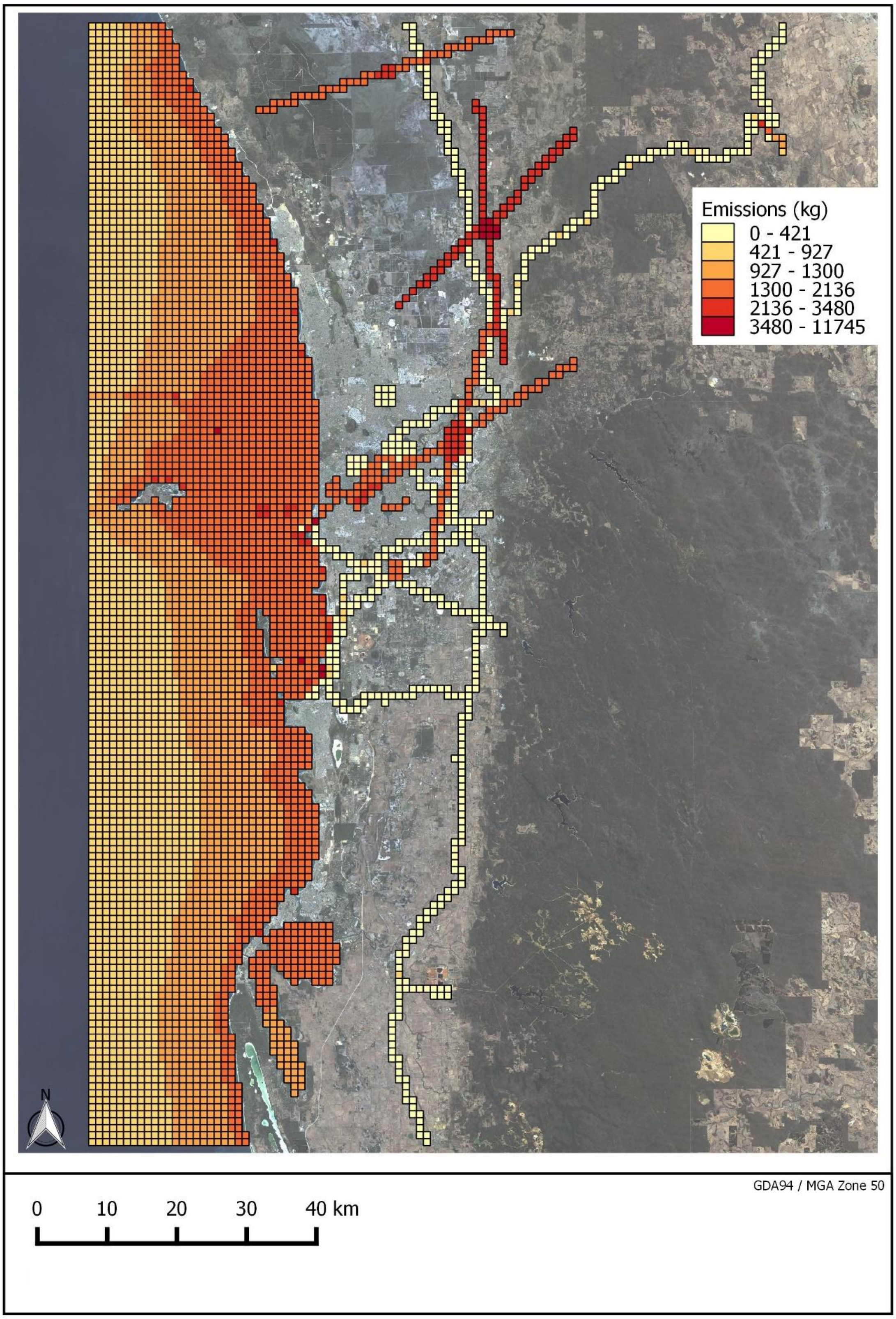


Figure 13 – Spatial allocation of off-road mobile VOC emissions

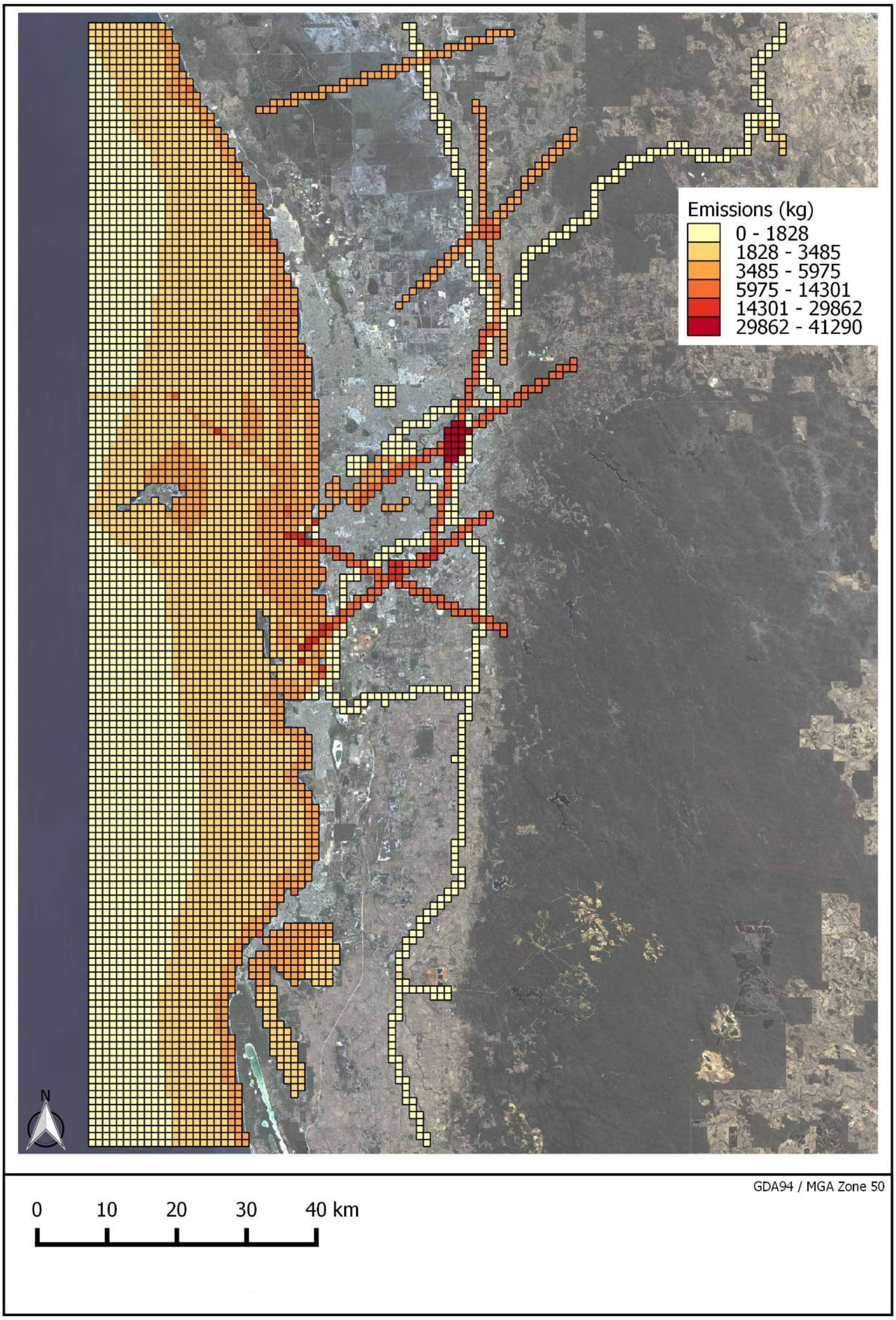


Figure 14 – Spatial allocation of off-road mobile CO emissions

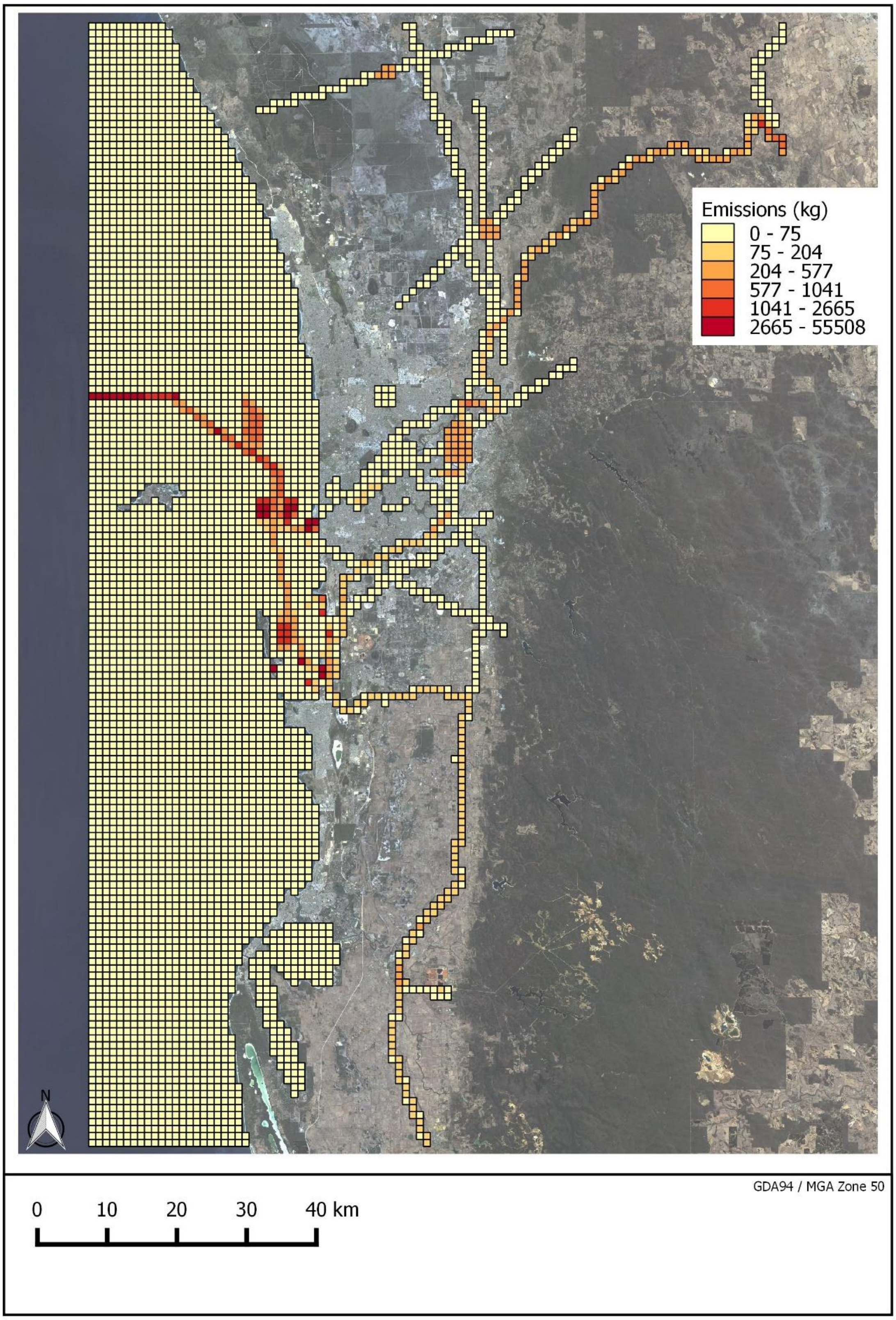


Figure 15 – Spatial allocation of off-road mobile PM_{10} emissions

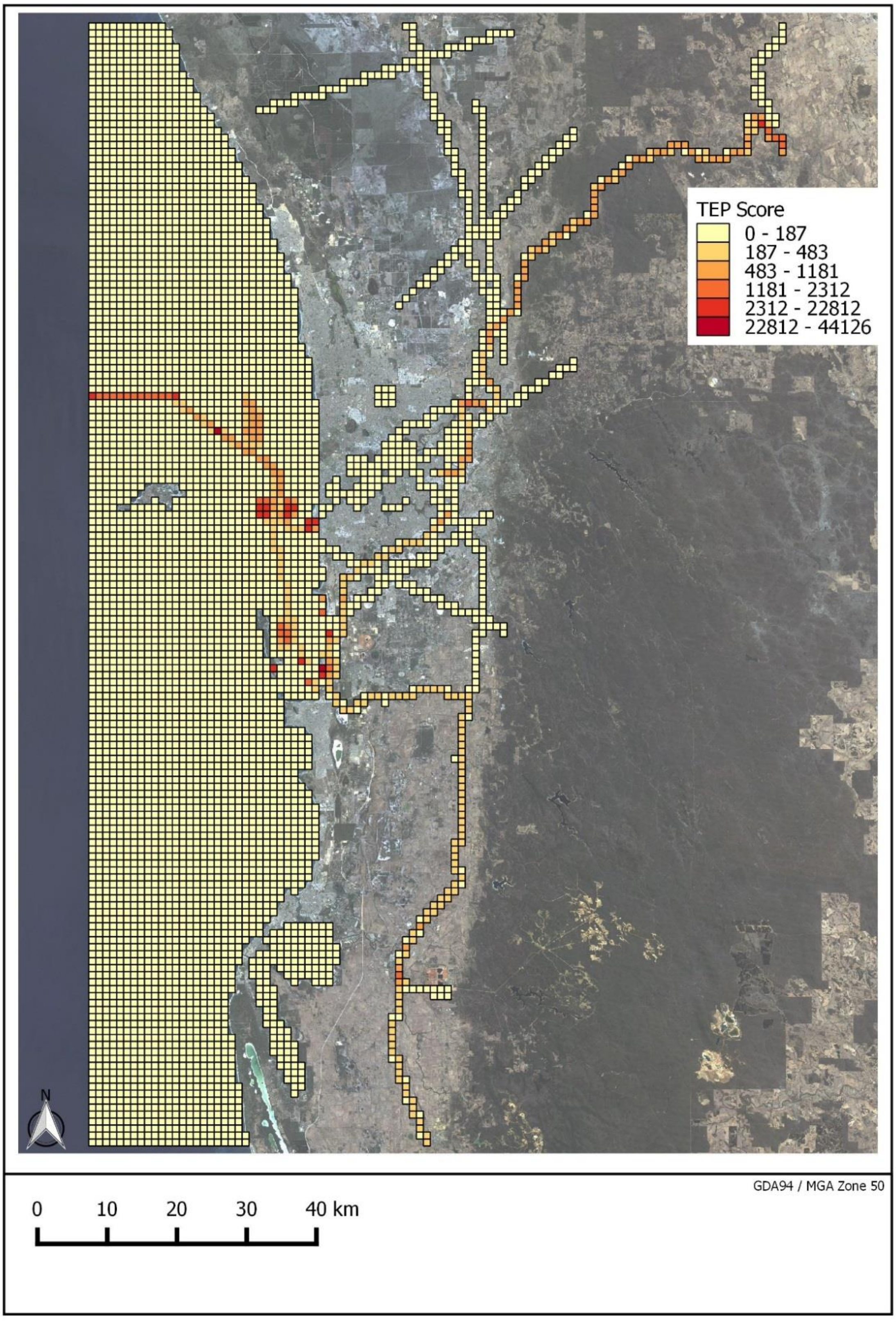


Figure 16 – Spatial allocation of off-road mobile TEP score

4 Key considerations

This study has found that:

- Shipping emissions were the most significant off-road mobile emission source in terms of emission risk. Shipping emissions were also the largest off-road mobile emission source for SO_2 and particles (PM_{10} and $PM_{2.5}$). Shipping emissions were mostly from ships at anchor or berth, burning low quality fuel.
- Emissions from shipping, aircraft and locomotives were concentrated along narrow transit lines, which increased the intensity of these emissions relative to the more diffuse emission sources of commercial and recreational boating.
- Polychlorinated dioxins and furans (TEQ) emissions were the most significant pollutant in terms of risk, making up 83 per cent of the total TEP score. Shipping and commercial boating were the main sources of this pollutant.
- The spatial allocation of commercial and recreational boating emissions was based on assumptions about activity between ports. Further investigation and measurement of recreational and commercial boating activity would significantly improve emission estimates and spatial allocation for these sources.

This study's outcomes should be viewed in the wider context of other major emission sources (natural, domestic, commercial and industrial, on-road vehicles) that were also part of the Perth Air Emissions Study 2011–2012.

