Emissions from Baltic Sea shipping in 2022

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Key findings

1. **Air emissions from waterborne traffic have increased (NO_x: +0.9%; SO_x: +2.0%; PM2.5: +1.9%; CO: +6.3%; CO_2: +3.1%) when compared to year 2021.** The emissions of CO_2 from non-IMO registered vessels were 12% of total CO_2 emitted from ships. During the 2022 study period, the number of IMO-registered vessels operating in the area has increased by +4.4%.

2. **Although the CO_2 emissions from ships in 2022 indicate a growth compared to the previous year, they are still lower than the pre-pandemic emission levels**. Emissions of CO_2 from ships were -6.4% lower than the 2019 CO_2 total, and 3.1% higher than the 2021 CO_2 total.

3. **Methane emissions were estimated as 6675 tonnes (+56% from previous year).** Most of the methane was released from RoRo (57%), liquid tankers (13%) and Ropax(10%) ships.

4. **Total emissions from IMO-registered vessels in the Baltic Sea in 2022 were 227 thousand tonnes of NO_x, 7.7 thousand tonnes of SO_x, 3.4 thousand tonnes of PM, 20.4 thousand tonnes of CO, 2.5 thousand tonnes Non-Methane Volatile Organic hydroCarbons (NMVOC) and 13.5 million tonnes of CO_2.** The CO_2 amount corresponds to 4.3 million tonnes of fuel (LNG: 4%; distillates: 71%; residual fuels: 25%). From total fuel consumption 13.2% was used in auxiliary engines and 3.1% in auxiliary boilers. These emissions contain only the IMO-registered traffic and do not include any contribution from inland waterway traffic or non-IMO registered vessels. **With all vessels sailing the Baltic Sea (excluding the inland waterway traffic), emission totals are NOx: 258 thousand tonnes, SOx: 8.9 thousand tonnes, PM: 4.0 thousand tonnes, CO: 26 thousand tonnes, NMVOC: 2.8 thousand tonnes and CO_2: 15.5 million tonnes.**

5. **Considering only vessels over 5000 GT,** the emissions were 200 thousand tonnes of NO_x (78% from NO_x total), 6.6 thousand tonnes of SO_x (74% from SO_x total), 2.9 thousand tonnes of PM2.5 (72% from PM2.5 total), 17.1 thousand tonnes of CO (65% from CO total), 11.7 million tonnes of CO_2 (76% from CO_2 total), 6.5 thousand tonnes of CH_4 (98% from CH_4 total) and 0.6 thousand tonnes of N_2O (79% from N_2O total). These totals consider both International and Domestic shipping contributions together.

6. **The most significant contribution to emissions can be associated with ro-ro passenger ships, liquid tankers and RoRo cargo ships.** In terms of million tonnes of CO_2 emitted, the respective shares for these vessel types in the presented order are 3.7 million tonnes (corresponds to 24% from total CO_2 emitted; +3.5% increase from 2021), 2.6 (corresponds to 17% from total

CO_2 emissions; +15% increase from 2021), 1.7 (corresponds to 11% from total CO_2 emissions; +8.1% increase from 2021).

7. **Overall transport work has increased by +2.0% while the total travelling distance of IMO-registered vessels have decreased by -6.7%**. The transport work of liquid tankers and ro-ro cargo ships (incl vehicle carriers) increased by +16.5%, and +2.4%, whereas the transport work of ro-ro passenger, dry cargo and containership segments decreased by -0.5%, -3.9% and -21.8%.

8. For 2022, **emissions of NH_3 and N_2O were included for the first time. These were 70 tonnes and 791 tonnes, respectively.** Ammonia slip arises from Tier III vessels which use SCR for NOx abatement. Currently, no ammonia-fueled ships are known to sail in the Baltic Sea area.

9. **In 2022, there were 3,124 ships which sailed in ice-covered areas**. Total travel distance of all vessels sailing in ice conditions was over 2.5 million nautical miles, mostly concentrated on Gulf of Finland (1.1 million nm) and the Bothnian Bay (1.0 million nm).

10. **During 2022, 1,814 ships with 5,000 gross tonnage and above were sailing in ice conditions in the Baltic Sea area**. These ships have been estimated to travel approximately 1.3 million nautical miles in ice conditions which corresponds to 3.8% of the total travel distance of these vessels.

11. **For all ship types, including the operation in ice conditions in the calculation increases the annual average Carbon intensity indicator (CII) by an average of 3.6% for ships with 5,000 gross tonnage and above.** The largest average increase takes place for general cargo ships with a difference of 6.8% between the CII values with and without sailing in ice conditions included in the calculation of the indicator. Gas tankers and passenger/cruise ships have the lowest change with less than 1% increase from including operation in ice in the average CII value.

12. **On the average, sea ice increases the total annual fuel consumption of ships with 5,000 gross tonnage and above sailing in ice conditions by 4.55% in the Baltic Sea in 2022.** The largest annual effect can be seen for general cargo ships and tankers of which fuel consumption has increased on average by 8.6% due to sailing in ice conditions. The lowest annual increase is for passenger and cruise ships with an increase of less than 1% in the fuel consumption caused by sea ice.

13. **Total effect of weather and sea condition on the total fuel consumption of shipping the in Baltic Sea in 2022 is 7.9%.** Winds, waves and sea currents affect ship passages globally, but sea ice cover is relevant only for some sea areas. From the total weather impact, an average contribution of +2.0% was predicted to arise from winter navigation in the Baltic Sea region.

14. The Ship Traffic Emission Assessment Model (STEAM) used in this work **provides fleet total fuel consumption which is within -1.9% of the MRV reports**. The average absolute deviation of a single vessel of the studied fleet is less than 13%. Both positive and negative uncertainties

exist. Largest uncertainty in predicted fuel consumption was found for chemical tankers, whereas the predictions were most accurate for container-ro-ro ships.

Abbreviations

AIS	Automatic Identification System
CH_4	Methane
CII	Carbon Intensity Index
CMEMS	Copernicus Marine Environment Monitoring Services
CO	Carbon monoxide
CO_2	Carbon dioxide
DCS	Data Collection System
EC	Elementary Carbon
EGCS	Exhaust Gas Cleaning System
ERA5	5^{th} atmospheric reanalysis of the global climate
GHG	GreenHouse Gas
GT	Gross Tonnage
HELCOM	Baltic Marine Environment Protection Commission
HFO	Heavy fuel oil
IMO	International Maritime Organization
IPCC	Intergovernmental Panel for Climate Change
LFO	Light Fuel Oil
LNG	Liquid Natural Gas
MEPC	Marine Environment Protection Committee
MMSI	Maritime Mobile Service Identity
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous oxide
NH_3	Ammonia
NMVOC	Non-methane volatile organic hydrocarbon
NO_x	Nitrogen oxides
OC	Organic carbon
PM2.5	Particulate Matter, smaller than 2.5 micrometer diameter
SCR	Selective Catalytic Reaction
SECA	Sulphur emission control area
SO_x	Sulfur oxides
STEAM	Ship Traffic Emission Assessment Model

1. Emissions of atmospheric pollutants

This work reports, the Baltic Sea ship emissions including contributions from wind, waves, sea currents and ice cover. The STEAM model used in this work was updated to version 4.3.1 with several new features, which enable new quantities to be studied, like N_2O and NH_3 emissions and distance travelled in ice-covered regions. The timeseries reported in previous ship emission reports is thus not directly comparable to the current one, but this report includes data generated with a previous model version for 2006-2020 and with the new version (2020-2022), to better illustrate the impact of model code changes to the Baltic Sea ship emissions timeseries. New features added to STEAM have not yet been reported in peer-reviewed literature, but basic modeling principles are available (Jalkanen et al., 2012, 2009, 2018; Johansson et al., 2013, 2017).

The emissions of all pollutants to air from Baltic Sea ship fleet have increased when compared to year 2021, indicating a slow recovery from the Covid19 pandemic which significantly reduced vessel activity in the area. However, the emissions in 2022 were less than the pre-pandemic levels. Emissions of all air pollutants have increased, and annual totals reported by sea area and vessel type are given in Table 1. The transport work of IMO registered ships increased from last year's value (+2.0%) and CO_2 emissions were increased by +2.4%. The total CO_2 emitted (all vessels) in 2022 was 15.5 million tonnes, which corresponds to roughly 1.7% of the global shipping CO_2 emissions in 2022 (FMI modelling using global 2022 AIS data). Considering only the international shipping, the share of the Baltic Sea shipping is about 1.4% of the global international shipping.

In addition to CO_2 emissions, also 791 tonnes of N_2O, 6675 tonnes of CH_4 and 206 tonnes of Elementary Carbon were released. Assuming 100-year values for global warming potentials, then the total CO_{2eq} emissions were 15.9 million tonnes for Baltic Sea shipping. Compared to the total CO_2 emissions of the fleet reporting to the EU MRV system, the share of Baltic Sea shipping is about 11.4%.

Table 1 Emissions from Baltic Sea shipping in 2022.

Baltic – 2022	MAIN_FUEL [10^3 ton]	AUX_FUEL [10^3 ton]	Boiler [10^3 ton]	NO_x [ton]	SO_x [ton]	PM_{25} [ton]	CO [ton]	CO_2 [10^3 ton]	CH_4 [ton]	N_2O [ton]	NH_3 [ton]	TRAVEL [10^6 nm]	TRAVEL IN ICE [10^6 nm]	TRANSPWORK [10^6 ton nm]	NMVOC [ton]	SHIPS
All	3810	955	138	258097	8880	4040	26238	15454	6675	791	70	80	2	581074	2840	37144
IMO	3602	567	132	227134	7712	3413	20392	13545	6675	712	70	60	2	578345	2513	9240
Baltic Proper	2317	475	61	152428	5175	2332	14507	8999	3565	463	38	46	0	344964	1638	3313
Kattegat	728	259	32	54858	1891	881	5951	3218	619	161	3	18	0	127188	589	24591
Gulf of Finland	436	139	34	31859	1093	503	3279	1918	968	99	10	7	1	80533	363	17326
Gulf of Bothnia	294	67	9	16392	622	275	2154	1154	1499	60	18	7	1	23449	216	15413
Gulf of Riga	35	15	3	2561	99	48	347	166	24	8	0	2	0	4940	33	2300
RoPax_ships	1028	126	9	60421	2124	872	4405	3683	687	192	53	8	0.29	16455	651	217
Vehicle_carriers	25	9	0	2176	56	25	138	107	8	6	0	0	0.01	2083	20	128
Ro-ro cargo ships	520	30	4	22163	839	356	3330	1715	3828	95	14	5	0.19	30603	311	157
Bulk_carriers	319	62	18	24356	753	347	1485	1265	47	68	0	5	0.12	141419	237	2023
General_cargo ships	387	65	32	24001	917	418	2649	1529	50	74	1	18	0.62	65795	274	2466
Container_ships	293	74	7	22977	689	336	1902	1179	327	62	0	4	0.11	71239	243	348
Reefers	33	4	1	3218	73	34	160	121	0	6	0	1	0.02	2812	22	109
Tankers	657	110	56	48146	1495	693	3757	2593	890	139	0	10	0.39	239098	485	2093
LNG_tankers	35	5	2	1258	40	20	407	123	559	8	0	0	0.02	6806	28	106
Gas_tankers	35	7	1	2498	83	36	173	140	3	7	0	1	0.01	4763	26	181
Passenger_ships	34	25	5	3212	123	48	384	203	0	9	0	3	0.15	0	33	575
Cruise ships	124	10	1	6324	248	102	715	426	124	22	1	1	0.00	0	83	100
Fishing_vessels	19	15	0	1656	66	28	188	108	0	5	0	3	0.08	0	20	790
Service_ships	20	15	0	1593	66	28	226	109	11	5	0	1	0.06	0	24	391
Miscellaneous	150	60	0	11072	397	184	1407	664	141	32	1	6	0.32	0	130	2790

Emission totals reported in Table 1 include emissions of both the IMO registered traffic and all vessels. The difference of these two is the vessel fleet which is smaller in size than the IMO registration threshold and the part of the fleet which operates only on national waters without an IMO number, using only MMSI code. Regardless, all vessel traffic using Automatic Identification System (AIS) transceivers is included in the modelling, but those traveling on inland waterways have been removed from the dataset. The five largest emission sources in the Baltic Sea fleet are the ro-ro passenger, tankers, roro cargo, general cargo and bulk cargo ships.

The lines in Figure 1 depict the emission trends over the study period and includes all vessels. The open symbols in Figure 1 indicate the total emissions of NOx and CO for large vessels which have an IMO registry number. It should be noted that Figure 1 includes results from two versions of STEAM which will not lead to identical results. Significant changes were made to the model code to facilitate new features like the inclusion of new pollutants and winter navigation statistics. The difference of emission totals between STEAM versions is between 1.5-3%, depending on the pollutant. This difference is illustrated in Figure 1 with discontinuity in the emission trend. For 2020, both model versions were run to determine the magnitude of the changes to emission totals which are a result of the model version change.

The lines used to plot data from 2020 to 2022 indicate the new model version emission totals, whereas the coloured symbols signal the 2020 results obtained using the older STEAM version. As can be seen from Figure 1, the differences are not large and the existing trends for 2006-2019, generated with the older model version, can be used together with the new STEAM data without adding significant uncertainty to emission totals throughout the 2006-2022 trends. It is likely that the period 2006-2019 will have some scatter because of variable ambient effects each year, if they were to be done with the new model version which includes ambient effects.

It should be kept in mind, that these numbers include only partial contribution from recreational boating which can be a significant source of Non-Methane Volatile Organic hydroCarbons (NMVOC) and CO emissions, especially during summer months. The AIS equipment is not mandatory for these vessels and thus their contribution to overall emissions are underestimated in the current analysis, but further details can be found in a recent work of Johansson et al (2020). The symbols and lines of Figure 1 diverge from 2014 onwards which is because of increasing number of small vessels in the AIS data. This underlines the need to present separate emission totals for large ships and smaller vessels.

