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# EU-MRV: an analysis of 2018's Ro-Pax $CO_2$ data

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*Abstract*—**This paper analyses the EU-MRV dataset containing $CO_2$ emission data from vessels calling at European harbours. The data is provided in an aggregated form for 2018 and we decided to focus on ferries. We augmented the original dataset with data from the Copernicus Marine Environment Monitoring Service, the IMO Global Integrated Shipping Information System, and an open repository of ferry data. An analysis of various energy efficiency indicators revealed some clustering in the vessel population and the key factors were year of build, vessel length, service speed, and fuel type. Georeferencing data provided additional information on the continental patterns of the Ro-Pax emissions.**

*Index Terms*—**Global warming, Environmental monitoring, Marine transportation.**

## I. Introduction

For decades the Intergovernamental Panel on Climate Change[1] has been warning about the current and future impacts of climate change, at a global, regional, and local scale, including air and marine heat waves, alterations in rain patterns and the availability of fresh water, ocean acidification and sea level rise, habitat and biodiversity loss, and a decrease of both ocean and crop productivity[2]. The ultimate driver of such rapid, unprecedented changes is the concentration of greenhouse gases (GHG) in the atmosphere, emitted through the combustion of fossil fuels, such as coal, oil, and natural gas. Carbon dioxide ($CO_2$) is the GHG responsible for most of the warming observed since the beginnings of the industrial age [1].

The European Union (EU) has set ambitious targets to curb $CO_2$ emissions and thus limit global warming and its detrimental consequences. In 2015 the European Parliament (EP) and the Council approved regulation number 757 on Monitoring, Reporting, and Verification of $CO_2$ emissions from vessels calling at harbours not only from EU Member States (MS) but within the European Economic Area (EEA) [2], [3]. The regulation regards vessels exceeding 5,000 gross tonnes, prescribes consistent and comparable $CO_2$ monitoring methods, and defines procedures for $CO_2$ reporting and the verification of reports. Since 2018, annually-aggregated emissions reports have been mandatory for each category of vessels, and these have been provided through a dedicated system supported by the European Maritime Safety Agency (EMSA): THETIS-MRV. These data were first published as scheduled on June 30, 2019.

Two other systems have come into existence since the EU-MRV has been in place: the Data Collection System (DCS) by the International Maritime Organization (IMO) [4] and the Chinese Regulation on Data Collection for Energy Consumption of Ships[3]. They differ in terms of the parameters monitored, type of reporting, and verification protocols. A legislative process is currently ongoing at the EP in order to align EU-MRV with IMO-DCS.

The THETIS-MRV dataset includes nearly 12,000 vessels, of various types including: container ships, tankers, chemical tankers, oil tankers, bulk carriers, and vehicle carriers. Ro-Pax ships, also known as "Ro-Ro passenger" vessels or simply "ferries", are also part of the EU-MRV fleet. According to Interferry, ferries globally transport over two billion passengers every year[4]. In addition, they are generally considered a cost-efficient means of displacing heavy-duty vehicles in coastal areas. Furthermore, in THETIS-MRV, ferries represent 3% of all vessels while accounting for 10% of all $CO_2$ emissions[5]. The latter observation raises the question of carbon intensity of vessels of this class: Can it be related to the navigational domain? Or perhaps to the characteristics of the vessels? If so, which characteristics and how? All this motivates a closer look at the Ro-Pax data available in the first EU-MRV report with reference to emissions from 2018. These data will represent the baseline of all future reports.

Our methodology is presented in Sect. II. The results are provided in Sect. III, and discussed in Sect. IV.

## II. Methods

Although data fusion presents various challenges related to data quality and consistency, as the data may have originally been collected for different purposes [5], it can greatly increase the value of information. For example, in [6] data fusion of kinematical (automatic identification system, AIS) and environmental data (sea state from model analyses) means that vessel speed loss in waves can be estimated without needing specific information about the vessels.

In order to enhance the information contents of the THETIS-MRV dataset we fused it with several other datasets (Sect. II-A) before analyzing it (Sect. II-B).

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[1]https://www.ipcc.ch/

[2]https://www.ipcc.ch/working-group/wg2/

[3]http://bit.ly/ChinaDC-LR

[4]https://interferry.com/ferry-industry-facts/

[5]In version #160, the total emissions are 141,088,729.6 t $CO_2$.

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## A. Datasets

The datasets used in this work are all open-access:

**THETIS-MRV**: this corresponds to version #160 (downloaded from EMSA[6] on February 28, 2020). Of all the vessels in the dataset, just the "Ro-pax ships" were extracted, resulting in 356 database entries. Each entry includes 61 fields, some of which are lacking some values. The first field is the IMO identification number of the vessel, which was used as primary key when fusing THETIS-MRV with the other datasets described below.

