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ORIGINAL RESEARCH ARTICLE

Impacts of mode shift on well-to-wheel emissions from inter-capital transport in Australia – Part II: Sea and air transport

Supplementary File

Table S1. Model definition for WTW emissions (sea and air transport)

Sea freight transport (maritime fuel oil and distillates)		
$\varepsilon_{(sea, f, WTW)} = e_{(sea, f, WTW)}/\theta_{(sea, f)}$	(I)	$\varepsilon_{(sea, f, WTW)}$ = WTW emission intensity (g CO_2-e/tkm) $e_{(sea, f, WTW)}$ = WTW emission factor (g CO_2-e/ship-km) $\theta_{(sea, f)}$ = payload tonnes/ship
Air passenger transport (kerosene)		
$\varepsilon_{(air, p, WTW)} = e_{(air, p, WTW)}/\phi_{(air, p)}$	(II)	$\varepsilon_{(air, p, WTW)}$ = WTW emission intensity (g CO_2-e/pkm) $e_{(road, f, TTW)}$ = TTW emission factor (g CO_2-e/aircraft-km) $\phi_{(air, p)}$ = occupancy (passengers/aircraft)
Air passenger transport (kerosene)		
$\varepsilon_{(air, f, WTW)} = e_{(air, f, WTW)}/\theta_{(air, f)}$	(III)	$\varepsilon_{(air, p, WTW)}$ = WTW emission intensity (g CO_2-e/pkm) $e_{(road, f, TTW)}$ = TTW emission factor (g CO_2-e/aircraft-km) $\theta_{(air, p)}$ = payload tonnes/aircraft

Abbreviations: TTW: 'Tank-to-wheel' for road and rail transport, 'tank-to-wake' for sea transport, and 'tank-to-wing' for air transport; WTW: Well-to-wheel/wake.

Table S2. Overview of input variable definitions (shipping)

Transport unit	Symbol	Model input variable				
		Units	Year	Typical value	Plausible Min-Max	Distribution
FS	$e_{(ship, TTW)}$ (emission factor)	g CO_2-e/ship-km	All	Var[a]	Var[a]	Var, model output[b]
FS	$u_{(ship, TTW)}$ (uncertainty factor)	-	All	1.00	0.85 – 1.15	Normal, **N** (1.00, 0.05)
FS	t (time spent at berth)	h	2019	33	28 – 39	Normal, **N** (33, 3)
			2030	33	28 – 39	Normal, **N** (33, 3)
			2050	33	28 – 39	Normal, **N** (33, 3)
FS	ν_{ss} (service speed)	kn	All	Var[a]	Var[a]	Dirac, **D** (x)[(a)]
FS	ν_c (current speed)	kn	All	Var[a]	-0.32/+0.32	$P(n_c) = \begin{cases} 0.5\, forc = +0.32 \\ 0.5\, forc = 0.32 \end{cases}$
FS_{bulk}	ν (operational speed)	kn	All	Var[a]	Var[a]	Uniform, U (10, ν_{ss})
$FS_{container}$			All	Var[a]	Var[a]	Uniform, **U** (15, ν_{ss})
FS	$d_{(ship)}$ (distance)	km	All	2250	2200 – 2300	Uniform, **U** (2200, 2300)
FS	c (cargo capacity)	t	All	Var[a]	Var[a]	Dirac, **D** (0.80 DWT)[(a)]
FS_{bulk}	$\theta_{(sea, f)}$	-	All	0.60	0.50 – 0.70	Uniform, **U** (0.50, 0.70)
$FS_{container}$	(payload)		All	0.70	0.60 – 0.80	Uniform, **U** (0.60, 0.80)
FS	γ (energy efficiency correction)	-	2019	1.00	1.00 – 1.00	Dirac, **D** (1)
			2030	0.85	0.80 – 0.90	Uniform, **U** (0.80, 0.90)
			2050	0.75	0.70 – 0.80	Uniform, **U** (0.70, 0.80)
FS	λ (upstream penalty)	-	2019	1.15	1.10 – 1.20	Uniform, **U** (1.10, 1.20)
			2030	1.15	1.10 – 1.20	Uniform, **U** (1.10, 1.20)
			2050	1.15	1.10 – 1.20	Uniform, **U** (1.10, 1.20)

[a]Values are variable and vessel-specific. They represent relevant ship/engine parameters.
[b]For a full description and explanation of MTEM structure, parameterization and validation, refer to References section in main article.[4,16,24,64]
[c]The Bernoulli distribution was used to randomly allocate the two weighted current speeds to the simulations.
Abbreviations: FS: Freight Ship (bulk carrier or container ship); MTEM: Maritime Transport Emission Model.