Appendices

Appendix A – Emission factors

Aircraft emission factors

Table 24 – Aircraft emission factors

Source[23]	Substance	Emission factor [24]	Units
Avgas – exhaust	Ammonia (total)	0.028	kg/kL
	Carbon monoxide	791.18	
	Oxides of nitrogen	1.88	
	Particulate matter ≤ 10 µm	12.95	
	Particulate matter ≤ 2.5 µm	8.93	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	0.299	
	Polychlorinated dioxins and furans (TEQ)	3.19×10^{-12}	
	Sulfur dioxide	0.829	
	Total volatile organic compounds	11.98	
Avtur – exhaust	Ammonia (total)	0.021	kg/kL
	Carbon monoxide	8.64	
	Oxides of nitrogen	10.36	
	Particulate matter ≤ 10 µm	0.18	
	Particulate matter ≤ 2.5 µm	0.18	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	0.0124	
	Polychlorinated dioxins and furans (TEQ)	4.36×10^{-9}	
	Sulfur dioxide	0.929	
	Total volatile organic compounds	1.40	
Ground support equipment and auxiliary power unit – exhaust	Ammonia (total)	0.022	kg/kL
	Carbon monoxide	79.41	
	Oxides of nitrogen	11.12	
	Particulate matter ≤ 10 µm	0.61	
	Particulate matter ≤ 2.5 µm	0.60	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	0.0006	
	Polychlorinated dioxins and furans (TEQ)	4.57×10^{-9}	
	Sulfur dioxide	0.082	
	Total volatile organic compounds	2.91	

[23] Air Emissions Inventory for the Greater Metropolitan Region of New South Wales 2008 Calendar Year (NSW EPA 2012), Table 3-15 (page 57).

[24] Polycyclic aromatic hydrocarbons (B[a]Peq) (PAH) emission factor is the weighted sum of speciated PAHs. Speciated PAH factors sourced from Pechan (2005), Table D2 (page D-16). PAH factors weighted using relative potencies from NPI (2015), Appendix E (page 52).

Source[23]	Substance	Emission factor [24]	Units
Loading Avgas to storage tanks	Total volatile organic compounds	1.67×10^{-2}	kg/kL
Loading Avgas to tankers	Total volatile organic compounds	0.41	kg/kL
Refuelling aircraft with Avgas	Total volatile organic compounds	0.99	kg/kL
Loading Avtur to storage tanks	Total volatile organic compounds	7.77×10^{-5}	kg/kL
Loading Avtur to tankers	Total volatile organic compounds	1.90×10^{-3}	kg/kL
Refuelling aircraft with Avtur	Total volatile organic compounds	4.60×10^{-3}	kg/kL

Commercial boating emission factors

Table 25 – Commercial boating emission factors

Source[25]	Substance	Emission factor [26]	Units
2-stroke petrol – exhaust	Ammonia (total)	0.029	kg/kL
	Carbon monoxide	332	
	Oxides of nitrogen	3.45	
	Particulate matter ≤ 10 µm	3.86	
	Particulate matter ≤ 2.5 µm	3.55	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	2.04×10^{-4}	
	Polychlorinated dioxins and furans (TEQ)	3.29×10^{-12}	
	Sulfur dioxide	0.15	
	Total volatile organic compounds	194	
4-stroke petrol – exhaust	Ammonia (total)	0.029	kg/kL
	Carbon monoxide	422	
	Oxides of nitrogen	20.9	
	Particulate matter ≤ 10 µm	0.18	
	Particulate matter ≤ 2.5 µm	0.17	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	3.30×10^{-5}	
	Polychlorinated dioxins and furans (TEQ)	3.29×10^{-12}	
	Sulfur dioxide	0.20	

[25] Air Emissions Inventory for the Greater Metropolitan Region of New South Wales 2008 Calendar Year (NSW EPA 2012), Table 3-52 (page 107).

[26] Polycyclic aromatic hydrocarbons (B[a]Peq) (PAH) emission factor is the weighted sum of speciated PAHs. Speciated PAH factors sourced from Pechan (2005), Table D2 (page D-16). PAH factors weighted using relative potencies from NPI (2015), Appendix E (page 52).

Source[25]	Substance	Emission factor [26]	Units
	Total volatile organic compounds	16.9	
Diesel – exhaust	Ammonia (total)	0.022	kg/kL
	Carbon monoxide	5.91	
	Oxides of nitrogen	34.7	
	Particulate matter ≤ 10 µm	0.78	
	Particulate matter ≤ 2.5 µm	0.75	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	1.18×10^{-6}	
	Polychlorinated dioxins and furans (TEQ)	4.57×10^{-9}	
	Sulfur dioxide	0.083	
	Total volatile organic compounds	1.33	
2-stroke petrol – evaporative	Total volatile organic compounds	2.22	kg/kL
4-stroke petrol – evaporative	Total volatile organic compounds	2.17	kg/kL
Diesel – evaporative	Total volatile organic compounds	0.030	kg/kL

Recreational boating emission factors

Table 26 – Recreational boating emission factors

Source[27]	Substance	Emission factor [28]	Units
2-stroke petrol – exhaust	Ammonia (total)	0.029	kg/kL
	Carbon monoxide	305	
	Oxides of nitrogen	3.18	
	Particulate matter ≤ 10 µm	3.67	
	Particulate matter ≤ 2.5 µm	3.38	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	1.90×10^{-4}	
	Polychlorinated dioxins and furans (TEQ)	3.29×10^{-12}	
	Sulfur dioxide	0.15	
	Total volatile organic compounds	184	
4-stroke petrol – exhaust	Ammonia (total)	0.029	kg/kL
	Carbon monoxide	368	
	Oxides of nitrogen	19.3	

[27] Air Emissions Inventory for the Greater Metropolitan Region of New South Wales 2008 Calendar Year (NSW EPA 2012), Table 3-138 (page 290).

[28] Polycyclic aromatic hydrocarbons (B[a]Peq) (PAH) emission factor is the weighted sum of speciated PAHs. Speciated PAH factors sourced from Pechan (2005), Table D2 (page D-16) and are based on a fraction of PM_{10}. PAH factors weighted using relative potencies from NPI (2015), Appendix E (page 52).

Source[27]	Substance	Emission factor [28]	Units
	Particulate matter ≤ 10 µm	0.17	
	Particulate matter ≤ 2.5 µm	0.16	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	3.11×10^{-5}	
	Polychlorinated dioxins and furans (TEQ)	3.29×10^{-12}	
	Sulfur dioxide	0.20	
	Total volatile organic compounds	13.8	
Diesel – exhaust	Ammonia (total)	0.022	kg/kL
	Carbon monoxide	11.7	
	Oxides of nitrogen	33.9	
	Particulate matter ≤ 10 µm	1.61	
	Particulate matter ≤ 2.5 µm	1.56	
	Polycyclic aromatic hydrocarbons (B[a]Peq)	2.42×10^{-6}	
	Polychlorinated dioxins and furans (TEQ)	4.57×10^{-9}	
	Sulfur dioxide	0.083	
	Total volatile organic compounds	3.84	
2-stroke petrol – evaporative	Total volatile organic compounds	28.9	kg/kL
4-stroke petrol – evaporative	Total volatile organic compounds	29.3	kg/kL
Diesel – evaporative	Total volatile organic compounds	0.080	kg/kL

Locomotive emission factors

Table 27 – Locomotive emission factors

Source	Substance	Emission factor [29]	Units
Locomotives	Ammonia (total)	0.022	kg/kL
	Beryllium and compounds	0.000050	
	Cadmium and compounds	0.000050	
	Carbon monoxide	7.03	
	Lead and compounds	0.00016	
	Oxides of nitrogen	47.2	
	Particulate matter ≤ 10 µm	1.76	
	Particulate matter ≤ 2.5 µm	1.71	

[29] Polycyclic aromatic hydrocarbons (B[a]Peq) (PAH) emission factor is the weighted sum of speciated PAHs. Speciated PAH factors sourced from Pechan (2005), Table D2 (page D-16) and are based on a fraction of PM_{10}. PAH factors weighted using relative potencies from NPI (2015), Appendix E (page 52).