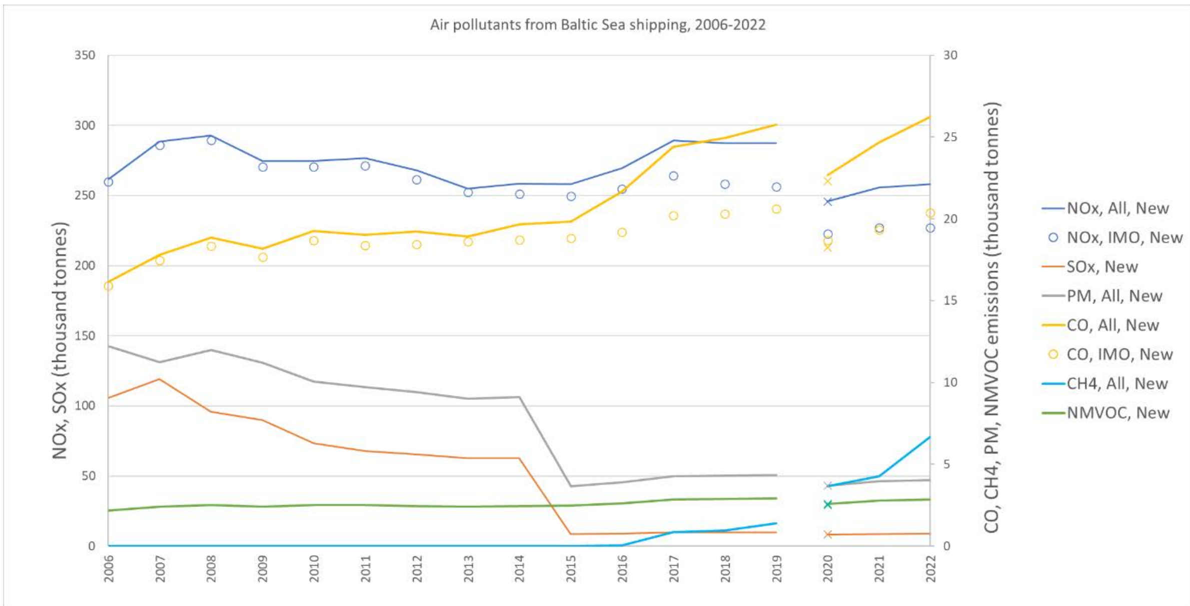


Figure 1 Emissions of NO_x, SO_x, $PM_{2.5}$, CO, CH_4 and NMVOC from ships in the Balti Sea during 2006-2022. Significant decreases in SO_x and $PM_{2.5}$ are results of regulatory changes concerning the maximum Sulphur content of fuel. Coloured symbols depict total emissions from all vessels with an active AIS transceiver, empty symbols indicate the contribution from IMO-registered ships only.

Figure 2 contains a summary of estimated fuel types used by the Baltic Sea fleet during 2006-2022. The coloured bars illustrate different fuel types. Increase of fuel consumption from 2021 to 2022 was +3.2%, which indicates a partial recovery of ship traffic from Covid19 pandemic. However, the fuel consumption total for all vessels in 2022 is still about 5.7% lower than in 2019.

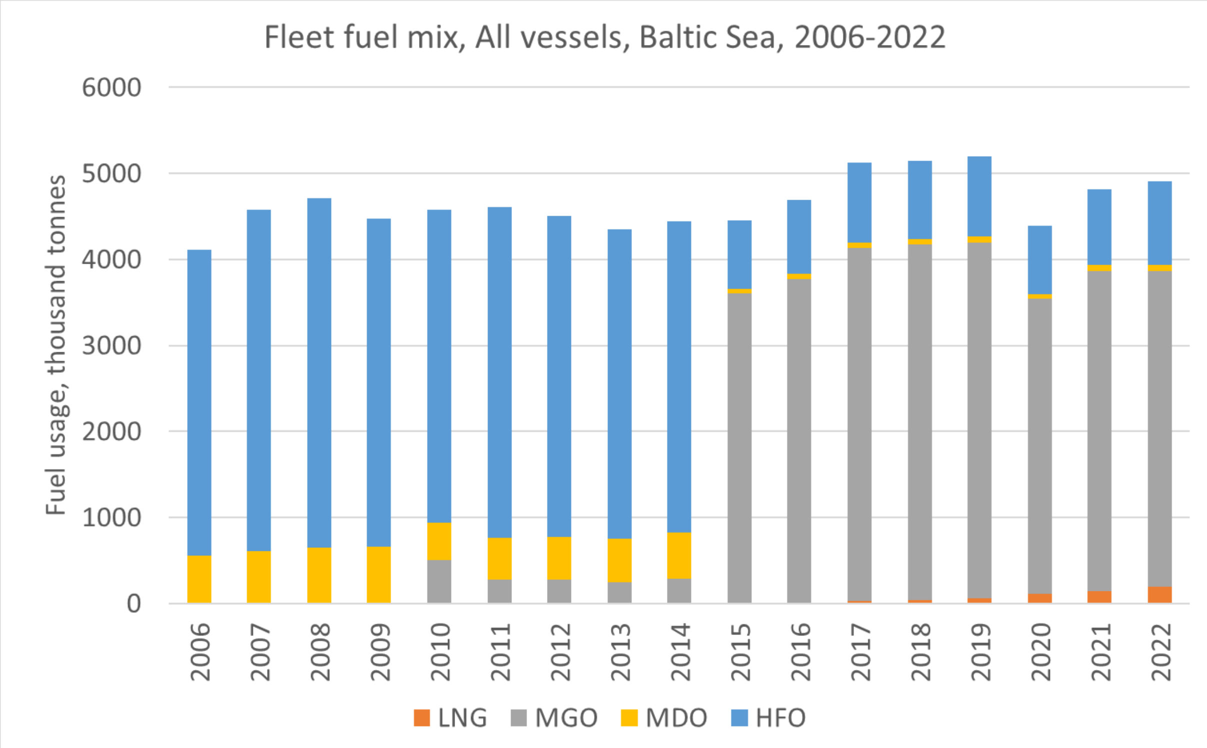


Figure 2 Estimated fuel used in ships operating in the Baltic Sea area in 2006-2022

Heavy fuel use is concentrated on ro-ro passenger ships, roro cargo and cruise ships, which are equipped with exhaust scrubbers and enable the use of HFO regardless of the tight sulphur rules of a SECA (Figure 3). Rest of the fleet is assumed to operate on distillate fuels. Low sulphur residual oils may be an option for a part of the fleet, but only limited measurement data is available of emission factors for marine engines run with these fuels. This prediction is made considering the engine specifications of vessels, which engines can use various fuels. HFO operation is considered in ships which have installed an EGCS.

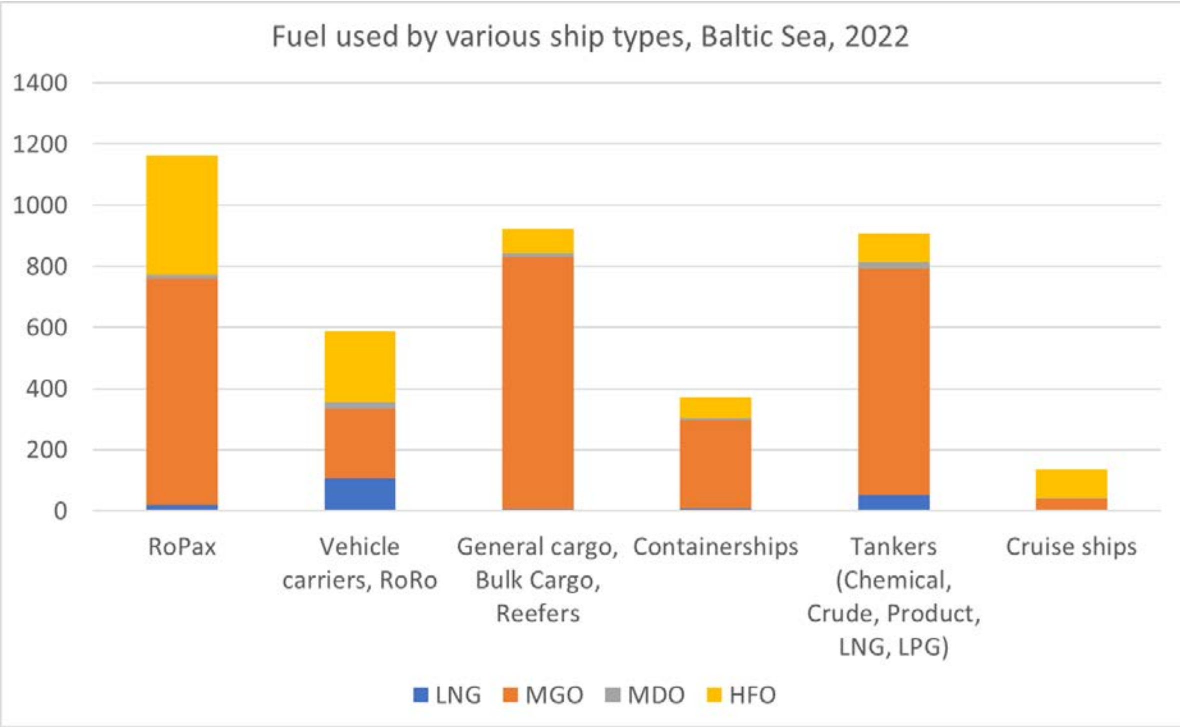
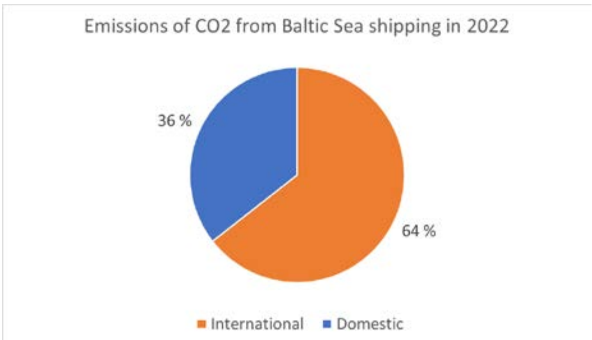


Figure 3 Estimated fuel used by various ship types in the Baltic Sea area during 2022.

In Figure 4, the share of fuel consumed in national and international shipping is reported for both 2022 and 2021. This allocation was made based on voyage-based definition consistent with the IPCC definitions and the Fourth IMO GHG study (Faber et al, 2020). According to the IMO GHG4 report, one third of the global fuel was reported to be consumed in national shipping. Regardless, if a vessel departs and arrives in a port within the same country, its activities are considered as national shipping. In contrast, if departure and arrival ports are in different countries, this voyage is international shipping.



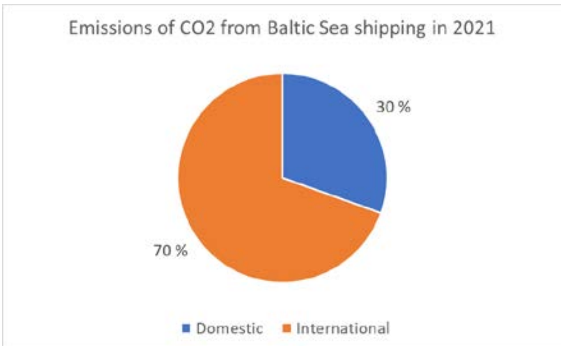


Figure 4 CO_2 emissions of the Baltic Sea fleet in 2022(left) and 2021(right), divided to domestic and international shipping contributions. The share of fuel used in national navigation is about 36%, whereas most of the fuel is consumed in international traffic (64%).

The largest fuel consumers in the Baltic Sea are the ro-ro passenger, tankers, and roro cargo ships, which mostly operate on international voyages. Most of the smaller vessel classes consume their fuel in national routes (Figure 5). The Covid19 pandemic had a major impact on cruise passenger ship operation in the Baltic Sea area and in 2020 most of the fuel used by the cruise passenger ships were used in domestic routes. In

2022 the fuel used in international voyages was about two thirds of the total cruise ship fuel consumption. However, before the pandemic, international navigation dominated (86%) the fuel consumption of cruise passenger ships, which indicates that cruise shipping has not returned to pre-pandemic operations. It is probable that these differences also reflect the changes in cruise ship routes to Russia.

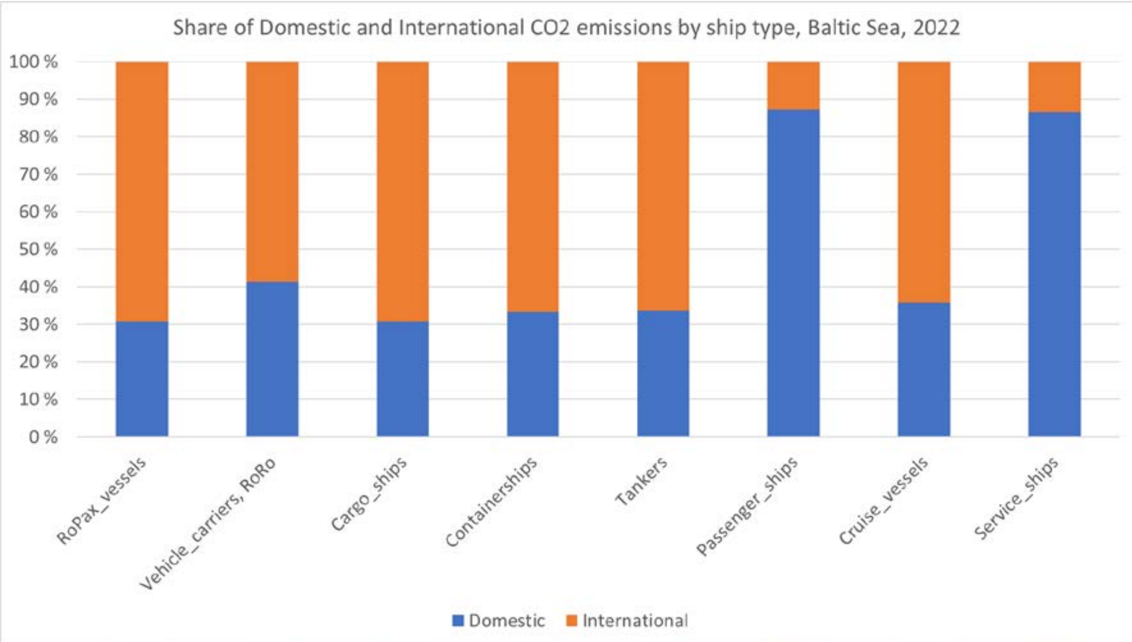


Figure 5 CO_2 emitted from various ship types in domestic and international voyages. Most of the fuel used by passenger, fishing and service vessels falls under national navigation. For other ship types, most of their fuel is used in international traffic.

The time spent in each operation mode for cruise ships also reflects the slow recovery after the pandemic and their activity profile resembles the prepandemic levels. In 2022, cruise vessels spent 59% of their active time at berth, and 37% percent of the time was spent cruising. Before the pandemic, the corresponding shares were 51% and 45%, respectively (Figure 6).