Table S3. Example input files for the ATEM

a. Example of an aircraft/engine parameter input file for ATEM emission simulations

acft	engine	t0_N	tcr_N	sfc_kgs.kN	cff3	cff2	cff1	h_ft	m_cr	bpr	taxi_kgs	oew_kg	mzfw_kg	mtow_kg	mfc_kg	mpl_kg	pax_min	pax_max	s_m2	cd0	k	m_crit	n_eng
A320	CFM56-5-A1	111200	22241	0.0169	0.438	-0.502	1.118	35000	0.8	6.0	0.1214591	42600	66000	78000	24210	23400	140	180	124.0	0.018	0.039	0.63	2
B737	CFM56-7B24	107650	24376	0.0178	0.471	-0.591	1.226	35000	0.8	5.2	0.1071818	37600	58600	70000	26000	21000	130	149	124.6	0.029	0.046	0.63	2

b. Example of a mission profile used as input in the ATEM emission simulations

	phase	category	aircraft	tas_kmh	tas_ms	rocd_kmh	delta_h_m	t_phase_min	gs_kmh	dist_km
1	Taxi out	LTO	A320	NA	NA	0.0000	0.0	NA	NA	0.000000
2	Take-off	LTO	A320	268.5400	74.59444	0.0000	0.0	0.500000	268.5400	0.000000
3	Climb-out to 3000 ft (FL 30)	LTO	A320	340.3050	94.52917	45.7200	914.4	1.200000	337.2198	6.744395
4	Climb-out to 5000 ft (FL 50)	CCD	A320	340.3050	94.52917	45.7200	609.6	0.800000	337.2198	4.496264
5	Climb-out to 15000 ft (FL 150)	CCD	A320	644.4960	179.02667	36.5760	3048.0	5.000000	643.4573	53.621441
6	Climb-out to 24000 ft (FL 240)	CCD	A320	741.1704	205.88067	25.6032	2743.2	6.428571	740.7280	79.363719
7	Climb-out to cruise altitude 35000 ft (FL 350)	CCD	A320	851.2940	236.47056	18.2880	3352.8	11.000000	851.0976	156.034554
8	Cruise at 35000 ft	CCD	A320	843.3720	234.27000	0.0000	0.0	NA	843.3720	NA
9	Initial descent to 24000 ft (FL 240)	CCD	A320	853.5434	237.09540	-18.2880	-3352.8	11.000000	853.3475	156.447041
10	Descent to 10000 ft (FL 100)	CCD	A320	703.5748	195.43744	-64.0080	-4267.2	4.000000	700.6572	46.710478
11	Descent to 3000 ft (FL 30)	CCD	A320	509.3000	141.47222	-27.4320	-2133.6	4.666667	508.5607	39.554720
12	Approach	LTO	A320	509.3000	141.47222	-27.4320	-914.4	2.000000	508.5607	16.952023
13	Landing	LTO	A320	253.7240	70.47889	0.0000	0.0	1.000000	253.7240	0.000000
14	Taxi in	LTO	A320	NA	NA	0.0000	0.0	NA	NA	0.000000