Source	Substance	Emission factor [29]	Units
	Polycyclic aromatic hydrocarbons (B[a]Peq)	0.0000026	
	Polychlorinated dioxins and furans (TEQ)	0.0000000046	
	Sulfur dioxide	0.082	
	Total volatile organic compounds	2.78	

Shipping emission factors

Table 28 – Shipping emission factors – transit

Machine type[30]	Fuel type[31]	Engine type[32]	BSFC (kg fuel/kWh)	Emission factor (g/kWh)[33]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH
ME	RO	SSD	195	0.5	18.1	1.42	1.31	10.3	0.3	3.00 x 10^{-03}	3.00 x 10^{-05}	2.54 x 10^{-06}	6.00 x 10^{-07}	2.00 x 10^{-04}	2.00 x 10^{-04}	3.90 x 10^{-04}	6.60 x 10^{-03}	3.90 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	RO	MSD	215	1.1	14.0	1.43	1.32	11.4	0.2	3.00 x 10^{-03}	3.00 x 10^{-05}	2.80 x 10^{-06}	6.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.30 x 10^{-04}	7.30 x 10^{-03}	4.30 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	RO	GT	305	0.1	6.1	1.47	1.35	16.1	0.1	4.00 x 10^{-04}	5.00 x 10^{-05}	3.97 x 10^{-06}	9.00 x 10^{-07}	3.00 x 10^{-04}	4.00 x 10^{-04}	6.10 x 10^{-04}	1.04 x 10^{-02}	6.10 x 10^{-06}	4.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	RO	ST	305	0.2	2.1	1.47	1.35	16.1	0.1	4.00 x 10^{-04}	5.00 x 10^{-05}	3.97 x 10^{-06}	9.00 x 10^{-07}	3.00 x 10^{-04}	4.00 x 10^{-04}	6.10 x 10^{-04}	1.04 x 10^{-02}	6.10 x 10^{-06}	4.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	MD	SSD	185	0.5	17.0	0.31	0.28	1.81	0.3	3.00 x 10^{-03}	3.00 x 10^{-05}	9.25 x 10^{-07}	9.00 x 10^{-09}	6.00 x 10^{-06}	9.00 x 10^{-06}	3.15 x 10^{-04}	2.00 x 10^{-04}	9.25 x 10^{-09}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	MSD	205	1.1	13.2	0.31	0.29	2.00	0.2	3.00 x 10^{-03}	3.00 x 10^{-05}	1.03 x 10^{-06}	1.00 x 10^{-08}	6.00 x 10^{-06}	1.00 x 10^{-05}	3.49 x 10^{-04}	2.00 x 10^{-04}	1.03 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	HSD	205	1.1	12.0	0.31	0.29	2.00	0.2	3.00 x 10^{-03}	3.00 x 10^{-05}	1.03 x 10^{-06}	1.00 x 10^{-08}	6.00 x 10^{-06}	1.00 x 10^{-05}	3.49 x 10^{-04}	2.00 x 10^{-04}	1.03 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	GT	300	0.1	5.9	0.35	0.32	2.93	0.1	4.00 x 10^{-04}	5.00 x 10^{-05}	1.50 x 10^{-06}	2.00 x 10^{-08}	9.00 x 10^{-06}	2.00 x 10^{-05}	5.10 x 10^{-04}	3.00 x 10^{-04}	1.50 x 10^{-08}	3.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	ST	300	0.2	2.0	0.35	0.32	2.93	0.1	4.00 x 10^{-04}	5.00 x 10^{-05}	1.50 x 10^{-06}	2.00 x 10^{-08}	9.00 x 10^{-06}	2.00 x 10^{-05}	5.10 x 10^{-04}	3.00 x 10^{-04}	1.50 x 10^{-08}	3.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
AE	RO	MSD	227	1.1	14.7	1.44	1.32	12.0	0.4	3.00 x 10^{-03}	3.00 x 10^{-05}	2.80 x 10^{-06}	6.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.30 x 10^{-04}	7.30 x 10^{-03}	4.30 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
AE	MD	MSD	217	1.1	13.9	0.32	0.29	2.12	0.4	3.00 x 10^{-03}	3.00 x 10^{-05}	1.03 x 10^{-06}	1.00 x 10^{-08}	6.00 x 10^{-06}	1.00 x 10^{-05}	3.49 x 10^{-04}	2.00 x 10^{-04}	1.03 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
AE	MD	HSD	217	1.1	11.8	0.32	0.29	2.12	0.4	3.00 x 10^{-03}	3.00 x 10^{-05}	1.03 x 10^{-06}	1.00 x 10^{-08}	6.00 x 10^{-06}	1.00 x 10^{-05}	3.49 x 10^{-04}	2.00 x 10^{-04}	1.03 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
AB	RO	–	305	0.2	2.1	1.47	1.35	16.1	0.1	3.00 x 10^{-03}	3.00 x 10^{-05}	2.80 x 10^{-06}	6.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.30 x 10^{-04}	7.30 x 10^{-03}	4.30 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}

[30] ME = Main engine, AE = Auxiliary engine, AB = Auxiliary boiler

[31] RO = Residual oil, MD = Marine distillate

[32] SSD = Slow-speed diesel, MSD = Medium-speed diesel, GT = Gas turbine, ST = Steam turbine, HSD = High-speed diesel

[33] CO, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC and PAH emission factors sourced from Goldsworthy and Goldsworthy (2015). Ammonia, metals and PCDF emission factors sourced from Cooper and Gustafsson (2004)

Machine type[34]	Fuel type[35]	Engine type[36]	BSFC (kg fuel/kWh)	Emission factor (g/kg fuel use)[37]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH
ME	RO	SSD		2.56	92.8	7.28	6.72	52.8	1.54	1.54×10^{-02}	1.54×10^{-04}	1.30×10^{-05}	3.08×10^{-06}	1.03×10^{-03}	1.03×10^{-03}	2.00×10^{-03}	3.38×10^{-02}	2.00×10^{-05}	1.54×10^{-03}	5.13×10^{-09}	2.26×10^{-02}
ME	RO	MSD		5.12	65.1	6.65	6.14	53.0	0.93	1.40×10^{-02}	1.40×10^{-04}	1.30×10^{-05}	2.79×10^{-06}	9.30×10^{-04}	1.40×10^{-03}	2.00×10^{-03}	3.40×10^{-02}	2.00×10^{-05}	1.40×10^{-03}	4.65×10^{-09}	2.05×10^{-02}
ME	RO	GT		0.33	20.0	4.82	4.43	52.8	0.33	1.31×10^{-03}	1.64×10^{-04}	1.30×10^{-05}	2.95×10^{-06}	9.84×10^{-04}	1.31×10^{-03}	2.00×10^{-03}	3.41×10^{-02}	2.00×10^{-05}	1.31×10^{-03}	3.28×10^{-09}	1.44×10^{-02}
ME	RO	ST		0.66	6.89	4.82	4.43	52.8	0.33	1.31×10^{-03}	1.64×10^{-04}	1.30×10^{-05}	2.95×10^{-06}	9.84×10^{-04}	1.31×10^{-03}	2.00×10^{-03}	3.41×10^{-02}	2.00×10^{-05}	1.31×10^{-03}	3.28×10^{-09}	1.44×10^{-02}
ME	MD	SSD		2.70	91.9	1.68	1.51	9.78	1.62	1.62×10^{-02}	1.62×10^{-04}	5.00×10^{-06}	4.86×10^{-08}	3.24×10^{-05}	4.86×10^{-05}	1.70×10^{-03}	1.08×10^{-03}	5.00×10^{-08}	1.08×10^{-03}	5.41×10^{-09}	1.35×10^{-02}
ME	MD	MSD		5.37	64.4	1.51	1.41	9.76	0.98	1.46×10^{-02}	1.46×10^{-04}	5.02×10^{-06}	4.88×10^{-08}	2.93×10^{-05}	4.88×10^{-05}	1.70×10^{-03}	9.76×10^{-04}	5.02×10^{-08}	9.76×10^{-04}	4.88×10^{-09}	1.22×10^{-02}
ME	MD	HSD		5.37	58.5	1.51	1.41	9.76	0.98	1.46×10^{-02}	1.46×10^{-04}	5.02×10^{-06}	4.88×10^{-08}	2.93×10^{-05}	4.88×10^{-05}	1.70×10^{-03}	9.76×10^{-04}	5.02×10^{-08}	9.76×10^{-04}	4.88×10^{-09}	1.22×10^{-02}
ME	MD	GT		0.33	19.7	1.17	1.07	9.77	0.33	1.33×10^{-03}	1.67×10^{-04}	5.00×10^{-06}	6.67×10^{-08}	3.00×10^{-05}	6.67×10^{-05}	1.70×10^{-03}	1.00×10^{-03}	5.00×10^{-08}	1.00×10^{-03}	3.33×10^{-09}	8.33×10^{-03}
ME	MD	ST		0.67	6.67	1.17	1.07	9.77	0.33	1.33×10^{-03}	1.67×10^{-04}	5.00×10^{-06}	6.67×10^{-08}	3.00×10^{-05}	6.67×10^{-05}	1.70×10^{-03}	1.00×10^{-03}	5.00×10^{-08}	1.00×10^{-03}	3.33×10^{-09}	8.33×10^{-03}
AE	RO	MSD		4.85	64.8	6.34	5.81	52.9	1.76	1.32×10^{-02}	1.32×10^{-04}	1.23×10^{-05}	2.64×10^{-06}	8.81×10^{-04}	1.32×10^{-03}	1.89×10^{-03}	3.22×10^{-02}	1.89×10^{-05}	1.32×10^{-03}	4.41×10^{-09}	1.94×10^{-02}
AE	MD	MSD		5.07	64.1	1.47	1.34	9.77	1.84	1.38×10^{-02}	1.38×10^{-04}	4.75×10^{-06}	4.61×10^{-08}	2.76×10^{-05}	4.61×10^{-05}	1.61×10^{-03}	9.22×10^{-04}	4.75×10^{-08}	9.22×10^{-04}	4.61×10^{-09}	1.15×10^{-02}
AE	MD	HSD		5.07	54.4	1.47	1.34	9.77	1.84	1.38×10^{-02}	1.38×10^{-04}	4.75×10^{-06}	4.61×10^{-08}	2.76×10^{-05}	4.61×10^{-05}	1.61×10^{-03}	9.22×10^{-04}	4.75×10^{-08}	9.22×10^{-04}	4.61×10^{-09}	1.15×10^{-02}
AB	RO	–		0.66	6.89	4.82	4.43	52.8	0.33	9.84×10^{-03}	9.84×10^{-05}	9.18×10^{-06}	1.97×10^{-06}	6.56×10^{-04}	9.84×10^{-04}	1.41×10^{-03}	2.39×10^{-02}	1.41×10^{-05}	9.84×10^{-04}	3.28×10^{-09}	1.44×10^{-02}