**CMEMS** The Copernicus Marine Environment Monitoring System[7] provides sea state analysis fields from numerical models run operationally for the various seas in Europe. Related domains and spatial resolutions are specified in Tab. I. Hourly-instantaneous significant wave height fields ($H_s$) for year 2018 were downloaded (a volume of about 0.1 TB) and aggregated on an annual basis. Tab. I also reports the counts of the Ro-Pax vessels based on their average location (see method explained in Sect. II-B1). Wherever a vessel's location belongs to a region with overlapping model outputs (cf. Fig. 1), it is attributed to the one with the highest resolution (i.e., smallest grid size).

**GISIS** is the Global Integrated Shipping Information System[8] which has been developed by the IMO and includes details on the ship and shipping company. From the public version of GISIS, we only extracted the year when the ship was built from the "date of build" parameter for each of the 356 THETIS-MRV Ro-Pax vessels.

**Ferry-site**[9] is an open repository with an emphasis on north European ferries. Whenever multiple values are provided for the parameters - length overall (LOA), service speed $v_{\mathrm{serv}}$, and number of passengers $n_P$ - we took their highest value; and lowest value for number of beds $n_B$ and cars $n_C$. LOA and $v_{\mathrm{serv}}$ were validated against the MS version in the GISIS database. Ferry-site also includes information about the route, from which the ports of call were parsed and georeferenced. Of the 356 THETIS-MRV Ro-Pax ferries, 342 were found also on Ferry-site.

## B. Analysis

The dataset resulting from fusing all the data presented in Sect. II-A is called hereafter the "augmented dataset". The data was processed in three steps, as reported below.

*1) Georeferencing:* For a preliminary classification of THETIS-MRV data with respect to the typical domain of operation, we associated a single geographical location with each Ro-Pax vessel. The rationale for this coarse assignment was to relate it to the temporal coarse (annual average) emission information available. Finer spatial analysis would entail having finer temporal emission data, but such data are not publicly available.

[6]https://mrv.emsa.europa.eu/#public/emission-report

[7]http://marine.copernicus.eu/

[8]https://gisis.imo.org/

[9]http://www.ferry-site.dk/

TABLE I
RO-PAX VESSELS IN EUROPEAN SEAS WITH THE GRID SIZE OF SEA STATE MODEL OUTPUTS (1 NMI = 1852 M)

| Domain | short name | Resolution [nmi] | # vessels |
|---|---|---|---|
| North West Shelf | NWS | 0.8 | 89 |
| Baltic Sea | Bal | 1.0 | 76 |
| Arctic Sea | Arc | 1.6 | 0 |
| Black Sea | BS | 1.7 | 2 |
| Mediterranean Sea | Med | 2.5 | 164 |
| Iberian-Biscay-Irish Seas | IBI | 3.0 | 11 |
| subtotal | | | 342 |
| outliers | $f_4$ of Sect. II-B2 (THETIS-MRV) | | 14 |
| total | | | 356 |

The representative location was computed as follows: the ferry ports of call were retrieved from Ferry-site, they were then georeferenced[10], and for each vessel the average position of all combinations of legs among those ports was computed.

Although our procedure is quite simple, it is appropriate for Ro-Pax vessels since their routes (unlike for example cruise ship routes) are for reasonably short distances and tend to be straight, though obviously depending on topological constraints and meteo-marine conditions. However, our procedure poses an issue for longer-range routes and for convex coastlines. Moreover, if a vessel operates between spatially-distinct clusters of ports of call, with only occasional transfer voyages between clusters, the representativeness of a mean annual location computed this way is questionable.

*2) Filtering:* The augmented dataset was filtered to prune entries (i.e., vessels) that included inconsistencies, that is:

- $f_1$) zero total $CO_2$ emissions - these entries do not add any information to the current analysis;
- $f_2$) emissions from MS ports greater than total emissions - this is an inconsistency in the data, as total emissions include by definition those among MS;
- $f_3$) off range carbon emission factor $C_F > 4$ - this cannot be true for most common fuel types, Tab. IV;
- $f_4$) no ports of call available or mean annual vessel location out of the EEA - this is not accepted as data in THETIS-MRV all refer to Ro-Pax ships calling at EEA ports.
- $f_5$) just a single port of call retrieved or average leg distance greater than 450 nmi (corresponding to 15 h navigation at a speed of 30 kts) - this implies no reliable identification of the place of operation.

Criteria $f_1$)-$f_4$) include 4.2% of the emissions from the Ro-Pax population and are applied throughout. Instead, $f_5$) is applied for specific purposes only. The number of vessels and emissions ascribed to each criterium is reported in Tab. II. Finally, there were some gaps in the THETIS-MRV dataset:

- $g_1$) no monitoring method reported - this is a mandatory field for EU-MRV and ships not reporting it are not compliant with the regulation;

[10]via https://getlatlong.net/

$g_2$) non null $CO_2$ emissions reported, but no total fuel consumption value - both data are needed in order to infer the fuel type (see Sect. II-B3).