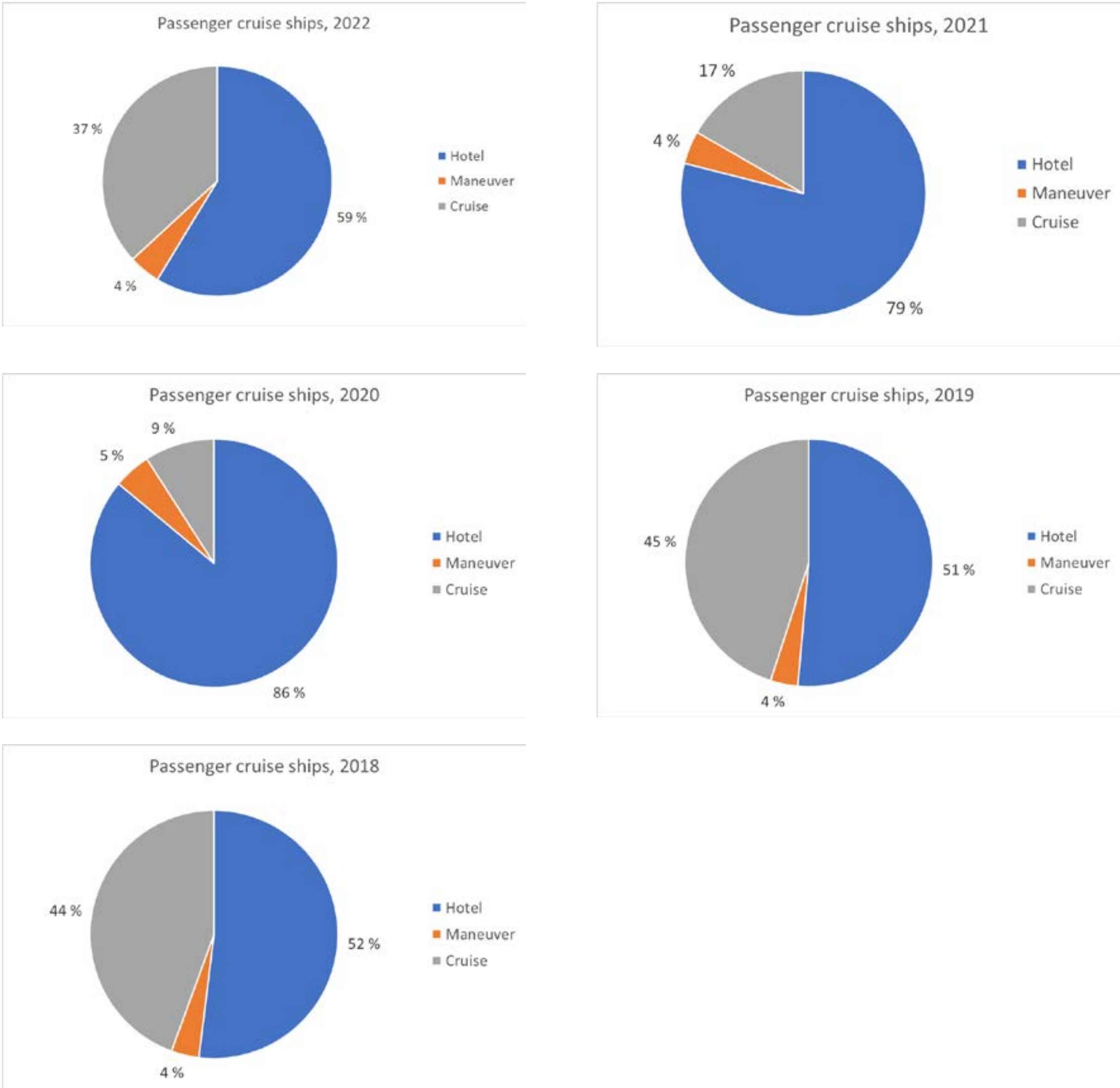


Figure 6 Time spent in each operation mode by Cruise ships during the period 2018-2022.

The share of fuel used during voyages and harbour visits are depicted in Figure 7. The top locations for fuel used at ports are Trelleborg (Sweden) and Tri-city (Gdansk/Gdynia/Sopot, Poland) area. Other emission hotspots are Lübeck, Rostock, Gothenburg and Świnoujście areas.

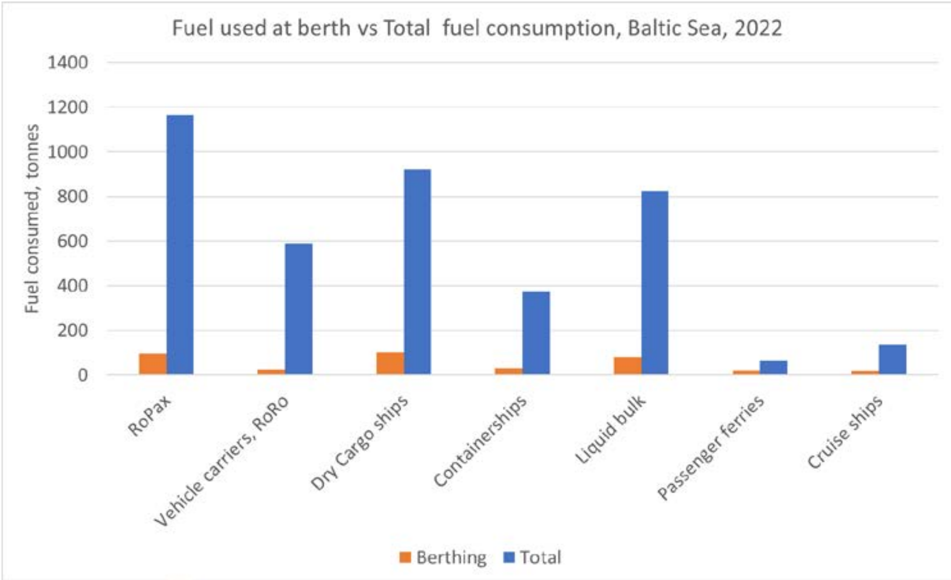


Figure 7 The share of fuel used in harbour areas by vessel type, Baltic Sea fleet, year 2021

2. Country specific CO_2 budgets of international shipping

The country specific import/export emissions of CO_2 from ships were calculated based on global 2022 STEAM runs. For each pair of countries, the emissions from ship traffic could be estimated based on the vessel traffic which happens between ports. Two examples of this data are given in Figure 8 and Figure 9, country specific totals are listed in Table 2. Maps for all Baltic Sea countries and their share of ship emitted CO_2 from export traffic are provided as internet links in Table 2. The export CO2 emission calculation was made considering any ship leaving from one country and traveling to any other country.

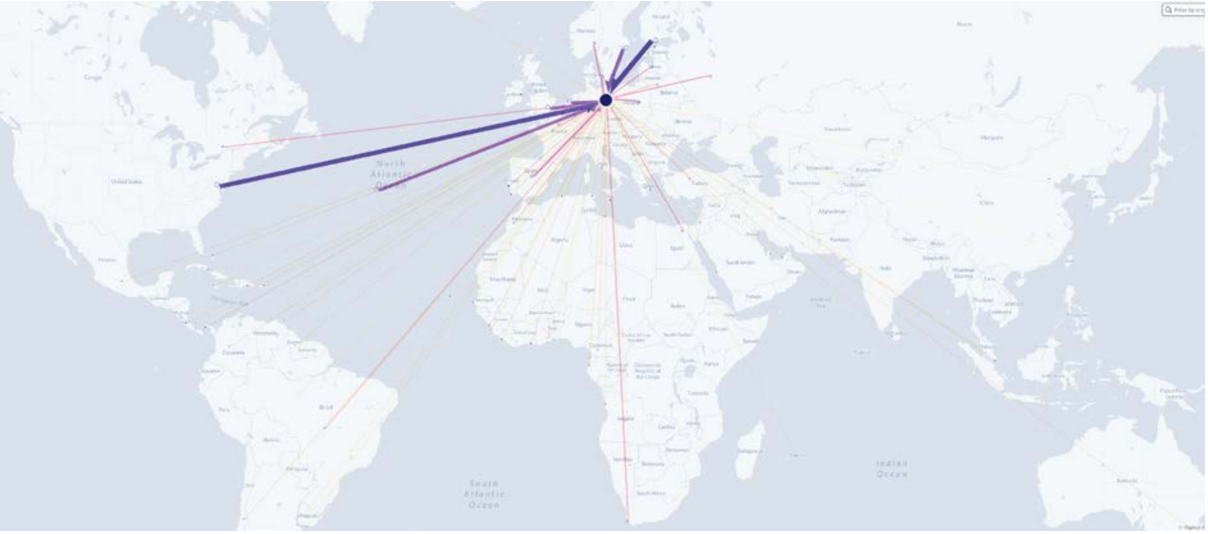


Figure 8 Example of CO_2 emissions of import traffic network of Germany. The width of the arrows and the size of the circles are relative to CO_2 emissions from ships travelling between different countries. For Germany, the largest import emissions were associated with ships coming from Finland, USA, the Netherlands and Sweden.

Figure 9 CO_2 emissions of import shipping for Russia. The arrow weight indicates the CO_2 emissions. From this it can be seen that Turkey and China were the largest trading partners of Russia in 2022 considering the import shipping.

Table 2 Country specific import/export emissions of CO_2 from global ship traffic in 2022. The table contains internet links for maps for each country. These emission totals were computed for global import/export shipping in 2022 between any two countries.

Baltic Sea countries	Export, 10^6 tonnes of CO_2	Import, 10^6 tonnes of CO_2	CO_2, 10^6 tonnes, 50% allocation
Estonia	0.79	1.21	1.0
Latvia	0.47	0.43	0.45
Lithuania	0.54	0.61	0.58
Poland	1.05	1.20	1.13
Germany	5.11	4.72	4.92
Denmark	2.95	2.65	2.8
Sweden	3.15	3.13	3.14
Finland	1.61	1.65	1.63
Russia	10.05	8.40	9.23
Baltic Sea countries	25.7	24.0	24.9

Calculating the emissions of ships sailing between two different countries includes only the international part of ship traffic. Reporting the CO_2 from both import and export traffic leads to double counting of emissions since routes between countries are considered both for import and export traffic. For example, considering the traffic between Finland and Germany; export from GE to FI is considered as export from GE and import to FI. For this reason, the total emissions computed this way are divided by two in Table 2 to avoid double counting and maintain consistency of emission totals.

This analysis can be repeated for all the countries of the world but reported here only for Baltic Sea countries. This way, all the trade activities of shipping emissions connected to any of the Baltic Sea countries globally accounts for about four percent from total of 620 million tonnes of CO_2 from international shipping in 2022. It should be noted that this total does not include domestic shipping. These numbers include explicitly the impact of wind, sea currents, the effect of waves and sea ice.

2. Effect of weather and sea conditions on fuel consumption and carbon intensity

Model runs have been done separately for each variable (ice, wind, currents, and waves) in order to allocate the impact on the total fuel consumption to the factor causing it. This might affect the estimate of the total annual fuel consumption as any possible combined effect of these variables on the fuel consumption of the vessel is not included in this study.

2.1. Materials and methods

The additional power need caused by sea ice is calculated using the method described in Juva and Riska (Juva and Riska, 2002). The model assumes that ice breakers are the only vessel type sailing independently in level ice. All other ship types are being assisted by an icebreaker and are therefore assumed to sail in broken ice in an ice channel. This assumption might result in underprediction of the resistance in ice conditions as icebreaker assistance is only provided in case the merchant ship is not able to sail in ice conditions in a safe manner. Coverage and thickness of the ice are obtained from Copernicus Marine Services (CMEMS) Global Ocean Physics Analysis and Forecast -product. In this study, the edge of the sea ice is defined based on the sea ice thickness; the ship is assumed to travel in ice conditions if the sea ice thickness in the area is more than zero meters.

Sea current data used in this study is from Global Ocean Physics Analysis and Forecast -product in CMEMS. Sea current velocity is used to calculate the relative speed of the ship which is used to calculate the water resistance. Additional resistance due to waves is calculated as described in our earlier work (Jalkanen et al., 2009) and the wave height and direction are obtained from CMEMS product Global Ocean Waves Analysis and Forecast. The method used in the earlier work of Jalkanen et al (Jalkanen et al., 2009), is originally based on the work of Townsin (Townsin et al., 1993). Wind resistance is computed following the method in Blendermann (1993, 1996) and using ERA5 data from Copernicus Climate Data Store. All meteorological data is updated every six hours in STEAM.

2.2. Total fuel consumption

In this chapter, results of the model runs including the effect of sea ice, wind, sea waves, and sea currents are shown. Total annual fuel consumption and the impact of different external factors were calculated for the entire fleet, including also ships with gross tonnage less than 5000, that have operated in the Baltic Sea in 2022. Total fuel consumption, and the increase in the total fuel consumption caused by including the sea ice, wind, sea waves, or sea currents was +7.9%. On average the contribution of sea ice cover to the Baltic Sea fleet fuel consumption was two percent. It should be noted that this contribution is relevant only for some sea areas, whereas wind, waves and sea currents are relevant for every sea region.

2.3. Effect of sea ice

An analysis of the effect of sea ice on the efficiency and fuel consumption of shipping in the Baltic Sea in 2022 was performed. Only ships in size class of 5000 gross tonnage and above have been included in this analysis.

During 2022, 1814 ships with 5000 gross tonnage and above were sailing in ice conditions in the Baltic Sea area. These ships have been estimated to travel 1.28 million nautical miles in ice conditions which corresponds to 3.8% of the total travel distance of these vessels. Miscellaneous ship type has the largest fraction of the travel distance operated in ice and this is mainly due to ice breakers that are included in this ship type. Cruise passenger ships, small passenger ships and service ships have operated less than 1% of their annual travel distance in ice conditions, which seems consistent of the fact that the peak season for these ships occurs during open water conditions.

2.3.1. Effect of sea ice on carbon intensity

The impact of sea ice on the annual carbon intensity of ships, which had sailed in ice conditions in 2022, was analyzed by modelling the CO_2 emissions from shipping with the STEAM model and comparing the carbon intensity of shipping in open water with the carbon intensity including the operation in ice conditions. This comparison was performed only for ships with 5000 gross tonnage or more that had sailed at least 10 kilometers both in ice conditions and open water. The minimum sailing distance of 10 km is set to reduce the impact of ships that have mainly been at berth or anchoring.

Number of ships included in the analysis of carbon intensity is given in Table 4. None of the cruise passenger ships and small passenger ships operated in ice conditions more than 10 km during the year and therefore, it was not possible to perform the analysis for these ship types.

Table 3 Number of ships included in the analysis of Carbon intensity indicator (CII) and the average share (%) of the total distance travelled in ice conditions by different ship types.

	Number of ships	Distance share travelled in ice (%)
Ro-Ro passenger ships	37	5.9
Vehicle carriers	8	6.1
Ro-Ro cargo ships	61	5.2
Bulk carriers	491	6.8
General cargo ships	345	6.4
Container ships	120	5.3
Refrigerated cargo carriers	51	4.3
Tankers	540	6.2
LNG carriers	8	3.6
Gas tankers	24	3.1
Passenger ships	0	0.0
Cruise passenger ships	0	0.0

Carbon intensity indicator is calculated as defined in International Maritime Organization (IMO) resolution MEPC.336(.76) i.e., the correction coefficients and voyage exclusions given in resolution MEPC.355(78), 2022 Interim guidelines on correction factors and voyage adjustments for CII calculations (CII guidelines, G5), were not included in the calculation of carbon intensity indicators in this study.:

$$CII_{ship} = \frac{M_{CO2}}{W} \tag{1}$$

where:

M_{CO2} = total mass of CO_2 (g),

W = transport work (ton nm).

The transport work is calculated as a product of ship's capacity (in tons) and the distance sailed (in nautical miles). For bulk carriers, LNG carriers, gas tankers, tankers, container ships, general cargo ships, ro-ro cargo ships and refrigerated cargo carriers, the deadweight tonnage is used to represent the capacity, and for passenger vessels, cruise passenger ships, vehicle carriers and ro-ro passenger ships, gross tonnage is used to represent the capacity.

The CII values have been calculated for each ship by with Eq. (1) including all of the ship's activity in the calculation, leaving out the sailed distance and the fuel consumed when the ship has been operating in ice conditions. Results are shown in Table 5. For all ship types, including the operation in ice conditions in the calculation increases the annual average Carbon intensity indicator (CII) by an average of 3.6% for ships with 5000 gross tonnage and above. The largest average increase takes place for general cargo ships with a difference of 6.8% between the CII values with and without sailing in ice conditions included in the calculation of the indicator. Gas tankers, and passenger and cruise ships have the lowest change with less than 1% increase from including operation in ice in the average CII value.