[34] ME = Main engine, AE = Auxiliary engine, AB = Auxiliary boiler

[35] RO = Residual oil, MD = Marine distillate

[36] SSD = Slow-speed diesel, MSD = Medium-speed diesel, GT = Gas turbine, ST = Steam turbine, HSD = High-speed diesel

[37] Emissions converted to g/kg fuel using $EF_{g/kg} = \frac{EF_{g/kWh}}{BSFC} \times 1000$

Table 29 – Shipping emission factors – manoeuvring

Machine type[38]	Fuel type[39]	Engine type[40]	BSFC (kg fuel/kWh)	Emission factor (g/kWh)[41]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH
ME	RO	SSD	195	0.5	18.1	1.42	1.31	10.3	0.3	3.00×10^{-03}	3.00×10^{-05}	2.79×10^{-06}	6.00×10^{-07}	2.00×10^{-04}	3.00×10^{-04}	4.30×10^{-04}	7.30×10^{-03}	4.29×10^{-06}	3.00×10^{-04}	1.00×10^{-09}	4.40×10^{-03}
ME	RO	MSD	215	1.1	14	1.43	1.32	11.4	0.2	3.00×10^{-03}	4.00×10^{-05}	3.07×10^{-06}	7.00×10^{-07}	2.00×10^{-04}	3.00×10^{-04}	4.70×10^{-04}	8.00×10^{-03}	4.73×10^{-06}	3.00×10^{-04}	1.00×10^{-09}	4.40×10^{-03}
ME	RO	GT	305	0.1	6.1	1.47	1.35	16.1	0.1	4.00×10^{-04}	5.00×10^{-05}	4.36×10^{-06}	1.00×10^{-06}	3.00×10^{-04}	4.00×10^{-04}	6.70×10^{-04}	1.14×10^{-02}	6.71×10^{-06}	5.00×10^{-04}	1.00×10^{-09}	4.40×10^{-03}
ME	RO	ST	305	0.2	2.1	1.47	1.35	16.1	0.1	4.00×10^{-04}	5.00×10^{-05}	4.36×10^{-06}	1.00×10^{-06}	3.00×10^{-04}	4.00×10^{-04}	6.70×10^{-04}	1.14×10^{-02}	6.71×10^{-06}	5.00×10^{-04}	1.00×10^{-09}	4.40×10^{-03}
ME	MD	SSD	185	0.5	17	0.31	0.28	1.81	0.3	3.00×10^{-03}	3.00×10^{-05}	1.02×10^{-06}	1.00×10^{-08}	6.00×10^{-06}	1.00×10^{-05}	3.50×10^{-04}	2.00×10^{-04}	1.02×10^{-08}	2.00×10^{-04}	1.00×10^{-09}	2.50×10^{-03}
ME	MD	MSD	205	1.1	13.2	0.31	0.29	2	0.2	3.00×10^{-03}	3.00×10^{-05}	1.13×10^{-06}	1.00×10^{-08}	7.00×10^{-06}	1.00×10^{-05}	3.80×10^{-04}	2.00×10^{-04}	1.13×10^{-08}	2.00×10^{-04}	1.00×10^{-09}	2.50×10^{-03}
ME	MD	HSD	205	1.1	12	0.31	0.29	2	0.2	3.00×10^{-03}	3.00×10^{-05}	1.13×10^{-06}	1.00×10^{-08}	7.00×10^{-06}	1.00×10^{-05}	3.80×10^{-04}	2.00×10^{-04}	1.13×10^{-08}	2.00×10^{-04}	1.00×10^{-09}	2.50×10^{-03}
ME	MD	GT	300	0.1	5.9	0.35	0.32	2.93	0.1	4.00×10^{-04}	5.00×10^{-05}	1.65×10^{-06}	2.00×10^{-08}	1.00×10^{-05}	2.00×10^{-05}	5.60×10^{-04}	3.00×10^{-04}	1.65×10^{-08}	3.00×10^{-04}	1.00×10^{-09}	2.50×10^{-03}
ME	MD	ST	300	0.2	2	0.35	0.32	2.93	0.1	4.00×10^{-04}	5.00×10^{-05}	1.65×10^{-06}	2.00×10^{-08}	1.00×10^{-05}	2.00×10^{-05}	5.60×10^{-04}	3.00×10^{-04}	1.65×10^{-08}	3.00×10^{-04}	1.00×10^{-09}	2.50×10^{-03}
AE	RO	MSD	227	1.1	14.7	1.44	1.32	12	0.4	3.00×10^{-03}	4.00×10^{-05}	3.07×10^{-06}	7.00×10^{-07}	2.00×10^{-04}	3.00×10^{-04}	4.70×10^{-04}	8.00×10^{-03}	4.73×10^{-06}	3.00×10^{-04}	1.00×10^{-09}	4.40×10^{-03}
AE	MD	MSD	217	1.1	13.9	0.32	0.29	2.12	0.4	3.00×10^{-03}	3.00×10^{-05}	1.13×10^{-06}	1.00×10^{-08}	7.00×10^{-06}	1.00×10^{-05}	3.80×10^{-04}	2.00×10^{-04}	1.13×10^{-08}	2.00×10^{-04}	1.00×10^{-09}	2.50×10^{-03}
AE	MD	HSD	217	1.1	11.8	0.32	0.29	2.12	0.4	3.00×10^{-03}	3.00×10^{-05}	1.13×10^{-06}	1.00×10^{-08}	7.00×10^{-06}	1.00×10^{-05}	3.80×10^{-04}	2.00×10^{-04}	1.13×10^{-08}	2.00×10^{-04}	1.00×10^{-09}	2.50×10^{-03}
AB	RO	–	305	0.2	2.1	1.47	1.35	16.1	0.1	3.00×10^{-03}	4.20×10^{-05}	3.53×10^{-06}	8.00×10^{-07}	2.40×10^{-04}	3.40×10^{-04}	5.42×10^{-04}	9.22×10^{-03}	5.43×10^{-06}	3.80×10^{-04}	1.00×10^{-09}	4.40×10^{-03}
				Emission factor (g/kg fuel use)[42]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH

[38] ME = Main engine, AE = Auxiliary engine, AB = Auxiliary boiler

[39] RO = Residual oil, MD = Marine diesel

[40] SSD = Slow-speed diesel, MSD = Medium-speed diesel, GT = Gas turbine, ST = Steam turbine, HSD = High-speed diesel

[41] CO, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC and PAH emission factors sourced from Goldsworthy and Goldsworthy (2015). Ammonia, metals and PCDF emission factors sourced from Cooper and Gustafsson (2004)

[42] Emissions converted to g/kg fuel using $EF_{g/kg} = \frac{EF_{g/kWh}}{BSFC} \times 1000$