c. Example of ISA input file (partial) for ATEM emission simulations

h_ft	h_m	t_rel	t_K	t_dC	p_rel	p_Nm2	p_lbft2	d_rel	d_kgm3	d_slft3	a_ms	a_fts	a_kt	p_hPa
0	0.0	1.0000	288.15	15	1.0000	101325	2116.2	1.0000	1.2250	0.002377	340.3	1116	661.5	1013.25
200	61.0	0.9986	287.75	14.6	0.9928	100595	2101.0	0.9942	1.2178	0.002363	340.1	1116	661.0	1005.95
400	121.9	0.9972	287.36	14.21	0.9856	99869	2085.8	0.9883	1.2107	0.002349	339.8	1115	660.6	998.69
600	182.9	0.9959	286.96	13.81	0.9785	99147	2070.7	0.9826	1.2036	0.002335	339.6	1114	660.1	991.47
800	243.8	0.9945	286.57	13.42	0.9714	98430	2055.7	0.9768	1.1966	0.002322	339.4	1113	659.7	984.30
1000	304.8	0.9931	286.17	13.02	0.9644	97717	2040.9	0.9711	1.1896	0.002308	339.1	1113	659.2	977.17
1200	365.8	0.9917	285.77	12.62	0.9574	97008	2026.0	0.9654	1.1826	0.002295	338.9	1112	658.7	970.08
1400	426.7	0.9904	285.38	12.23	0.9504	96303	2011.3	0.9597	1.1756	0.002281	338.7	1111	658.3	963.03
1600	487.7	0.9890	284.98	11.83	0.9435	95602	1996.7	0.9540	1.1687	0.002268	338.4	1110	657.8	956.02
1800	548.6	0.9876	284.58	11.43	0.9366	94905	1982.1	0.9484	1.1618	0.002254	338.2	1110	657.4	949.05
2000	609.6	0.9862	284.19	11.04	0.9298	94213	1967.7	0.9428	1.1549	0.002241	337.9	1109	656.9	942.13

Abbreviation: ATEM: Air Transport Emission Model.

Table S4. Overview of input variable definitions (aviation|aircraft)

Transport unit	Symbol	Model input variable				
		Units	Year	Typical value	Plausible Min-Max	Distribution
FA	$e_{(aircraft, TTW)}$ (emission factor)	g CO_2-e/aircraft-km	All	Variable[a]	Variable[a]	Var, model output [b]
FA	$u_{(aircraft, TTW)}$ (uncertainty factor)	-	All	1.00	0.85 – 1.15	Normal, **N** (1.00, 0.05)
FA (A320)	wf (weighting factor)	-	All	0.30	0.30 – 0.30	Dirac, **D** (0.30)
FA (B737)			All	0.70	0.70 – 0.70	Dirac, **D** (0.70)
FA	$d_{(aircraft)}$ (distance)	km	All	1481	1479 – 1482	Uniform, **U** (1479, 1482)
FA	$w_{(aircraft)}$ (wind impact)	-	All	1.00	0.90 – 1.10	Triangular, **T** (0.90, 1.10, 1.00)
FA	$t_{taxi, out}$ (taxi time)	min	All	10	5 – 30	Triangular, **T** (5, 30, 10)
FA	$t_{taxi, in}$ (taxi time)	min	All	6	5 – 10	Triangular, **T** (5, 10, 6)
FA	m_{pax} (passenger mass)	kg	All	95	90 – 100	Uniform, **U** (90, 100)
FA	l_{pax} (load factor)	-	All	0.81	0.75 – 0.95	Triangular, **T** (0.75, 0.95, 0.81)
FA	s (seats)	-	All	Var[a]	Var[a]	Uniform, **U** (min_{pax}, max_{pax}) [c]
FA	γ (energy efficiency correction)	-	2019	1.00	1.00 – 1.00	Dirac, **D** (1)
			2030	0.80	0.75 – 0.85	Uniform, **U** (0.75, 0.85)
			2050	0.55	0.50 – 0.60	Uniform, **U** (0.50, 0.60)
FA	λ (upstream penalty)	-	2019	1.25	1.20 – 1.30	Normal, **N** (1.25, 0.02)
			2030	1.25	1.20 – 1.30	Normal, **N** (1.25, 0.02)
			2050	1.25	1.20 – 1.30	Normal, **N** (1.25, 0.02)
FA	θ (non-CO_2 effect)	-	2019	1.80	1.00 – 2.50	Triangular, **T** (1.00, 2.50, 2.00)
			2030	1.80	1.00 – 2.50	Triangular, **T** (1.00, 2.50, 2.00)
			2050	1.80	1.00 – 2.50	Triangular, **T** (1.00, 2.50, 2.00)

[a]Values are variable and aircraft/engine-specific. They represent relevant aircraft/engine parameters.