Table 4 The average annual Carbon intensity indicator CII (g-CO2 ton^{-1} nm^{-1}) for each ship type calculated by including both the operation in ice conditions and in open water, including only operation in ice and including only operation in open water. The final column shows the change in CII when the operation in ice is included in the calculation.

	All operation	Operation only in ice	Operation only in open water	Change (%) due to operation in ice
Ro-Ro passenger ships	15.98	17.11	15.79	+ 1.23
Vehicle carriers	10.41	11.95	10.32	+ 0.83
Ro-Ro cargo ships	29.77	38.53	29.17	+ 2.06
Bulk carriers	5.60	8.07	5.45	+ 2.74
General cargo ships	12.86	19.48	12.04	+ 6.81
Container ships	14.19	19.94	13.83	+ 2.60
Refrigerated cargo carriers	20.34	29.03	19.92	+ 2.08
Tankers	6.87	10.42	6.66	+ 3.28
LNG carriers	13.46	18.43	13.25	+ 1.62
Gas tankers	15.63	19.35	15.54	+ 0.55
Passenger ships	n/a	n/a	n/a	n/a
Cruise passenger ships	n/a	n/a	n/a	n/a
MEAN	**9.9**	**14.2**	**9.5**	**+ 3.6**

Figure 9 shows increase in CII values of individual ships as a function of the percentage of the annual distance the ship has travelled in ice conditions. For a few ships, the CII value decreases when operation in ice conditions is included in the calculation. This is caused by high hoteling emissions that increase the CII value calculated for only open water operation and thus, including the operation in ice conditions decreases the overall CII value of the ship. Sea ice only affects the required propulsion power and therefore, has no impact on the fuel consumption and emissions of the ship while berthing or anchoring.

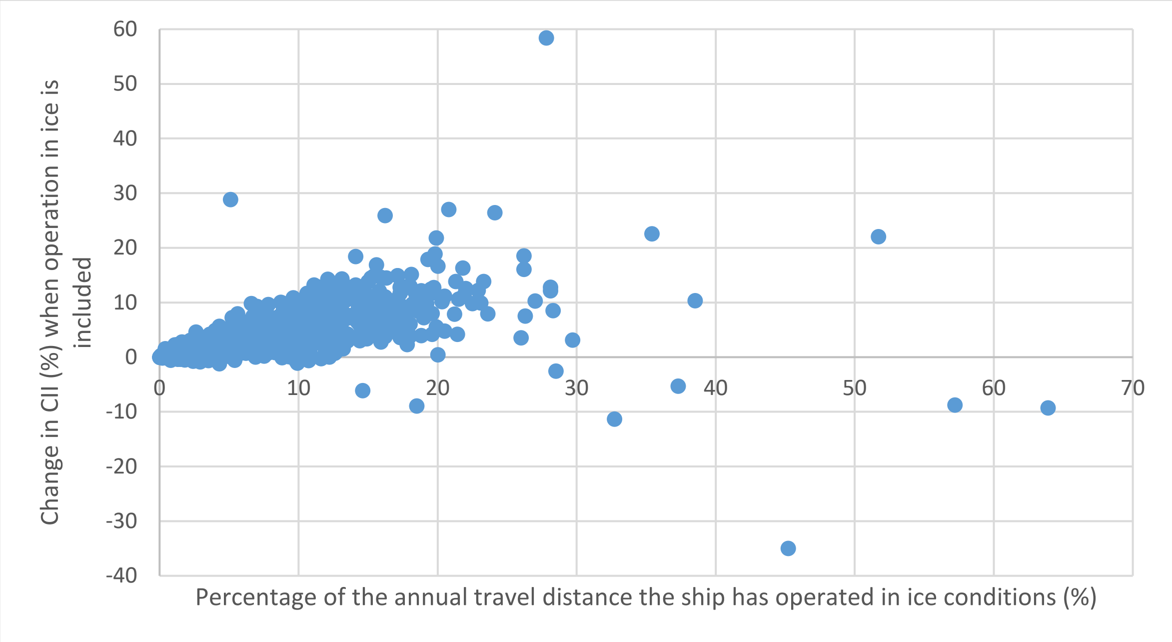


Figure 10 Increase in CII due to sea ice as a function of the percentage of the annual travel distance the ship has operated in ice conditions in the Baltic Sea in 2022. Only commercial ships with 5000 gross tonnage or above that have operated in ice conditions are included.

2.3.2. Effect of sea ice on fuel consumption

The impact of sea ice on the total annual fuel consumption of all ships that have sailed in the Baltic Sea area was also analyzed. Model runs were done separately with and without the effect of sea ice to estimate the increase in annual fuel consumption caused by ice conditions in the Baltic Sea in 2022. All ships with 5,000 gross tonnage and above were included in the analysis, regardless of if they had operated only in open water.

The total annual fuel consumption in the Baltic Sea without and with the effect of sea ice, and the increase in the total fuel consumption in percentages of the total fuel consumed annually due to ice conditions, are shown in Table 6. On average, sea ice increases the total fuel consumption of ships sailing in the Baltic Sea area by +4.5% in 2022. Regarding the different ship types, the largest average annual effect can be seen for general cargo ships of which fuel consumption has increased on average by +8.6% due to sailing in ice conditions. The lowest annual increase is for passenger ships with no significant increase in the fuel consumption caused by sea ice.

Table 5 Total fuel consumption of ships with 5000 gross tonnage or above without and including the impact of sea ice, as well as the increase in the total fuel consumption cause by sea ice in the Baltic Sea in 2022.

	Without sea ice (tons of fuel)	Including sea ice (tons of fuel)	Increase caused by sea ice (%)
Ro-Ro passenger ships	996433	1034504	+ 3.82
Vehicle carriers	30820	31772	+ 3.09
Ro-Ro cargo ships	479394	501674	+ 4.65
Bulk carriers	363406	377013	+ 3.74
General cargo ships	168503	182934	+ 8.56
Container ships	339844	354061	+ 4.18
Refrigerated cargo carriers	30350	31953	+ 5.28
Tankers	670979	713082	+ 6.27
LNG carriers	38784	40089	+ 3.36
Gas tankers	35866	36868	+ 2.79
Passenger ships	10481	10481	0.00
Cruise passenger ships	125243	125427	+ 0.15
TOTAL	**3290102**	**3439858**	**+ 4.55**

Figure 10 shows the increase in annual fuel consumption of individual ships due to operation in ice as a function of the percentage of the annual travel distance the ship has operated in ice conditions in 2022 in the Baltic Sea. Commercial ships with 5,000 gross tonnage or above that have travelled in ice are included in the analysis. This graph illustrates that although the average increase in fuel consumption is relatively low, for individual vessels that operate often in ice conditions, the annual increase in the fuel consumption might be significant.

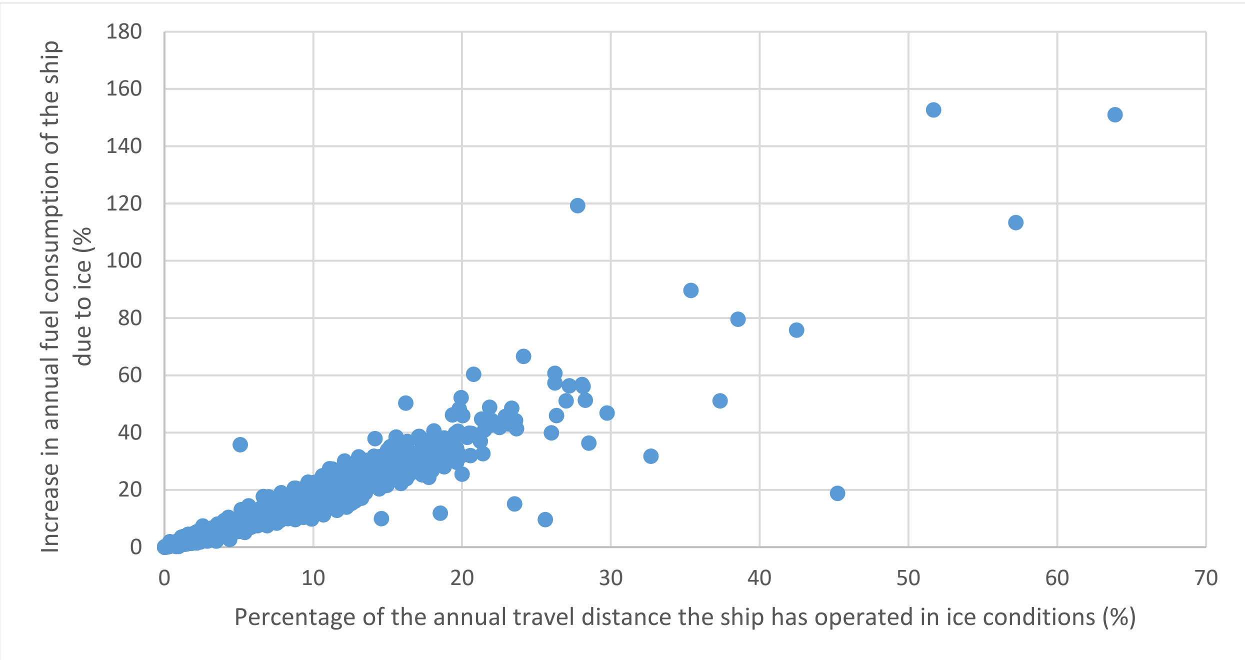


Figure 11 Increase in annual fuel consumption of ships due to sea ice as a function of the percentage of the annual travel distance the ship has operated in ice conditions in the Baltic Sea in 2022. Only commercial ships with 5,000 gross tonnage or above that have operated in ice conditions are included.

Figure 11 below shows the total fuel consumption in ice conditions during the year 2022 in the Baltic Sea. This figure includes all ship types and size classes that have sailed in the Baltic Sea. This figure depicts the maximum ice extent during the target year 2022.

Figure 12 Total annual fuel consumption (kg) in ice conditions in the Baltic Sea in 2022

3. Uncertainty of emission modelling and the comparison of predicted (STEAM) to reported fuel consumption (MRV)

The comparison between model predictions and reported fuel consumption for ships sailing in the EU sea areas can be done based on the Monitoring, Reporting and Verification (MRV) data. The starting point for modelling is somewhat different than the MRV system requirements, which complicates the comparison. Certain quantities, like annual fuel consumed, can only be compared for that part of the fleet when all ship activity is completely covered in the MRV scheme.

The calculations of this uncertainty assessment are based on global AIS data obtained from Orbcomm Ltd. The volume, and update rate of vessel positions, is significantly lower than in the HELCOM Baltic Sea data, which may have an impact on the accuracy of model predictions.

The global modelling was simulated with ambient effects enabled. Data from the Copernicus Marine Environment Monitoring Services (CMEMS) were used to describe the ambient conditions in 2022.

3.1. Introduction

The European Monitoring, Reporting and Verification mechanism (MRV) facilitates comparisons of annual fuel consumption and CO_2 emission reports of ships to corresponding modelling results from FMI STEAM model. However, these two approaches are not fully consistent with each other, because they serve different purposes and were constructed to fulfil different needs. For this uncertainty evaluation, global modeling covering year 2022was made (Figure 12). In the MRV reporting, fuel consumption of voyages which either start or end at EU area must be included, only, regardless of geographic location. STEAM does not make this distinction, because it involves all shipping by default. In principle, a more robust comparison could be made with IMO Data Collection System (DCS), which would allow a perfect match considering the vessel activity, but DCS reporting was not available for this study.

The principal difference of global modelling and MRV reporting makes 1:1 comparison somewhat complicated, because MRV reporting represents a subset of global shipping. An attempt is made in this document to point out STEAM model performance against the MRV fuel reports in parts where the vessel activity is expected to be similar in both approaches.

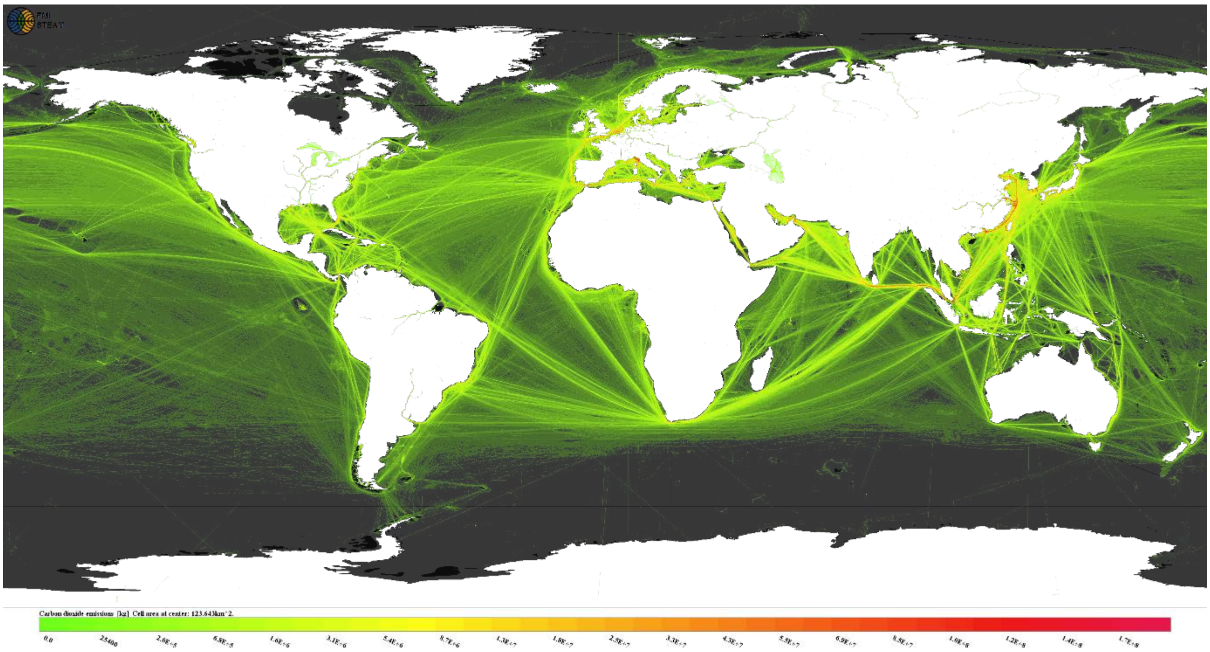


Figure 13 Global CO_2 emissions from ships in 2022. These data are used in the STEAM model uncertainty evaluation when comparing model predictions to MRV fuel reports.

3.2. General remarks about comparisons

Some general conditions were set up to facilitate the comparisons, which include the following:

1) Travel distance calculated from AIS position reports by STEAM must be 90-110% of the MRV distance total. The MRV distance total was calculated from “Total fuel consumption, tonnes” and “Annual average fuel consumption per distance, kg/nm” data fields by dividing the former with the latter (noting the unit change from tonnes to kg). This ensures that both MRV and STEAM describe roughly the same vessel activity which occurs inside the EU domain. This, however, excludes long-haul intercontinental voyages which mostly fall outside the EU domain. This requirement ruled out most of the vessels but allowed comparisons between 1313 ships from 11135 included in MRV system for year 2022.
2) Vessel matching was done by the IMO number.
3) When conditions 1 and 2 were valid, fuel consumption of all engines were summed together in STEAM to indicate the fuel consumed in tonnes by each vessel.
4) CO_2 emissions which occurred within ports under an EU Member State jurisdiction at berth are required to be reported in MRV. While STEAM includes vessel fuel consumption totals at berth, it does not make a distinction whether this occurs in a port which is under a Member State jurisdiction or not. This makes comparisons challenging.
5) Effects of wind, sea currents, waves and ice cover were **included** in the modelling. The additional resistance because of biofouling was **included** and modelled by adding 5% to vessel resistance. Impact of squat was **excluded** from the modelled totals because global bathymetric datasets were not available. It should be noted that MRV totals include all these effects, whereas the predicted numbers reported here include some of these.