Machine type[38]	Fuel type[39]	Engine type[40]	BSFC (kg fuel/kWh)	Emission factor (g/kWh)[41]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH
ME	RO	SSD		2.56	92.8	7.28	6.72	52.8	1.54	1.54×10^{-02}	1.54×10^{-04}	1.43×10^{-05}	3.08×10^{-06}	1.03×10^{-03}	1.54×10^{-03}	2.21×10^{-03}	3.74×10^{-02}	2.20×10^{-05}	1.54×10^{-03}	5.13×10^{-09}	2.26×10^{-02}
ME	RO	MSD		5.12	65.1	6.65	6.14	53.0	0.93	1.40×10^{-02}	1.86×10^{-04}	1.43×10^{-05}	3.26×10^{-06}	9.30×10^{-04}	1.40×10^{-03}	2.19×10^{-03}	3.72×10^{-02}	2.20×10^{-05}	1.40×10^{-03}	4.65×10^{-09}	2.05×10^{-02}
ME	RO	GT		0.33	20.0	4.82	4.43	52.8	0.33	1.31×10^{-03}	1.64×10^{-04}	1.43×10^{-05}	3.28×10^{-06}	9.84×10^{-04}	1.31×10^{-03}	2.20×10^{-03}	3.74×10^{-02}	2.20×10^{-05}	1.64×10^{-03}	3.28×10^{-09}	1.44×10^{-02}
ME	RO	ST		0.66	6.89	4.82	4.43	52.8	0.33	1.31×10^{-03}	1.64×10^{-04}	1.43×10^{-05}	3.28×10^{-06}	9.84×10^{-04}	1.31×10^{-03}	2.20×10^{-03}	3.74×10^{-02}	2.20×10^{-05}	1.64×10^{-03}	3.28×10^{-09}	1.44×10^{-02}
ME	MD	SSD		2.70	91.9	1.68	1.51	9.78	1.62	1.62×10^{-02}	1.62×10^{-04}	5.51×10^{-06}	5.41×10^{-08}	3.24×10^{-05}	5.41×10^{-05}	1.89×10^{-03}	1.08×10^{-03}	5.51×10^{-08}	1.08×10^{-03}	5.41×10^{-09}	1.35×10^{-02}
ME	MD	MSD		5.37	64.4	1.51	1.41	9.76	0.98	1.46×10^{-02}	1.46×10^{-04}	5.51×10^{-06}	4.88×10^{-08}	3.41×10^{-05}	4.88×10^{-05}	1.85×10^{-03}	9.76×10^{-04}	5.51×10^{-08}	9.76×10^{-04}	4.88×10^{-09}	1.22×10^{-02}
ME	MD	HSD		5.37	58.5	1.51	1.41	9.76	0.98	1.46×10^{-02}	1.46×10^{-04}	5.51×10^{-06}	4.88×10^{-08}	3.41×10^{-05}	4.88×10^{-05}	1.85×10^{-03}	9.76×10^{-04}	5.51×10^{-08}	9.76×10^{-04}	4.88×10^{-09}	1.22×10^{-02}
ME	MD	GT		0.33	19.7	1.17	1.07	9.77	0.33	1.33×10^{-03}	1.67×10^{-04}	5.50×10^{-06}	6.67×10^{-08}	3.33×10^{-05}	6.67×10^{-05}	1.87×10^{-03}	1.00×10^{-03}	5.50×10^{-08}	1.00×10^{-03}	3.33×10^{-09}	8.33×10^{-03}
ME	MD	ST		0.67	6.67	1.17	1.07	9.77	0.33	1.33×10^{-03}	1.67×10^{-04}	5.50×10^{-06}	6.67×10^{-08}	3.33×10^{-05}	6.67×10^{-05}	1.87×10^{-03}	1.00×10^{-03}	5.50×10^{-08}	1.00×10^{-03}	3.33×10^{-09}	8.33×10^{-03}
AE	RO	MSD		4.85	64.8	6.34	5.81	52.9	1.76	1.32×10^{-02}	1.76×10^{-04}	1.35×10^{-05}	3.08×10^{-06}	8.81×10^{-04}	1.32×10^{-03}	2.07×10^{-03}	3.52×10^{-02}	2.08×10^{-05}	1.32×10^{-03}	4.41×10^{-09}	1.94×10^{-02}
AE	MD	MSD		5.07	64.1	1.47	1.34	9.77	1.84	1.38×10^{-02}	1.38×10^{-04}	5.21×10^{-06}	4.61×10^{-08}	3.23×10^{-05}	4.61×10^{-05}	1.75×10^{-03}	9.22×10^{-04}	5.21×10^{-08}	9.22×10^{-04}	4.61×10^{-09}	1.15×10^{-02}
AE	MD	HSD		5.07	54.4	1.47	1.34	9.77	1.84	1.38×10^{-02}	1.38×10^{-04}	5.21×10^{-06}	4.61×10^{-08}	3.23×10^{-05}	4.61×10^{-05}	1.75×10^{-03}	9.22×10^{-04}	5.21×10^{-08}	9.22×10^{-04}	4.61×10^{-09}	1.15×10^{-02}
AB	RO	–		0.66	6.89	4.82	4.43	52.8	0.33	9.84×10^{-03}	1.38×10^{-04}	1.16×10^{-05}	2.62×10^{-06}	7.87×10^{-04}	1.11×10^{-03}	1.78×10^{-03}	3.02×10^{-02}	1.78×10^{-05}	1.25×10^{-03}	3.28×10^{-09}	1.44×10^{-02}

Table 30 – Shipping emission factors – anchor and berth

Machine type[43]	Fuel type[44]	Engine type[45]	BSFC (kg fuel/kWh)	Emission factor (g/kWh)[46]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH
ME	RO	SSD	195	0.5	18.1	1.42	1.31	10.3	0.3	3.00 x 10^{-03}	3.00 x 10^{-05}	2.95 x 10^{-06}	7.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.50 x 10^{-04}	7.70 x 10^{-03}	4.54 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	RO	MSD	215	1.1	14	1.43	1.32	11.4	0.2	3.00 x 10^{-03}	3.00 x 10^{-05}	2.95 x 10^{-06}	7.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.50 x 10^{-04}	7.70 x 10^{-03}	4.54 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	RO	GT	305	0.1	6.1	1.47	1.35	16.1	0.1	3.00 x 10^{-03}	3.00 x 10^{-05}	2.95 x 10^{-06}	7.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.50 x 10^{-04}	7.70 x 10^{-03}	4.54 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	RO	ST	305	0.2	2.1	1.47	1.35	16.1	0.1	3.00 x 10^{-03}	3.00 x 10^{-05}	2.95 x 10^{-06}	7.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.50 x 10^{-04}	7.70 x 10^{-03}	4.54 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
ME	MD	SSD	185	0.5	17	0.31	0.28	1.81	0.3	3.00 x 10^{-03}	3.00 x 10^{-05}	1.09 x 10^{-06}	1.00 x 10^{-08}	7.00 x 10^{-06}	1.00 x 10^{-05}	3.70 x 10^{-04}	2.00 x 10^{-04}	1.09 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	MSD	205	1.1	13.2	0.31	0.29	2	0.2	3.00 x 10^{-03}	3.00 x 10^{-05}	1.09 x 10^{-06}	1.00 x 10^{-08}	7.00 x 10^{-06}	1.00 x 10^{-05}	3.70 x 10^{-04}	2.00 x 10^{-04}	1.09 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	HSD	205	1.1	12	0.31	0.29	2	0.2	3.00 x 10^{-03}	3.00 x 10^{-05}	1.09 x 10^{-06}	1.00 x 10^{-08}	7.00 x 10^{-06}	1.00 x 10^{-05}	3.70 x 10^{-04}	2.00 x 10^{-04}	1.09 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	GT	300	0.1	5.9	0.35	0.32	2.93	0.1	3.00 x 10^{-03}	3.00 x 10^{-05}	1.09 x 10^{-06}	1.00 x 10^{-08}	7.00 x 10^{-06}	1.00 x 10^{-05}	3.70 x 10^{-04}	2.00 x 10^{-04}	1.09 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
ME	MD	ST	300	0.2	2	0.35	0.32	2.93	0.1	3.00 x 10^{-03}	3.00 x 10^{-05}	1.09 x 10^{-06}	1.00 x 10^{-08}	7.00 x 10^{-06}	1.00 x 10^{-05}	3.70 x 10^{-04}	2.00 x 10^{-04}	1.09 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
AE	RO	MSD	227	1.1	14.7	1.44	1.32	12	0.4	3.00 x 10^{-03}	3.00 x 10^{-05}	2.95 x 10^{-06}	7.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.50 x 10^{-04}	7.70 x 10^{-03}	4.54 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
AE	MD	MSD	217	1.1	13.9	0.32	0.29	2.12	0.4	3.00 x 10^{-03}	3.00 x 10^{-05}	1.09 x 10^{-06}	1.00 x 10^{-08}	7.00 x 10^{-06}	1.00 x 10^{-05}	3.70 x 10^{-04}	2.00 x 10^{-04}	1.09 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
AE	MD	HSD	217	1.1	11.8	0.32	0.29	2.12	0.4	3.00 x 10^{-03}	3.00 x 10^{-05}	1.09 x 10^{-06}	1.00 x 10^{-08}	7.00 x 10^{-06}	1.00 x 10^{-05}	3.70 x 10^{-04}	2.00 x 10^{-04}	1.09 x 10^{-08}	2.00 x 10^{-04}	1.00 x 10^{-09}	2.50 x 10^{-03}
AB	RO	–	305	0.2	2.1	1.47	1.35	16.1	0.1	3.00 x 10^{-03}	3.00 x 10^{-05}	2.95 x 10^{-06}	7.00 x 10^{-07}	2.00 x 10^{-04}	3.00 x 10^{-04}	4.50 x 10^{-04}	7.70 x 10^{-03}	4.54 x 10^{-06}	3.00 x 10^{-04}	1.00 x 10^{-09}	4.40 x 10^{-03}
				Emission factor (g/kg fuel use)[47]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH
ME	RO	SSD		2.56	92.8	7.28	6.72	52.8	1.54	1.54 x 10^{-02}	1.54 x 10^{-04}	1.51 x 10^{-05}	3.59 x 10^{-06}	1.03 x 10^{-03}	1.54 x 10^{-03}	2.31 x 10^{-03}	3.95 x 10^{-02}	2.33 x 10^{-05}	1.54 x 10^{-03}	5.13 x 10^{-09}	2.26 x 10^{-02}
ME	RO	MSD		5.12	65.1	6.65	6.14	53.0	0.93	1.40 x 10^{-02}	1.40 x 10^{-04}	1.37 x 10^{-05}	3.26 x 10^{-06}	9.30 x 10^{-04}	1.40 x 10^{-03}	2.09 x 10^{-03}	3.58 x 10^{-02}	2.11 x 10^{-05}	1.40 x 10^{-03}	4.65 x 10^{-09}	2.05 x 10^{-02}