[b]In ATEM the total trip fuel consumption and greenhouse gas (GHG) emissions are estimated as a function of various input variable distributions in combination with: (i) the following specific aircraft and engine parameters: MTOW (maximum take-off weight, t, operational empty weight (OEW), dynamic pressure, wing reference area, reference cruise Mach number, critical Mach number, zero-lift drag coefficient, lift-induced drag coefficient, number of engines, maximum static thrust at sea level, fuel flow coefficients, thrust specific fuel consumption at cruise, reference cruise altitude, maximum fuel capacity, and (ii) the following general model variables: fuel fraction start-to-cruise (0.0259), fuel fraction cruise-to-engine-off (0.0060). The aircraft/engine parameters were obtained from various studies. [25,32,35-39]

[c]min_{pax} and max_{pax} represent the aircraft-specific minimum and maximum number of passengers, respectively. It is noted that the number of passengers is computed as the number of seats (s) × the load factor (l_{pax}) and total passenger load is computed as the number of seats (s) × the load factor (l_{pax}) × average passenger mass (m_{pax}).

Abbreviation: FA: Freight air.

Table S5. WTW emission intensity distributions for sea transport by year and main ship type, including time at berth and in-transit emissions (g CO_2-e/tkm)

Transport unit	Variable	WTW emission intensity (g CO_2-e/tkm)				
		Units	Year	Typical value	Plausible Min-Max	Distribution
FS_{bulk}	E (f) $_{sea, blc, WTW}$	g CO_2-e/tkm	2019	7	4 – 15	Non-standard beta, **B** (2.36, 5.50)
			2030	6	3 – 12	Non-standard beta, **B** (2.73, 7.53)
			2050	4	2 – 8	Gamma, **G** (11.99, 2.91)
$FS_{container}$	E (f) $_{sea, cnt, WTW}$	g CO_2-e/tkm	2019	16	8 – 29	Gamma, **G** (11.61, 0.75)
			2030	13	6 – 25	Non-standard beta, **B** (2.17, 4.28)
			2050	9	4 – 20	Non-standard beta, **B** (1.93, 4.16)

Abbreviations: FS: Freight ship (bulk carrier or container ship); WTW: Well-to-wheel/wake.

Table S6. WTW emission intensity distributions for air transport by year, excluding radiative forcing effects of aircraft at altitude (g CO_2-e/pkm or g CO_2-e/tkm).

Transport unit	Variable	WTW emission intensity (g CO_2-e/pkm or tkm)				
		Units	Year	Typical value	Plausible Min-Max	Distribution
PA	E (p) $_{air, WTW}$	g CO_2-e/pkm	2019	166	102 – 223	Non-standard beta, **B** (5.69, 3.59)
			2030	133	82 – 179	Non-standard beta, **B** (7.59, 4.18)
			2050	89	54 – 119	Weibull, **W** (7.78, 136.0)
FA	E (f) $_{air, WTW}$	g CO_2-e/tkm	2019	1345	617 – 2290	Non-standard beta, **B** (1.55, 2.50)
			2030	1077	494 – 1834	Non-standard beta, **B** (1.61, 2.25)
			2050	719	330 – 1225	Non-standard beta, **B** (1.57, 2.31)

Abbreviations: FA: Freight air; PA: Passenger aircraft; WTW: Well-to-wheel/wake.

Table S7. WTW emission intensity distributions for air transport by year, including radiative forcing effects of aircraft at altitude (g CO_2-e/pkmor g CO_2-e/tkm)

Transport unit	Variable	WTW emission intensity (g CO_2-e/pkm or tkm)				
		Units	Year	Typical value	Plausible Min- Max	Distribution
PA	E (p) $_{air, WTW*}$	g CO_2-e/pkm	2019	304	134 – 494	Non-standard beta, **B** (3.83, 4.59)
			2030	243	107 – 396	Non-standard beta, **B** (4.42, 5.30)
			2050	162	71 – 264	Non-standard beta, **B** (4.10, 4.51)
FA	E (f) $_{air, WTW*}$	g CO_2-e/tkm	2019	2465	794 – 5025	Non-standard beta, **B** (2.27, 4.41)
			2030	1975	634 – 4022	Non-standard beta, **B** (2.20, 4.02)
			2050	1319	424 – 2683	Non-standard beta, **B** (2.35, 4.61)

Abbreviations: FA: Freight air; PA: Passenger air; WTW: Well-to-wheel/wake.