3.3. Overall results

Comparisons of annual totals of fuel consumed require that both MRV and STEAM describe the same vessel activity. Since STEAM describes all vessel activity of the global fleet regardless of point of origin/destination it is not directly comparable to MRV which includes a subset of global vessel activity.

The MRV scheme includes reporting of fuel used in different types of travel; to/from ports in the EU jurisdiction as well as those occurring visiting ports under Member State jurisdiction. By default, STEAM makes no difference whether emissions occur in ports governed by an EU Member State or not and this makes MRV comparisons to STEAM predictions very challenging in case of port emissions.

An accuracy comparison was completed between the STEAM modelled results for 2022 taking in account all weather parameters and the EU MRV database for the corresponding year. Version 54 (dated 28th August 2023) of the MRV data was downloaded from mrv.emsa.europa.eu. The dataset contains information for 12842 unique vessels with specific IMO numbers. 204 vessels in MRV had a fuel consumption marked Division by zero and were removed from the comparison. The STEAM 2022 modelled results dataset contains data of 615780 AIS broadcasting vessels of which 98699 had unique IMO numbers. 1503 vessels had entries in STEAM with multiple MMSI numbers, which could indicate change of flag state during year 2022 or error in the AIS data. In total 11135 ships were left for comparison.

Distances calculated in the MRV and STEAM were compared to each other. First, the distances sailed in STEAM were converted to nautical miles by diving the modelled kilometres by 1.825. Out of 11135 vessels in the combined dataset, 1313 vessels had a distance difference between STEAM and MRV less than 10%, 1751 vessels less than 20% and 2633 less than 50%.

3.3.1. Total annual fuel and CO_2

The total annual fuel consumed of the 1313 vessels within 10% of distance difference was 8,105,345 tonnes as per MRV and 7,951,293 tonnes predicted by STEAM – a difference of -1.9%. The total annual CO_2 emitted by the same 1313 vessels was 25,311,897 tonnes as per MRV and 25,012,955 tonnes as per STEAM – a difference of -1.2%. Total annual fuel consumed, and CO_2 emitted by vessel type are in Table 7.

STEAM seems to underpredict fuel consumption for most vessel types (10 vessel types) apart from the combination carriers and roro-type vessels (roro, ropax and vehicle carrier). The last row of Table 7 reports the difference between MRV reports and STEAM predictions for the set of 1313 ships. As can be seen, the difference between CO_2 emissions (-1.2%) and fuel consumed (-1.9%) are not identical. Potential explanations are the disagreement of fuel types predicted by the model and reported in MRV, and differences between CO_2 emission factors used in STEAM and MRV. STEAM uses CO_2 emission factors from the 3rd IMO GHG report, without the inclusion of Light Fuel Oil. Since part of the fuel reported in MRV is LFO, this will contribute towards the difference between CO2 and the amount fuel used in Table 7.

Table 6 Vessels by type, their number with annual total distance within less than 10% and 20% of STEAM and MRV, total annual fuel consumed, and CO_2 emitted as per MRV and STEAM and the difference between reported and modelled in percentage. A negative difference indicates that STEAM is underpredicting and a positive that STEAM is overpredicting.

Vessels		MRV		STEAM		Differences (%)	
Type	Number	Fuel (t)	CO_2 (t)	Fuel (t)	CO_2 (t)	Fuel	CO_2
Bulk	60	248945	782982	235262	745745	-5.5%	-4.8%
Chemical tanker	167	509993	1609991	400623	1255234	-27.3%	-28.3%
Container vessel	239	1337175	4162402	1244501	3935505	-7.4%	-5.8%
Container/ roro	8	51497	162000	52529	166422	2.0%	2.7%
Gas carrier	39	136890	429573	125194	393426	-9.3%	-9.2%
General cargo	189	417052	1320284	338148	1068372	-23.3%	-23.6%
LNG carrier	17	246183	711155	194526	566321	-26.6%	-25.6%
Oil tanker	111	467485	1477779	424936	1334046	-10.0%	-10.8%
Other	29	127587	398260	109554	347838	-16.5%	-14.5%
Passenger	21	293711	926359	255332	805053	-15.0%	-15.1%
Reefer	1	2242	7163	917	2902	-144.5%	-146.9%
Ropax	282	3029094	9498312	3220131	10124930	6.3%	6.6%
Roro	124	1105536	3455335	1138453	3794723	7.8%	8.9%
Vehicle carrier	25	127660	356841	147241	459952	13.3%	22.4%
All vessels	1313	8105345	25311897	7951293	25012955	-1.9%	-1.2%

3.3.2. Correlation between STEAM and MRV

In Figure 13 the 1313 vessels with an annual distance sailed within 10% of STEAM and MRV are plotted for total annual fuel consumed in metric tons and in Figure 14 for total annual CO_2 emitted. Different vessel types as characterised in the MRV database are plotted with corresponding colours. The correlation between STEAM and MRV fuel data is 0.954 (95% confidence interval 0.949-0.958, $p<0.001$). The goodness of fit (adjusted r^2) of a linear regression between the annual fuel consumptions is 0.910 ($p<0.001$).

If the 1751 vessels with an annual distance sailed difference of less than 20% are compared, the correlation between total annual fuel consumed is 0.947 (95% confidence interval 0.942-0.951, $p<0.001$) and the goodness of fit (adj. r_2) of a linear regression is 0.897 ($p<0.001$). The correlation between the 2633 vessels with an annual distance sailed difference of less than 50% is 0.927 (95% confidence interval 0.921-0.932, $p<0.001$) and the goodness of fit of a linear regression is 0.859 ($p<0.001$).

The correlation between STEAM modelled total annual CO_2 emitted and MRV reported total annual CO_2 emitted is 0.952 (95% confidence interval 0.947-0.957, $p<0.001$) and the goodness of fit (adjusted r^2) of a linear regression between annual CO_2 emitted is 0.906 ($p<0.001$).

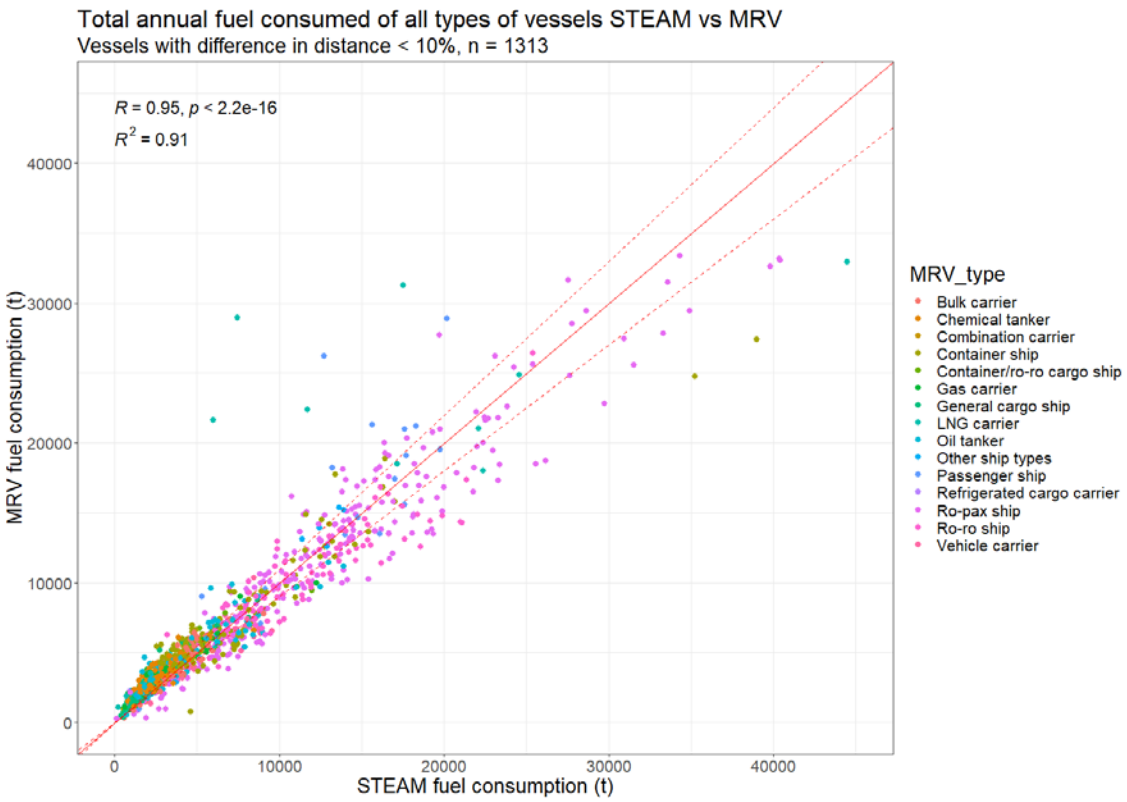


Figure 14 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) with different vessel types coloured. The plot consists of the 1313 vessels that have a difference <10% between the total annual distance sailed in STEAM and MRV. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation.

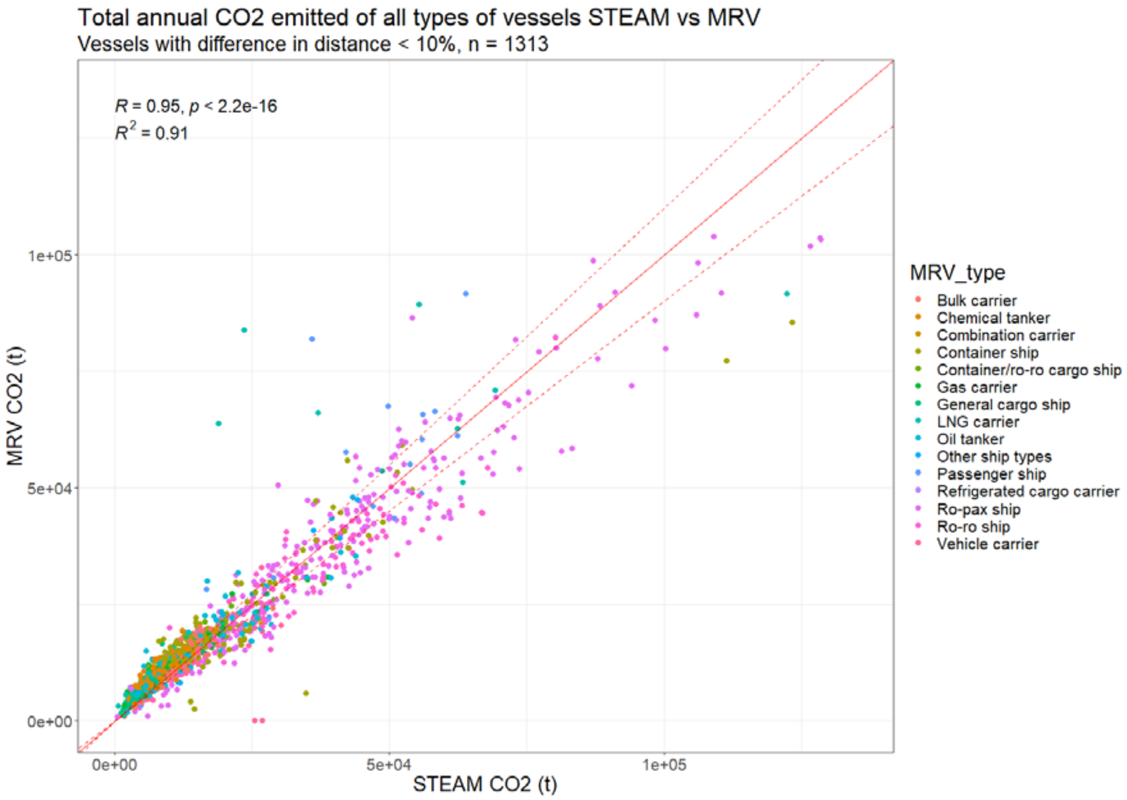


Figure 15 Scatterplot of total annual CO_2 emitted between STEAM (x-axis) and MRV (y-axis) with different vessel types coloured. The plot consists of the 1313 vessels that have a difference <10% between the total annual distance sailed in STEAM and MRV. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation.

3.3.3. Differences between ship types and outliers

Some differences can be observed between different vessel types. Scatterplots for each vessel type are presented in Figure 15 to Figure 28. The goodness of fit of linear regression varies and is heavily driven by outliers. Some outliers could be reporting errors in the MRV data even though it is verified by a third party. Others are missing specific data from the vessel database that STEAM uses for modelling.

For example, four RoPax vessels were retrofitted to be battery powered and therefore STEAM overpredicts them by 280%-574%. Also, STEAM underpredicts gas turbine powered LNG tankers significantly.

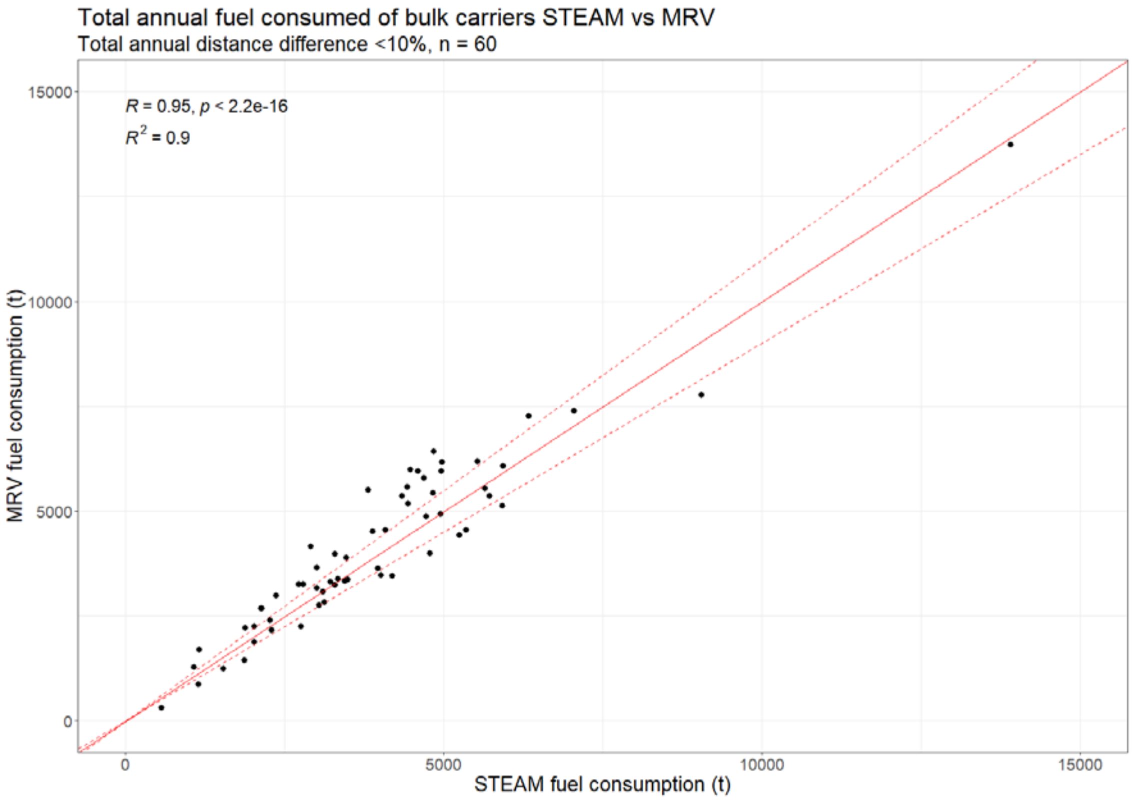


Figure 16 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of bulk carriers. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit (R^2) of linear regression in the top left corner.