43 ME = Main engine, AE = Auxiliary engine, AB = Auxiliary boiler

44 RO = Residual oil, MD = Marine diesel

45 SSD = Slow-speed diesel, MSD = Medium-speed diesel, GT = Gas turbine, ST = Steam turbine, HSD = High-speed diesel

46 CO, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC and PAH emission factors sourced from Goldsworthy and Goldsworthy (2015). Ammonia, metals and PCDF emission factors sourced from Cooper and Gustafsson (2004)

47 Emissions converted to g/kg fuel using $EF_{g/kg} = \frac{EF_{g/kWh}}{BSFC} \times 1000$

Machine type[43]	Fuel type[44]	Engine type[45]	BSFC (kg fuel/kWh)	Emission factor (g/kWh)[46]																	
				CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn	PCDF	PAH
ME	RO	GT		0.33	20.0	4.82	4.43	52.8	0.33	9.84×10^{-03}	9.84×10^{-05}	9.67×10^{-06}	2.30×10^{-06}	6.56×10^{-04}	9.84×10^{-04}	1.48×10^{-03}	2.52×10^{-02}	1.49×10^{-05}	9.84×10^{-04}	3.28×10^{-09}	1.44×10^{-02}
ME	RO	ST		0.66	6.89	4.82	4.43	52.8	0.33	9.84×10^{-03}	9.84×10^{-05}	9.67×10^{-06}	2.30×10^{-06}	6.56×10^{-04}	9.84×10^{-04}	1.48×10^{-03}	2.52×10^{-02}	1.49×10^{-05}	9.84×10^{-04}	3.28×10^{-09}	1.44×10^{-02}
ME	MD	SSD		2.70	91.9	1.68	1.51	9.78	1.62	1.62×10^{-02}	1.62×10^{-04}	5.89×10^{-06}	5.41×10^{-08}	3.78×10^{-05}	5.41×10^{-05}	2.00×10^{-03}	1.08×10^{-03}	5.89×10^{-08}	1.08×10^{-03}	5.41×10^{-09}	1.35×10^{-02}
ME	MD	MSD		5.37	64.4	1.51	1.41	9.76	0.98	1.46×10^{-02}	1.46×10^{-04}	5.32×10^{-06}	4.88×10^{-08}	3.41×10^{-05}	4.88×10^{-05}	1.80×10^{-03}	9.76×10^{-04}	5.32×10^{-08}	9.76×10^{-04}	4.88×10^{-09}	1.22×10^{-02}
ME	MD	HSD		5.37	58.5	1.51	1.41	9.76	0.98	1.46×10^{-02}	1.46×10^{-04}	5.32×10^{-06}	4.88×10^{-08}	3.41×10^{-05}	4.88×10^{-05}	1.80×10^{-03}	9.76×10^{-04}	5.32×10^{-08}	9.76×10^{-04}	4.88×10^{-09}	1.22×10^{-02}
ME	MD	GT		0.33	19.7	1.17	1.07	9.77	0.33	1.00×10^{-02}	1.00×10^{-04}	3.63×10^{-06}	3.33×10^{-08}	2.33×10^{-05}	3.33×10^{-05}	1.23×10^{-03}	6.67×10^{-04}	3.63×10^{-08}	6.67×10^{-04}	3.33×10^{-09}	8.33×10^{-03}
ME	MD	ST		0.67	6.67	1.17	1.07	9.77	0.33	1.00×10^{-02}	1.00×10^{-04}	3.63×10^{-06}	3.33×10^{-08}	2.33×10^{-05}	3.33×10^{-05}	1.23×10^{-03}	6.67×10^{-04}	3.63×10^{-08}	6.67×10^{-04}	3.33×10^{-09}	8.33×10^{-03}
AE	RO	MSD		4.85	64.8	6.34	5.81	52.9	1.76	1.32×10^{-02}	1.32×10^{-04}	1.30×10^{-05}	3.08×10^{-06}	8.81×10^{-04}	1.32×10^{-03}	1.98×10^{-03}	3.39×10^{-02}	2.00×10^{-05}	1.32×10^{-03}	4.41×10^{-09}	1.94×10^{-02}
AE	MD	MSD		5.07	64.1	1.47	1.34	9.77	1.84	1.38×10^{-02}	1.38×10^{-04}	5.02×10^{-06}	4.61×10^{-08}	3.23×10^{-05}	4.61×10^{-05}	1.71×10^{-03}	9.22×10^{-04}	5.02×10^{-08}	9.22×10^{-04}	4.61×10^{-09}	1.15×10^{-02}
AE	MD	HSD		5.07	54.4	1.47	1.34	9.77	1.84	1.38×10^{-02}	1.38×10^{-04}	5.02×10^{-06}	4.61×10^{-08}	3.23×10^{-05}	4.61×10^{-05}	1.71×10^{-03}	9.22×10^{-04}	5.02×10^{-08}	9.22×10^{-04}	4.61×10^{-09}	1.15×10^{-02}
AB	RO	–		0.66	6.89	4.82	4.43	52.8	0.33	9.84×10^{-03}	9.84×10^{-05}	9.67×10^{-06}	2.30×10^{-06}	6.56×10^{-04}	9.84×10^{-04}	1.48×10^{-03}	2.52×10^{-02}	1.49×10^{-05}	9.84×10^{-04}	3.28×10^{-09}	1.44×10^{-02}

Appendix B — Speciation profiles

Aircraft speciation factors

Table 31 – Aircraft VOC speciation profile

Substance	Speciation (kg/kg VOC)[48]
Benzene	0.0072
Toluene (methylbenzene)	0.0062
Xylenes (individual or mixed isomers)	0.001

Table 32 – Aircraft particulate speciation profile

Substance	Speciation (kg/kg VOC)[49]
Chlorine and compounds	0.07
Chromium (total)	0.0005
Cobalt and compounds	0.0005
Copper and compounds	0.0005
Manganese and compounds	0.0005
Nickel and compounds	0.0005
Zinc and compounds	0.0005

Commercial and recreational boating speciation factors

Table 33 – Commercial and recreational boating VOC speciation profiles

Source	Substance	Speciation (kg/kg VOC)[50]
2-stroke petrol – exhaust	Acetaldehyde	0.0017
	Acrolein	0.00030
	1,3-Butadiene (vinyl ethylene)	0.0021
	Benzene	0.025
	Ethylbenzene	0.024
	Formaldehyde (methyl aldehyde)	0.0025
	n-Hexane	0.014
	Styrene (ethenylbenzene)	0.0013
	Toluene (methylbenzene)	0.098
	Xylenes (individual or mixed isomers)	0.11

[48] Speciation profiles: ORGPROF 708 and ORGPROF 100 (CARB, 2015)

[49] Speciation profile: PMPROF 400 (CARB, 2014b)

[50] Exhaust emission speciation sourced from Pechan (2005), Table D-1 (page D-8 to D-16). Evaporative emission speciation sourced from DECC (2007), Table 3.3 (page 20) and Table 3.4 (page 21).