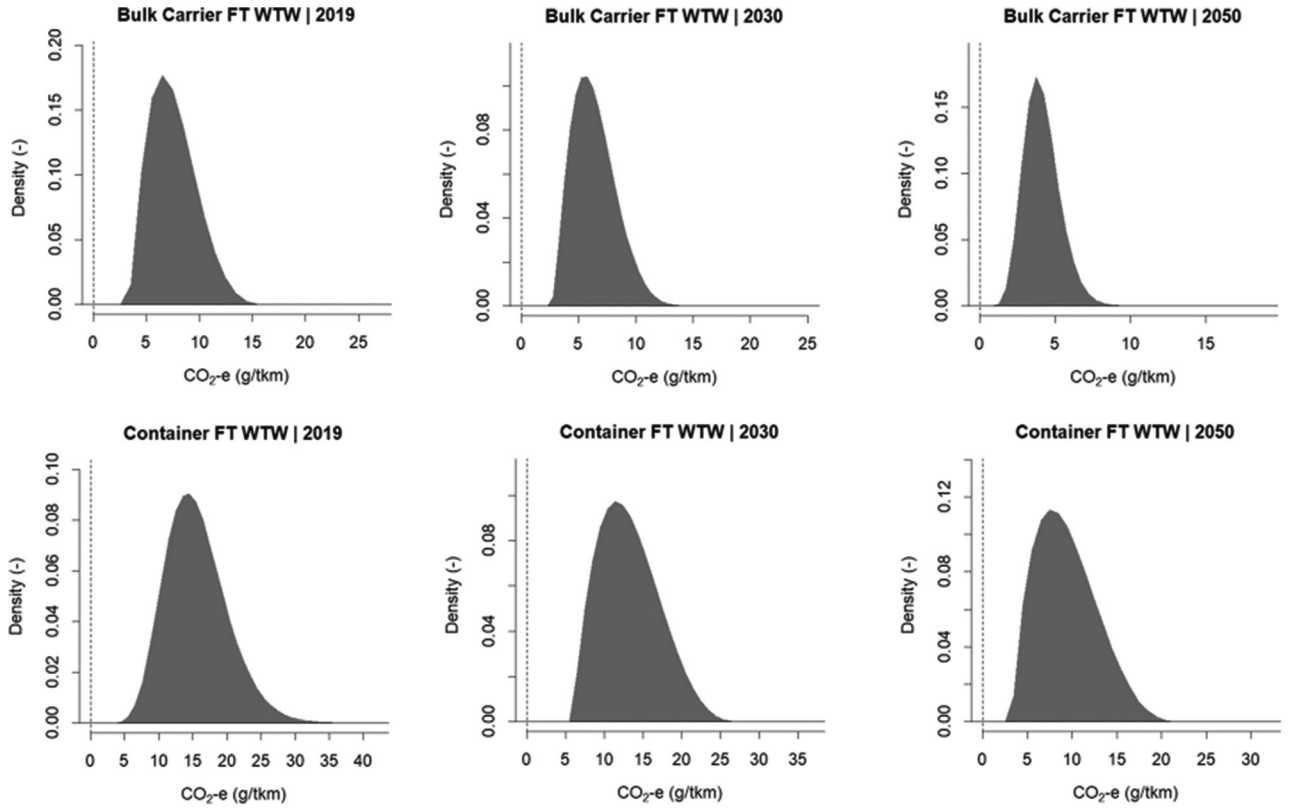

Figure S1. Fitted parametric WTW emission factor distributions by ship type and year, including time at berth and in-transit emissions.
Abbreviations: FT: Freight transport; WTW: Well-to-wheel/wake.