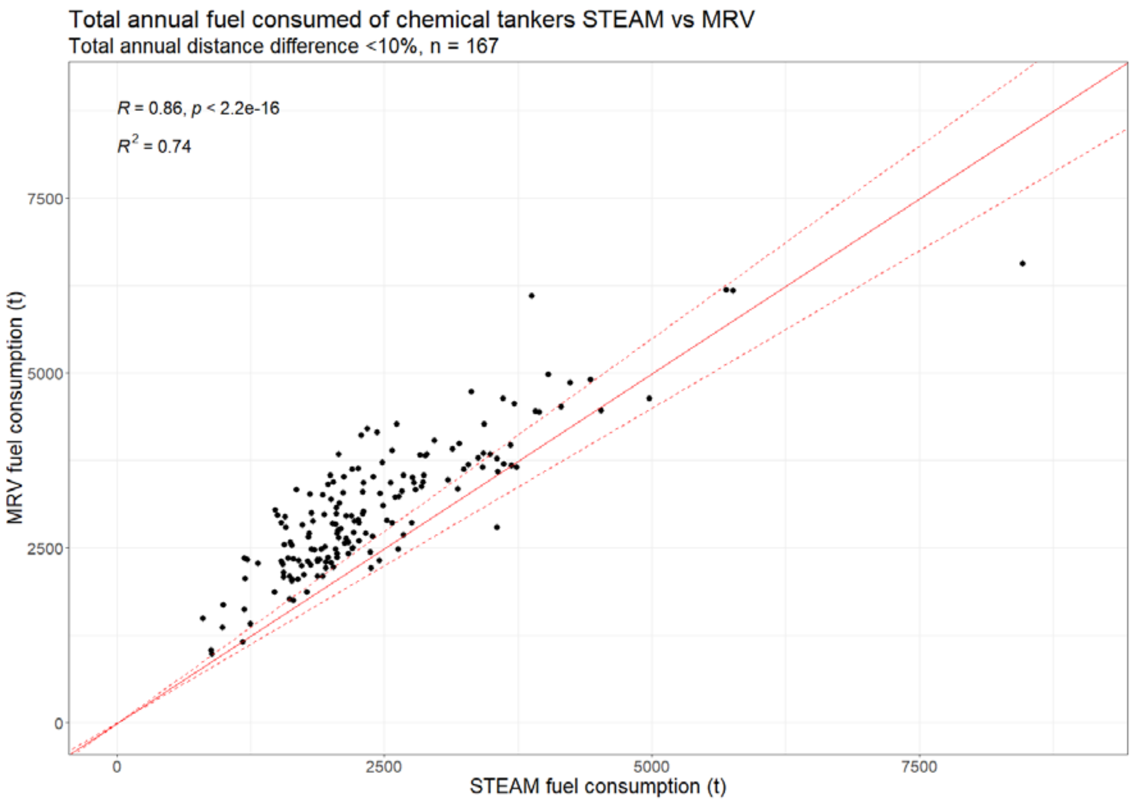


Figure 17 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of chemical tankers. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

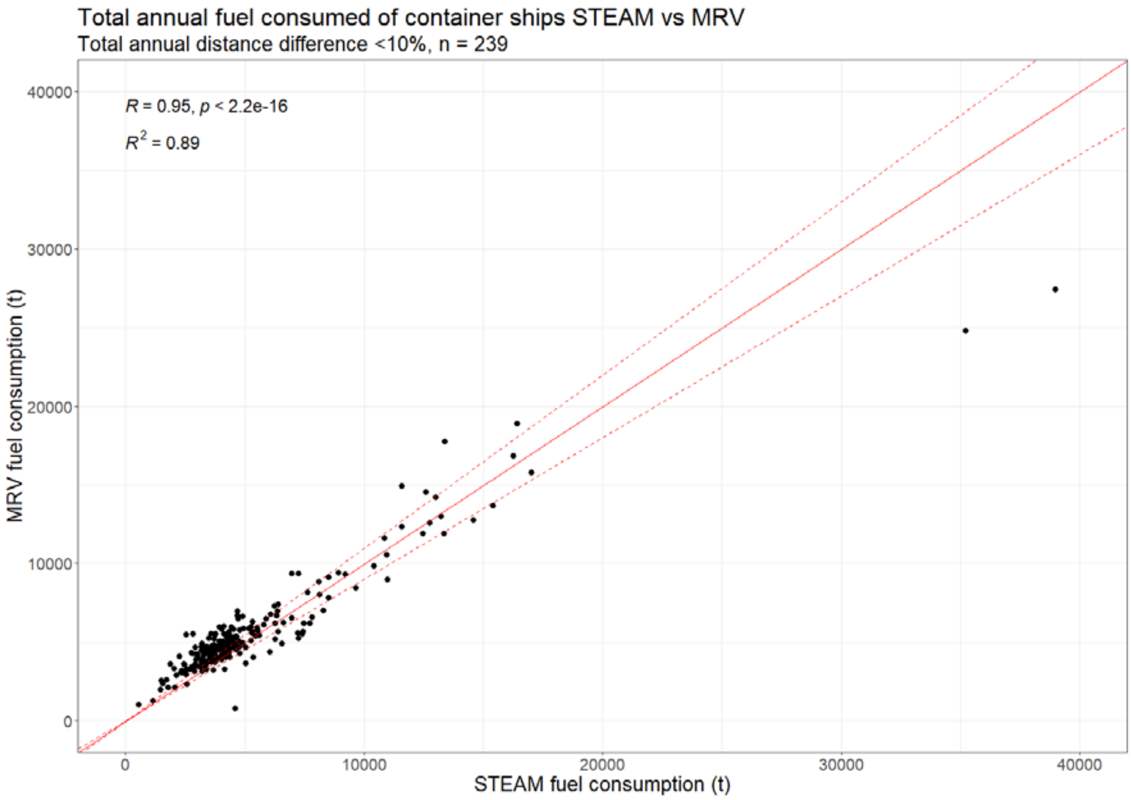


Figure 18 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of container vessels. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

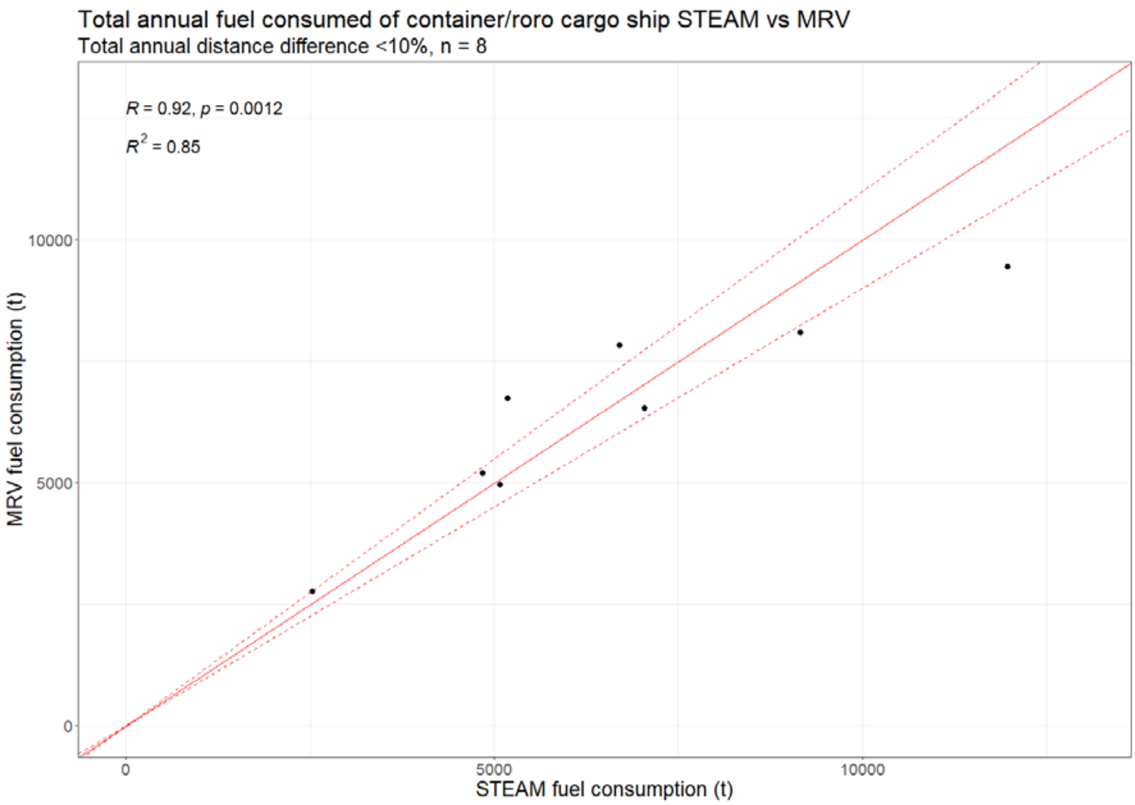


Figure 19 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of container/roro cargo ships. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

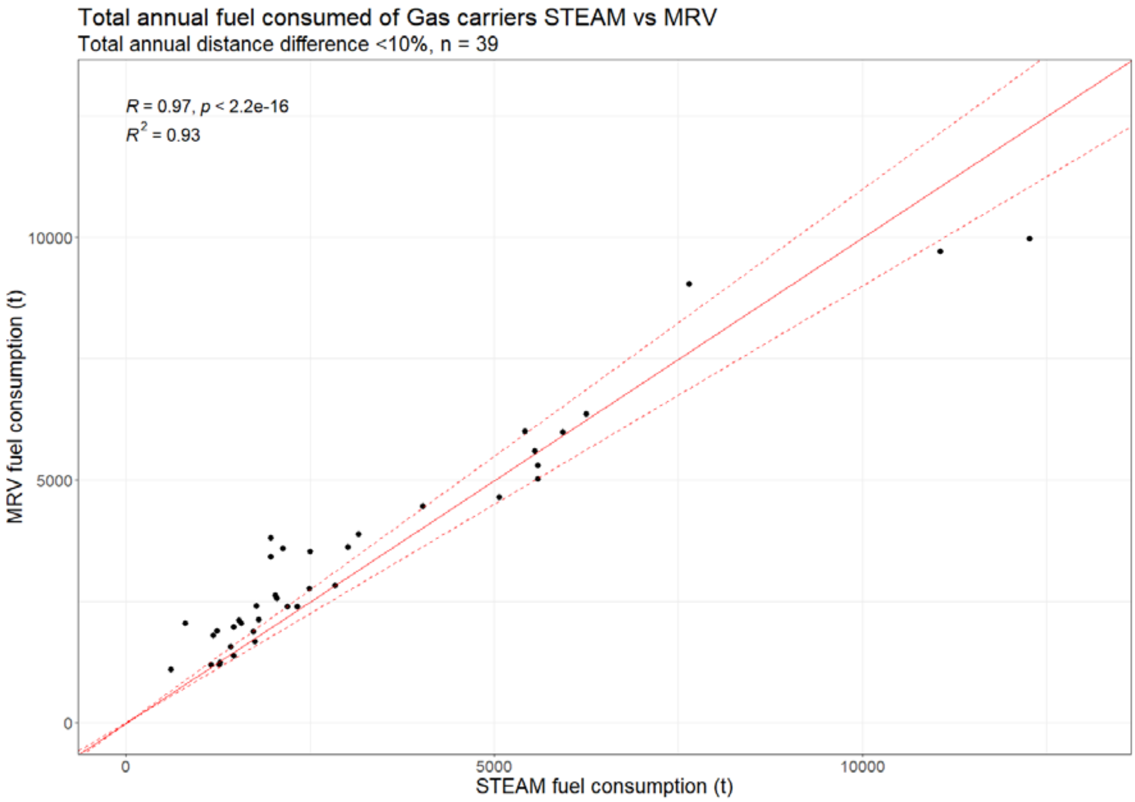


Figure 20 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of gas carriers. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

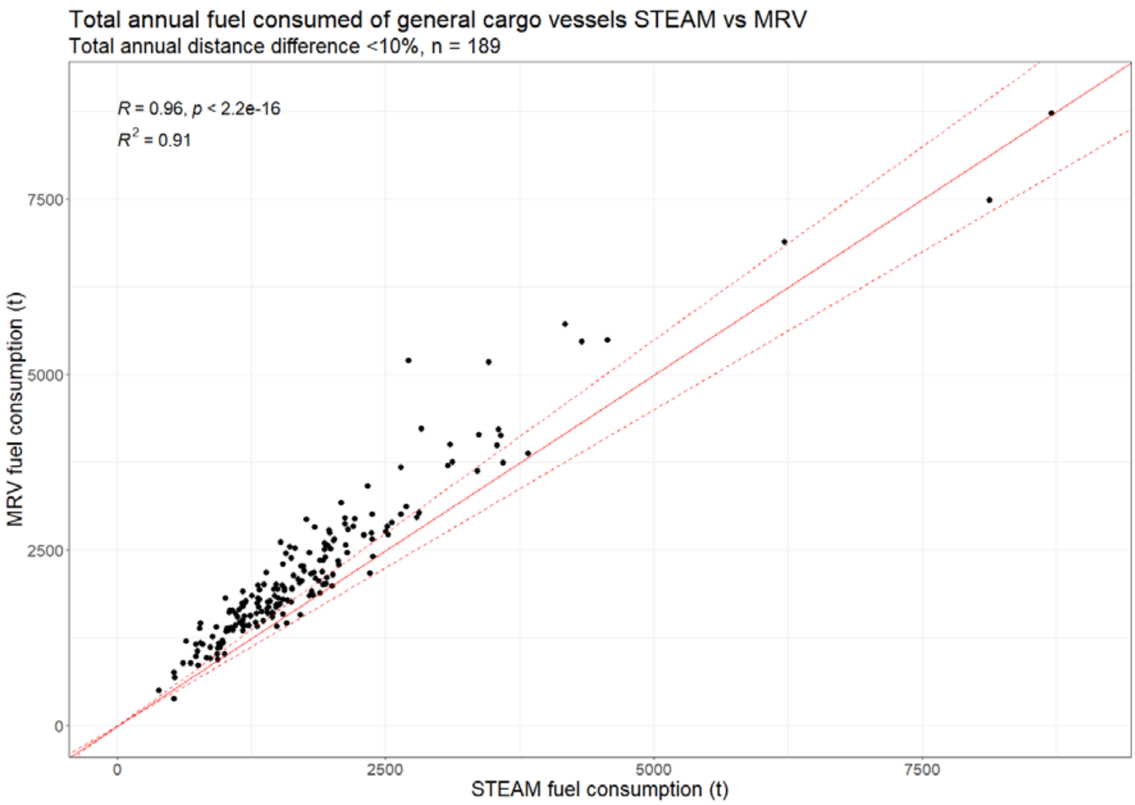


Figure 21 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of general cargo vessels. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