Source	Substance	Speciation (kg/kg VOC)[50]
4-stroke petrol – exhaust	Acetaldehyde	0.0041
	Acrolein	0.00070
	1,3-Butadiene (vinyl ethylene)	0.0095
	Benzene	0.052
	Ethylbenzene	0.020
	Formaldehyde (methyl aldehyde)	0.017
	n-Hexane	0.0099
	Styrene (ethenylbenzene)	0.00076
	Toluene (methylbenzene)	0.072
	Xylenes (individual or mixed isomers)	0.068
Diesel – exhaust	Acetaldehyde	0.053
	Acrolein	0.0030
	1,3-Butadiene (vinyl ethylene)	0.0019
	Benzene	0.020
	Ethylbenzene	0.0031
	Formaldehyde (methyl aldehyde)	0.12
	n-Hexane	0.0016
	Styrene (ethenylbenzene)	0.00059
	Toluene (methylbenzene)	0.015
	Xylenes (individual or mixed isomers)	0.011
2-stroke and 4-stroke petrol – evaporative	Benzene	0.0078
	Cyclohexane	0.00050
	Ethylbenzene	0.0010
	n-Hexane	0.0022
	Toluene (methylbenzene)	0.019
	Xylenes (individual or mixed isomers)	0.0055
Diesel – evaporative	Cumene (1-methylethylbenzene)	0.050
	Ethylbenzene	0.0059
	Toluene (methylbenzene)	0.028
	Xylenes (individual or mixed isomers)	0.090

Table 34 – Commercial and recreational boating particulate speciation profiles

Source	Substance	Speciation (kg/kg TSP)[51]
2-stroke and 4-stroke petrol	Total suspended particulate (TSP)	PM_{10} x 1.03
	Chlorine and compounds	0.070
	Chromium (total)	0.00050
	Cobalt and compounds	0.00050
	Manganese and compounds	0.00050
	Nickel and compounds	0.00050
Diesel	Total suspended particulate (TSP)	PM_{10} x 1.00
	Antimony and compounds	0.000139
	Arsenic and compounds	0.0000040
	Cadmium and compounds	0.000067
	Chlorine and compounds	0.00027
	Chromium (total)	0.000010
	Cobalt and compounds	0.0000060
	Copper and compounds	0.000030
	Lead and compounds	0.000030
	Manganese and compounds	0.000023
	Mercury and compounds	0.000026
	Nickel and compounds	0.000016
	Selenium and compounds	0.0000050
	Zinc and compounds	0.00040

[51] Speciation profiles: ORGPROF 708 and ORGPROF 100 (CARB, 2015)

[51] Speciation profile: PMPROF 400 (CARB, 2014b)

[51] Exhaust emission speciation sourced from Pechan (2005), Table D-1 (page D-8 to D-16). Evaporative emission speciation sourced from DECC (2007), Table 3.3 (page 20) and Table 3.4 (page 21).

[51] Speciation profiles: PMPROF 400 (petrol) and PMPROF 425 (diesel) (CARB 2014a, 2014b)

Locomotive speciation factors

Table 35 – Locomotive VOC speciation profiles

Source	Substance	Speciation (kg/kg VOC)[52]
Locomotives	Acetaldehyde	0.053
	Acrolein	0.0030
	1,3-Butadiene (vinyl ethylene)	0.0019
	Benzene	0.020
	Ethylbenzene	0.0031
	Formaldehyde (methyl aldehyde)	0.12
	n-Hexane	0.0016
	Styrene (ethenylbenzene)	0.00059
	Toluene (methylbenzene)	0.015
	Xylenes (individual or mixed isomers)	0.011

Shipping speciation factors

Table 36 – Shipping particulate speciation profile

Fuel type	Substance	Speciation (kg/kg TSP)[53]
Residual oil	Cobalt and compounds	0.0005
	Manganese and compounds	0.0005
Marine distillate	Antimony and compounds	0.000036
	Chlorine and compounds	0.000344
	Cobalt and compounds	0.000011
	Manganese and compounds	0.00004

Table 37 – Shipping VOC speciation profile

Substance	Speciation (kg/kg VOC)[54]
Benzene	0.0216
Ethylbenzene	0.0007
Formaldehyde (methyl aldehyde)	0.001
n-Hexane	0.0159
Toluene (methylbenzene)	0.0215
Xylenes (individual or mixed isomers)	0.011

[52] Emission speciation sourced from Pechan (2005), Table D-1 (page D-8 to D-16).

[53] Speciation profiles: PMPROF 113 (Residual oil) and PMPROF 425 (Marine distillate)

[54] Speciation profiles: ORGPROF 504 (CARB, 2015)

Appendix C – Toxic equivalency potential score

Table 38 – NPI substance TEP rating

Substance	Non-cancer risk score (TEP)[55]
Acetaldehyde	9.3
Acetic acid (ethanoic acid)	N/A
Acetone	0.05
Acetonitrile	30
Acrolein	1,600
Acrylamide	2,000
Acrylic acid	62
Acrylonitrile (2-propenenitrile)	38
Ammonia (total)	3.8
Aniline (benzenamine)	91
Antimony and compounds	8,100
Arsenic and compounds	84,000
Benzene	8.1
Benzene hexachloro- (HCB)	21,000
Beryllium and compounds	24,000
Biphenyl (1,1-biphenyl)	0.98
Boron and compounds	N/A
Butadiene (vinyl ethylene)	2.2
Cadmium and compounds	1,900,000
Carbon disulfide	1.2
Carbon monoxide	0.14
Chlorine and compounds	N/A
Chlorine dioxide	N/A
Chloroethane (ethyl chloride)	0.02
Chloroform (trichloromethane)	14
Chlorophenols (di, tri, tetra)	51
Chromium (III) compounds	N/A
Chromium (VI) compounds	3,100

[55] based on toluene equivalent

Substance	Non-cancer risk score (TEP)[55]
Cobalt and compounds	31,000
Copper and compounds	13,000
Cumene (1-methylethylbenzene)	0.41
Cyanide (inorganic) compounds	580
Cyclohexane	0.02
Dibromoethane	1,500
Dibutyl phthalate	11
Dichloroethane	4.2
Dichloromethane	7
Ethanol	N/A
Ethoxyethanol	N/A
Ethoxyethanol acetate	N/A
Ethyl acetate	0.09
Ethyl butyl ketone	N/A
Ethylbenzene	0.14
Ethylene glycol (1,2-ethanediol)	0.25
Ethylene oxide	56
Di-(2-Ethylhexyl) phthalate (DEHP)	33
Fluoride compounds	3.6
Formaldehyde (methyl aldehyde)	16
Glutaraldehyde	N/A
Hexane	N/A
Hydrochloric acid	12
Hydrogen sulfide	34
Lead and compounds	580,000
Magnesium oxide fume	N/A
Manganese and compounds	780
Mercury and compounds	5,000,000
Methanol	0.09
Methoxyethanol	N/A
Methoxyethanol acetate	N/A
Methyl ethyl ketone	0.05
Methyl isobutyl ketone	0.03

Substance	Non-cancer risk score (TEP)[55]
Methyl methacrylate	0.53
Methylene-bis(2-chloroaniline) (MOCA)	N/A
Methylene bis (phenylisocyanate)	N/A
Nickel and compounds	3,200
Nickel carbonyl	N/A
Nickel subsulfide	N/A
Nitric acid	2.1
Organo-tin compounds	N/A
Oxides of nitrogen	2.2
Particulate matter ≤ 2.5 µm	17
Particulate matter ≤ 10 µm	1.5
Phenol	0.38
Phosphoric acid	16
Polychlorinated biphenyls	2,000,000
Polychlorinated dioxins and furans (TEQ)	880,000,000,000
Polycyclic aromatic hydrocarbons (B[a]Peq)	N/A
Selenium and compounds	2,400
Styrene (ethenylbenzene)	0.08
Sulfur dioxide	3.1
Sulfuric acid	N/A
Tetrachloroethane	56
Tetrachloroethylene	65
Toluene (methylbenzene)	1
Toluene-2,4-diisocyanate	N/A
Total nitrogen	N/A
Total phosphorus	N/A
Total volatile organic compounds	1
Trichloroethane	4.9
Trichloroethylene	0.63
Vinyl chloride monomer	69
Xylenes (individual or mixed isomers)	0.27
Zinc and compounds	190

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