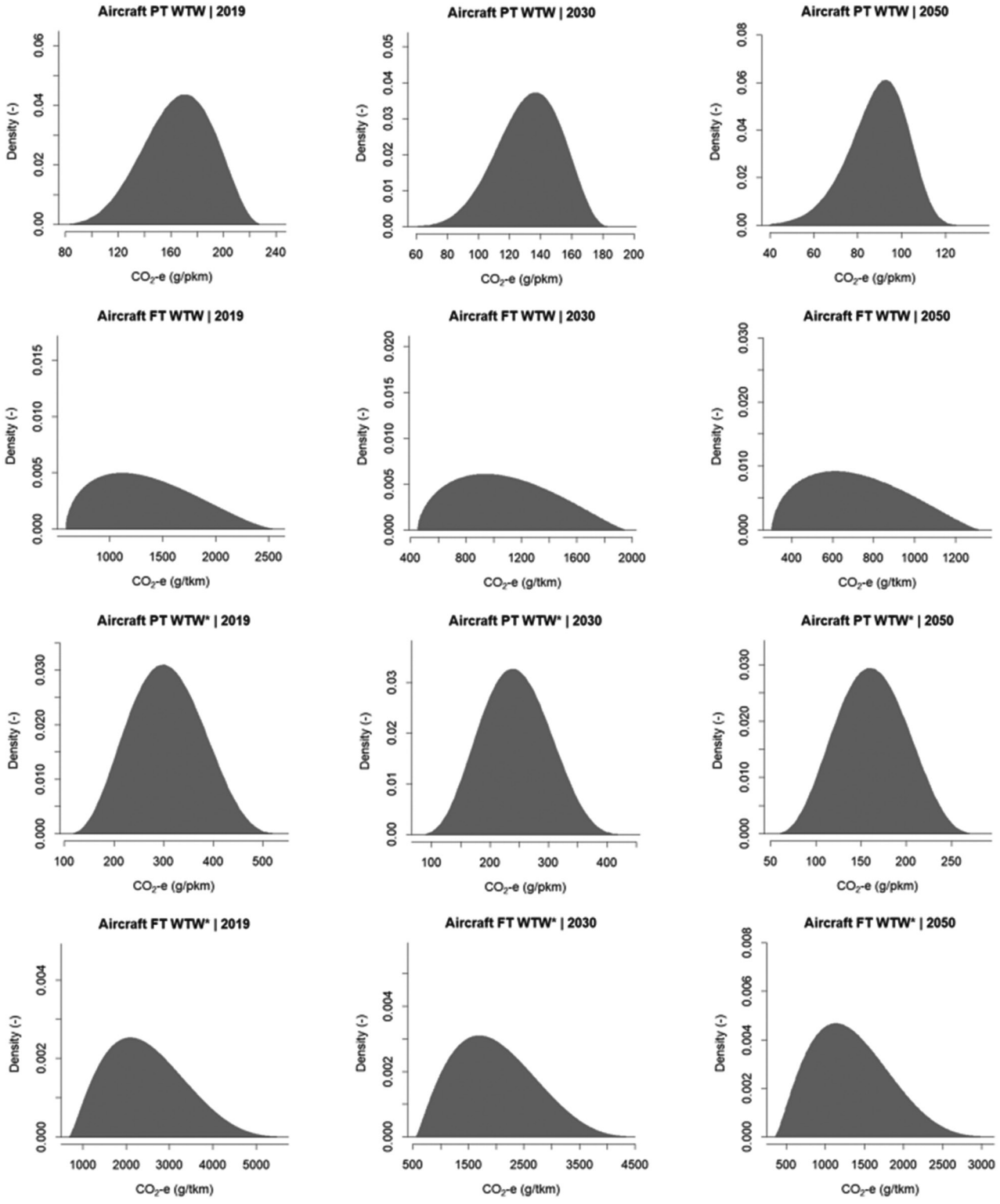

Figure S2. Fitted parametric WTW emission factor distributions by aircraft use type and year, excluding (tp) and including (bottom, denoted with WTW*) radiative forcing effects of aircraft at altitude.
Abbreviations: FT: Freight transport; PT: Passenger transport; WTW: Well-to-wheel/wake.