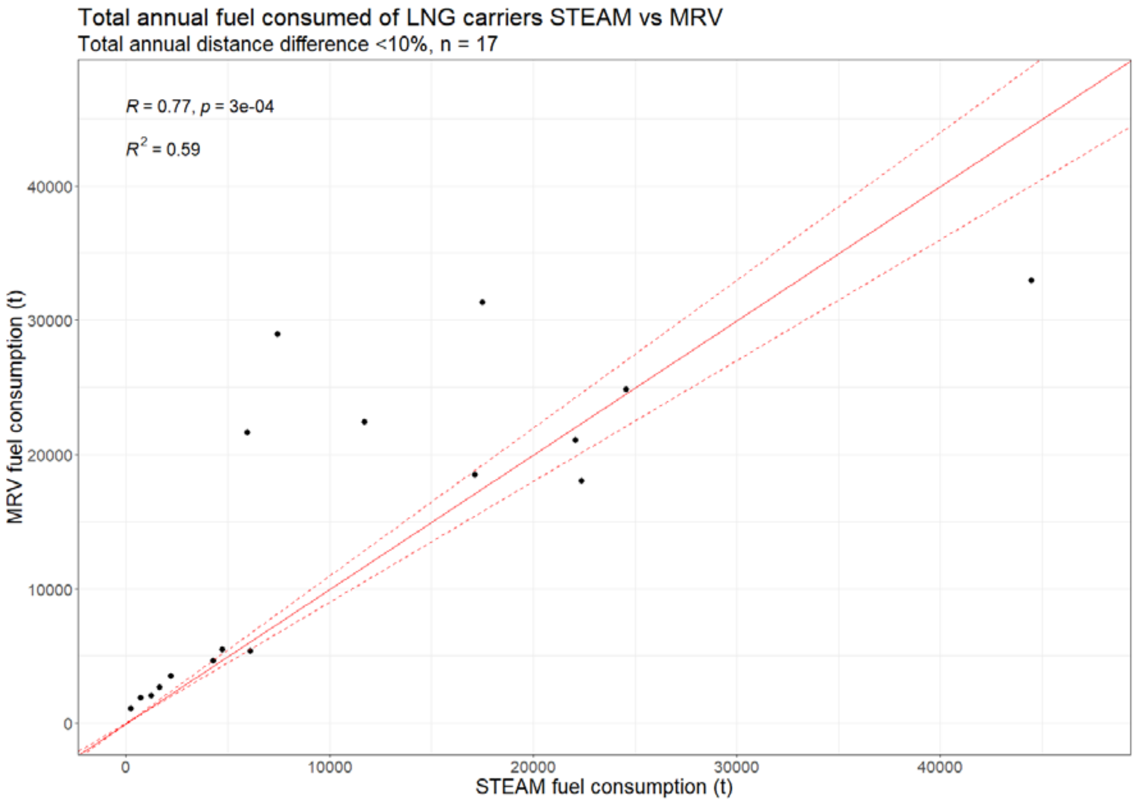


Figure 22 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of LNG carriers. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

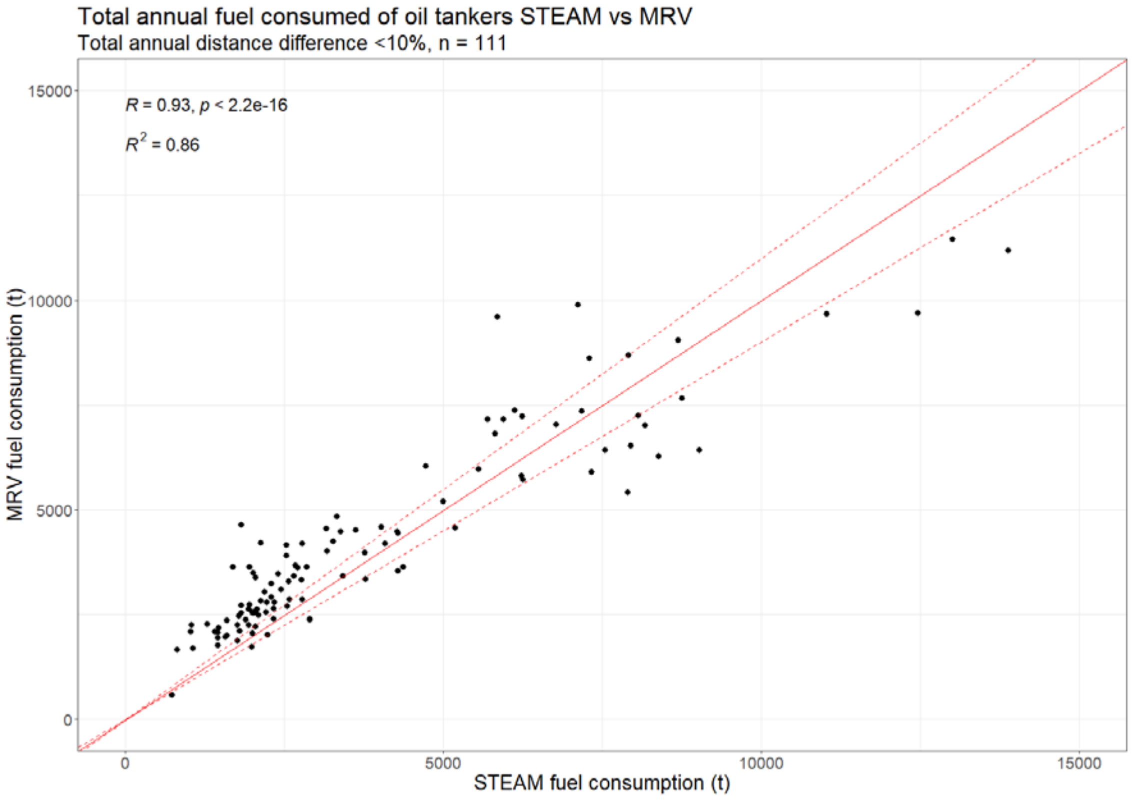


Figure 23 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of oil tankers. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

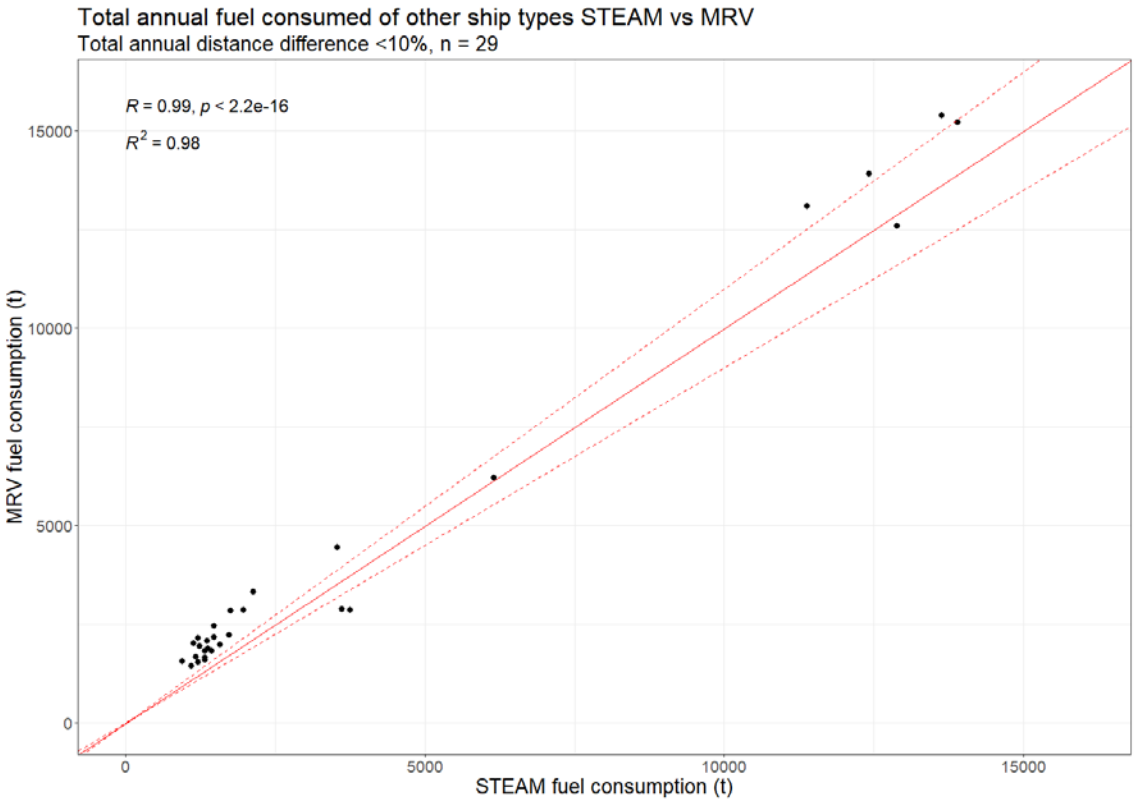


Figure 24 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of other vessel types. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

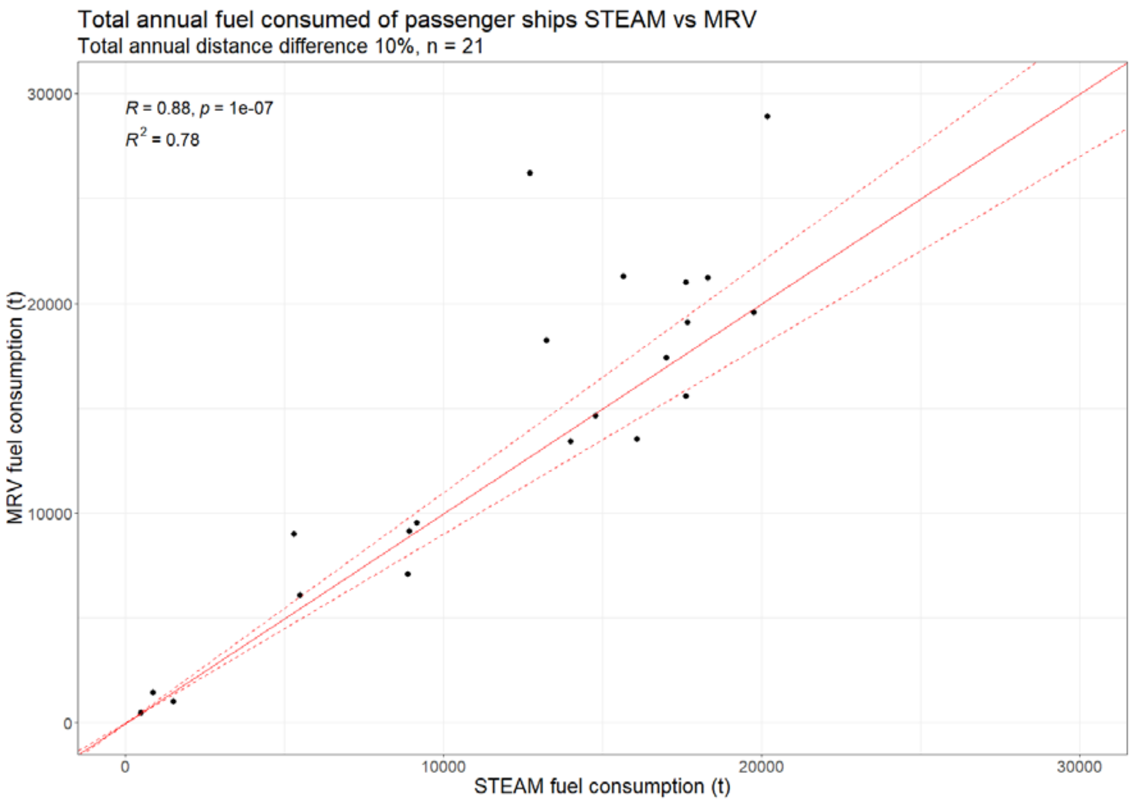


Figure 25 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of passenger ships. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

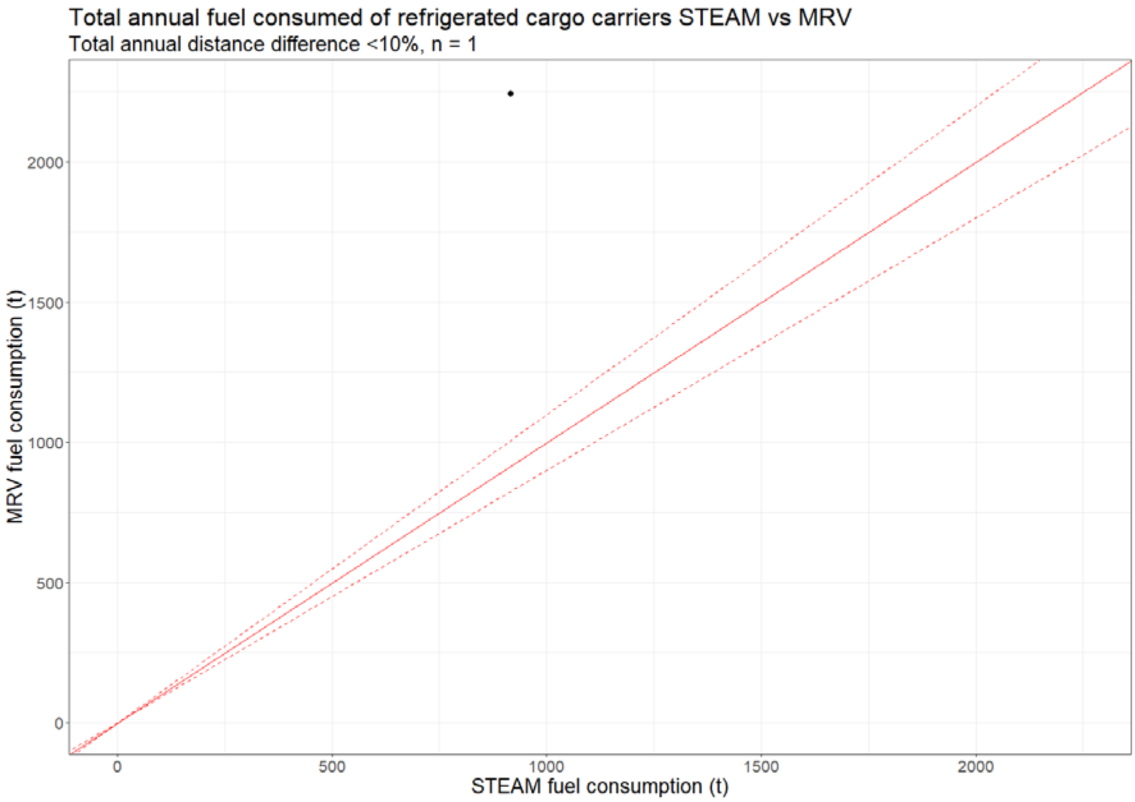


Figure 26 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of refrigerated cargo carriers. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation.

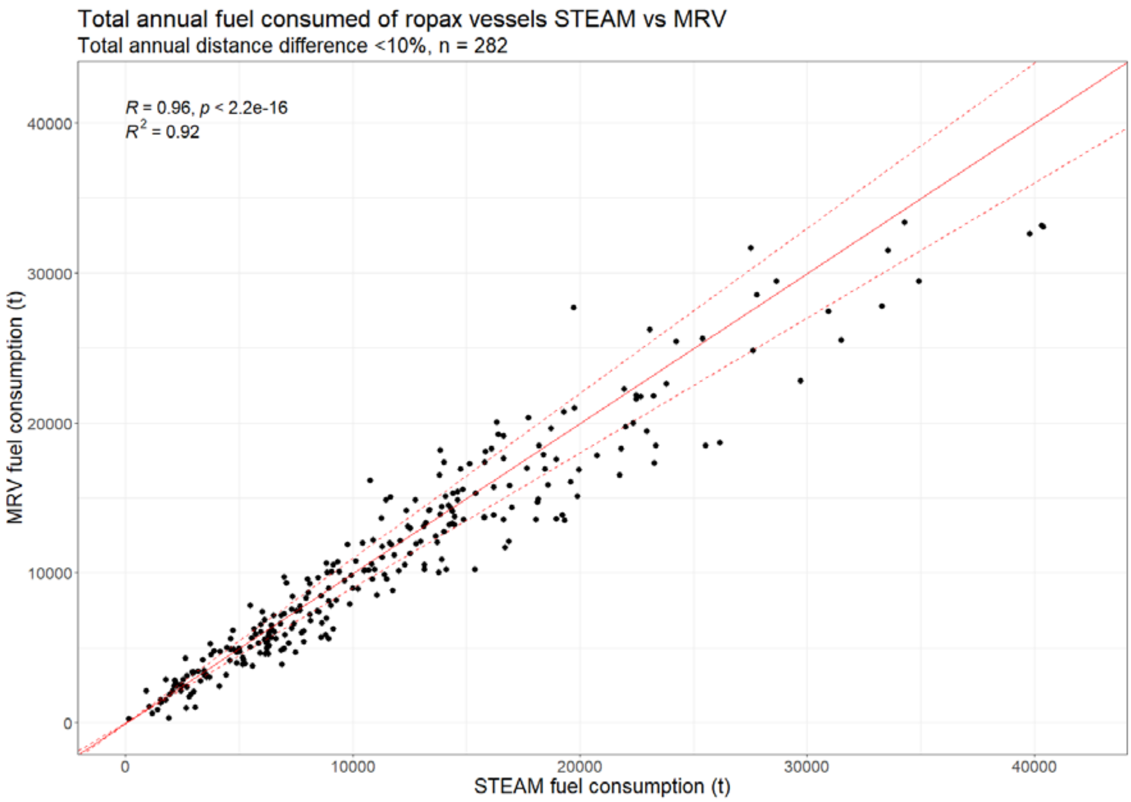


Figure 27 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of ropax vessels. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

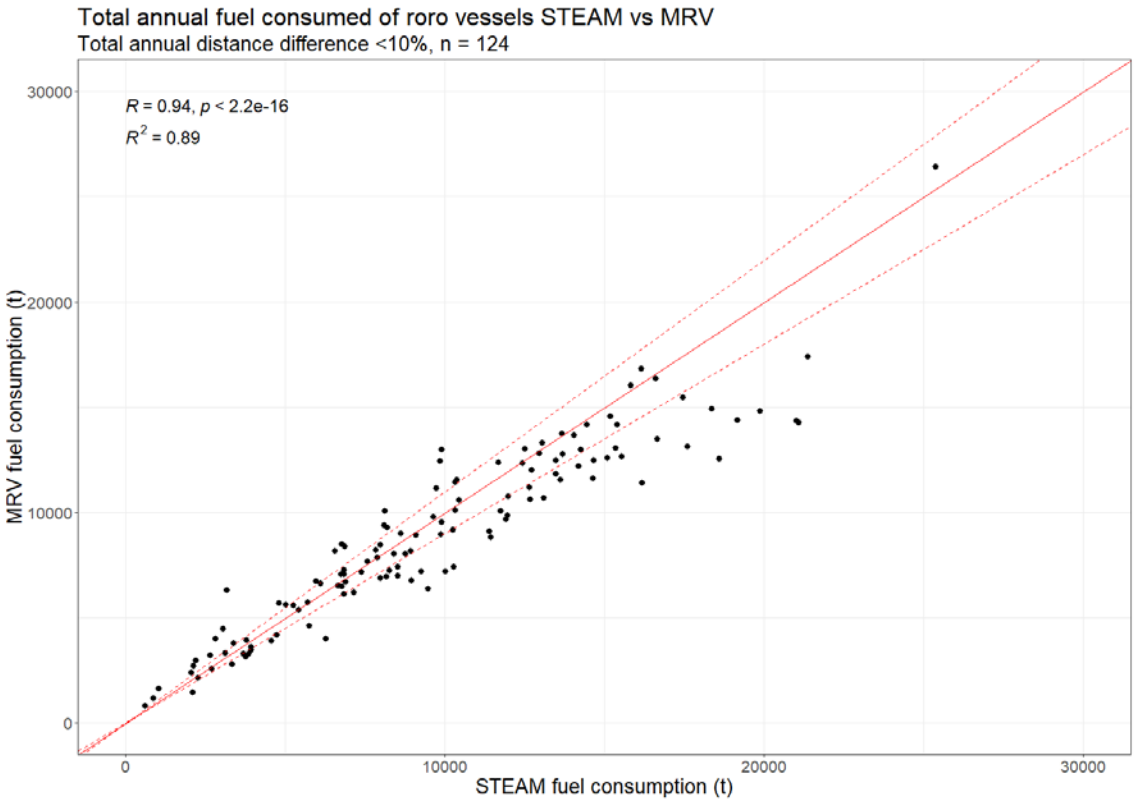


Figure 28 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of roro vessels. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

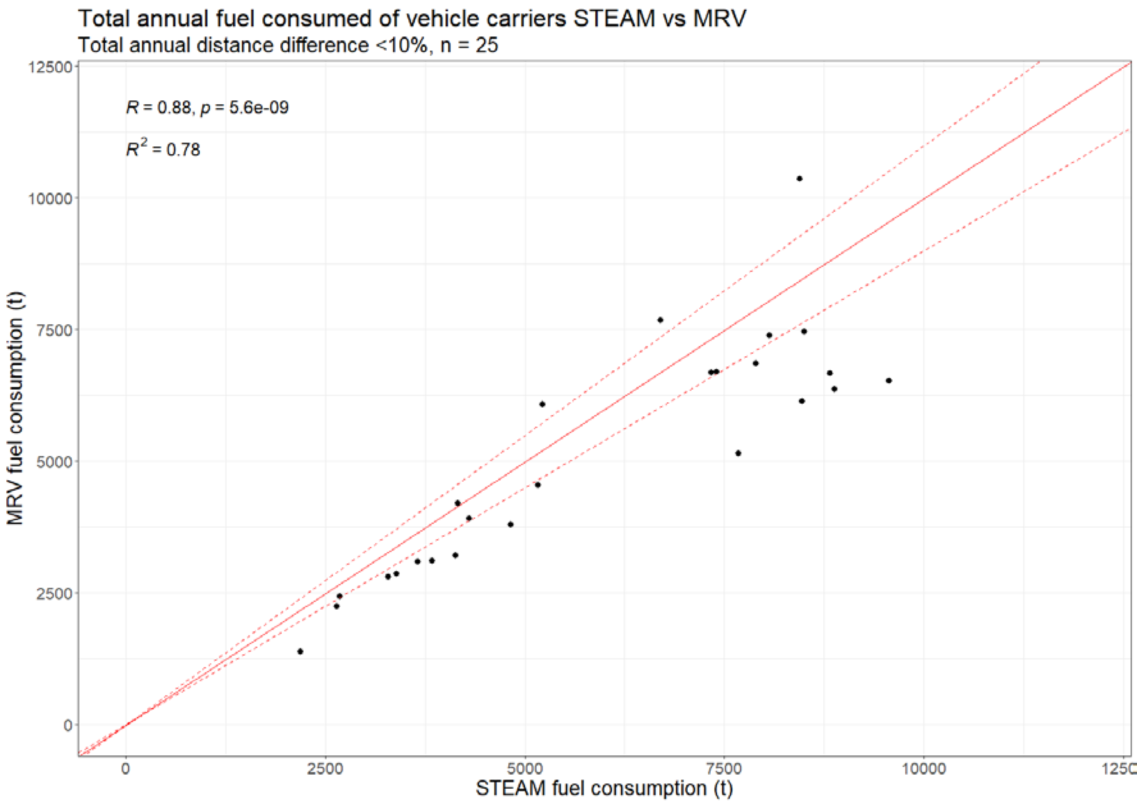


Figure 29 Scatterplot of total annual fuel consumed between STEAM (x-axis) and MRV (y-axis) of vehicle carriers. The solid red line indicates 100% correlation between STEAM and MRV and the dashed lines a 10% deviation from perfect correlation. Correlation (R) and goodness of fit of linear regression (R^2) in the top left corner.

4. Summary

The comparisons reveal that a good match can be obtained when fleet fuel consumption and CO_2 emissions are compared. The Ship Traffic Emission Assessment Model (STEAM) used in this work provides fleet total fuel consumption which is within -1.9% of the MRV reports, which is an improvement over the accuracy of 2021 comparison probably because for 2022 all relevant ambient datasets were available for global calculations.

During the berthing period, ships normally require auxiliary power for onboard systems. If there are inaccuracies in auxiliary power prediction, the impact of these inaccuracies will be emphasized with increasing berthing time. However, there are also other contributions to inaccuracies, like the simplistic description of resistance caused by biofouling and exclusion of squat in the modelling.

The average absolute deviation of a single vessel of the studied fleet is about 13%. Both positive and negative uncertainties exist. Discrepancies are usually connected to incomplete technical description of vessels, mistakes in auxiliary engine power prediction, data gaps concerning the position updates from Automatic Identification System (AIS) and weather contributions.

In several cases, outliers exist both on the STEAM predictions and MRV fuel reports. Resolving potential errors in MRV data should be communicated further to the European Maritime Safety Agency, but that is beyond the scope of this work.

Data

The emission estimates for the year 2022 are based on over 882 million AIS-messages sent by 37,144 different ships, of which 9,240 had an IMO registry number indicating commercial marine traffic. The AIS position reports were received by terrestrial base stations in the Baltic Sea countries and collected to regional HELCOM AIS data server. Emissions are generated using the Ship Traffic Emission Assessment Model, version 4.3.1 (STEAM; (Jalkanen et al., 2009, 2012, 2018, 2021; Johansson et al., 2013, 2017).

The AIS data for year 2022 had no temporal gaps, AIS data was available throughout the year and the temporal coverage was 100%. This is the first time for HELCOM AIS service with a perfect service record. Most of the messages originate from South-Western region of the Baltic Sea near the Danish and southern Swedish sea areas (Figure 29). For the most part of the year 2022, data flow was around 100,000 messages per hour.

The uncertainty evaluation and comparison to EU MRV fuel reporting was made using global AIS data for 2022 from Orbcomm Ltd. This global dataset includes both terrestrial and satellite AIS position reports and includes over 8.4 billion (10^9) position reports. STEAM also uses the technical details of the global fleet based on IHS Markit database.

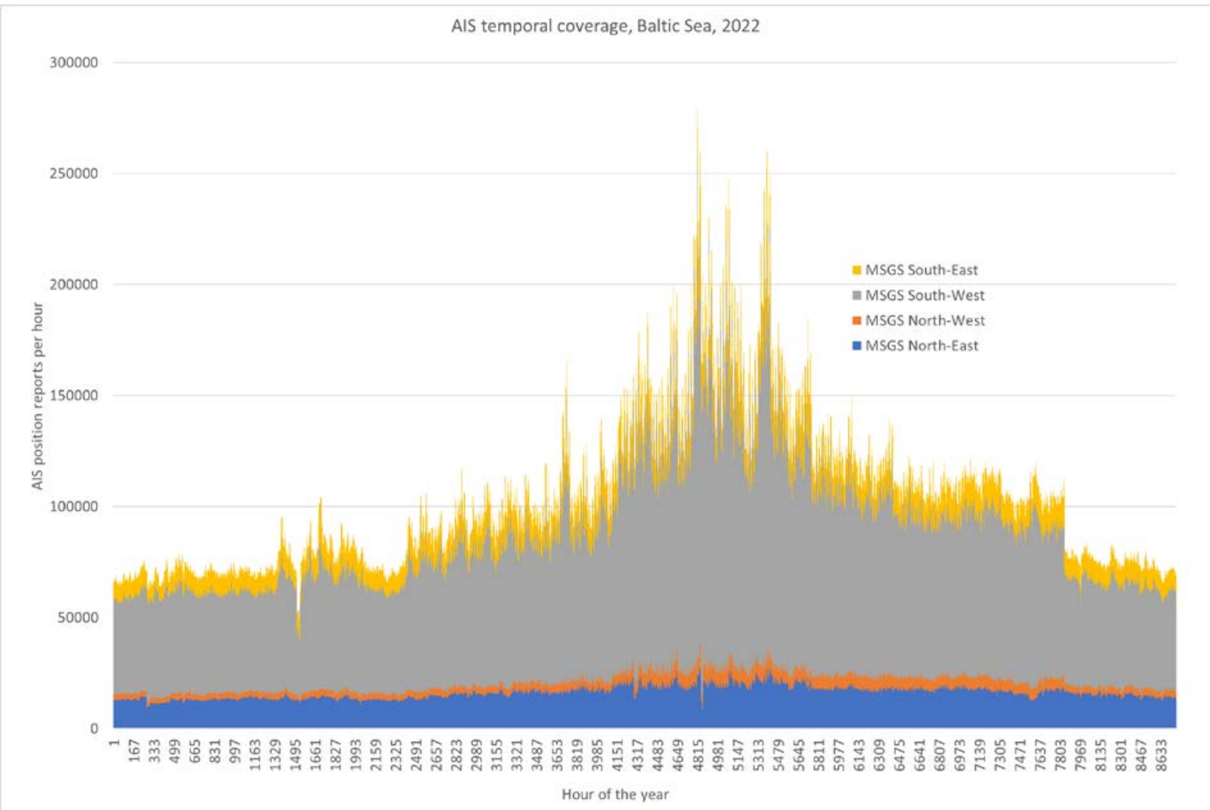


Figure 30 AIS-data hourly coverage in different parts of the Baltic Sea region for 2022.

Metadata

The STEAM model was updated to version 4.3.1 for this work, some of which are listed below:

a) Added the NH_3 and N_2O pollutant species. This enabled modeling of ammonia slip from SCR units. It also enables modeling of ammonia/diesel mixtures as ship fuel.
b) Added variables “Fuel in ice” and “Travel in ice” variables to all statistics. This enables tracking of winter navigation effects throughout the global fleet at ship level.

It should be noted that current estimates do not include contributions from vessels without active AIS equipment.

All calculations were made including the effects of sea currents, winds, waves and ice cover thickness. Impact of biofouling to vessel resistance was modeled with a simplified scaling approach, and impact of squat was neglected entirely.

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