TABLE II
OUTLIERS ACCORDING TO THE CRITERIA OF SECT. II-B2

| criterium | # vessels | $CO_2$ emissions [ton] | % |
|---|---|---|---|
| $f_1$ | 1 | 0.00 | 0.0 |
| $f_2$ | 3 | 60,242.61 | 0.4 |
| $f_3$ | 1 | 75,880.91 | 0.5 |
| $f_4$ | 14 | 448,148.27 | 3.0 |
| $f_5$ | 78 | 2,610,077.09 | 18.6 |
| $g_1$ | 31 | 1,258,810.47 | 9.0 |
| $g_2$ | 7 | 293,298.06 | 2.1 |

*3) Derived quantities:* Fuel type was inferred from the fuel emission factor $C_F$. The latter was obtained from THETIS-MRV data as the ratio of total $CO_2$ emissions to total fuel consumption. The closest value among the emission factors[11] reported in Tab. IV was used for assigning the fuel type.

An effective velocity $v_{\text{eff}}$ can be computed by taking the ratio of the total $CO_2$ emissions ($C$) not at berth ($C_b$) to the total time spent at sea $T_s$ and dividing by the $CO_2$ emissions per distance $dC/dx$:

$$v_{\text{eff}} = \frac{(C - C_b)}{T_s} \Big/ \frac{dC}{dx} \tag{1}$$

In the EU-MRV revision proposal[12], "hours underway" replaces "time at sea", as in the IMO-DCS. In fact, "hours underway" provides a more accurate estimation of $v_{\text{eff}}$.

Ship energy efficiency is a crucial indicator for any regulatory framework, as absolute emissions should be compared to distance sailed, capacity, transport work, or some other normalization parameter. A brief account of the use of various indicators in the ongoing debate on the assessment of energy efficiency is provided in [7]. IMO adopted the Energy Efficiency Design Index (EEDI) for new ships in 2011 [8]. EU-MRV mandates report several fields that can be used to assess energy efficiency. The emissions per distance sailed per passenger is a form of Energy Efficiency Operational Indicator, here called "EEOIpax". Finally, the Energy Efficiency per Service Hour (EESH) is given by the ratio of total emissions $C$ by total time at sea $T_s$.

## III. RESULTS

This section presents the results of applying the methodology outlined in Sect. II. As mentioned in Sect. II-B1, some of the mean annual locations are weakly identified, and this may occasionally (less than 8% of the ships) mean that they are near the coast but actually on land.

[11]http://bit.ly/verifaviaCF
[12]http://bit.ly/COM2019-38

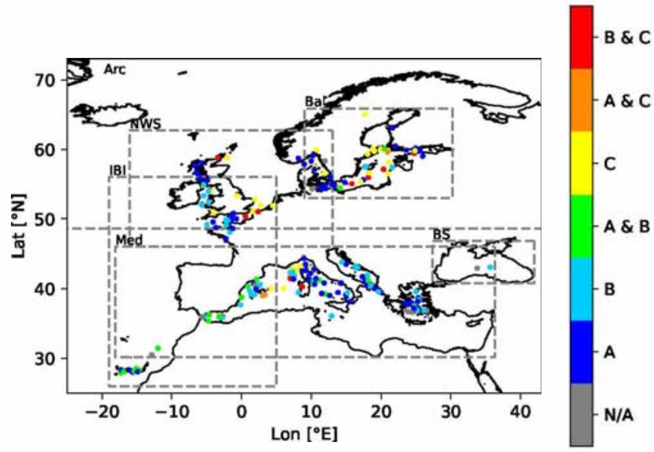


Fig. 1. $CO_2$ monitoring methods (cf. Tab. III). The dashed boxes correspond to the domains of Tab. I.

### A. $CO_2$ monitoring method

In accordance with the EU-MRV Regulation [2], for each vessel one of the four $CO_2$ monitoring methods in Tab. III must be selected. Method A corresponds to the top-down approach also used in the Third IMO GHG Study [9]. However, a few Ro-Pax vessels in the THETIS-MRV dataset do not have a value for the monitoring method (set $g_1$ of Sect. II-B2). Some vessels also reported more than one method. Fig. 1 highlights that method D (direct $CO_2$ measurement) was not used by any Ro-Pax ships in 2018. Method C was primarily used in the North West Shelf (NWS) and Baltic seas. However, there are some "Cs" in the northern Tyrrhenian Sea, two "B&Cs" in the Mediterranean, and several "As" in both the NWS and the Baltic. No ferries were identified in the vicinity of Iceland, though Iceland is part of the EEA.

### B. Speed

In Fig. 2 the effective speed $v_{\text{eff}}$ from Eq. 1 is compared to the service speed $v_{\text{serv}}$. While both are well correlated, on average $v_{\text{eff}}$ is about 5 kts lower than $v_{\text{serv}}$. This might not just correspond to a slow-steaming practice, but also to the overestimation of travel time in $v_{\text{eff}}$ due to use of $T_s$ in Eq. 1.

We introduce the Froude number $F_n = v_{\text{serv}}/\sqrt{g \cdot \text{LOA}}$ for relating speed to LOA[13], which exhibits a large spread in the ferry population (cf. Fig. 8). Furthermore, at least for

[13]$g = 9.8$ m/s$^2$ is the gravity acceleration.

TABLE III
EU-MRV $CO_2$ MONITORING METHODS

| name | description |
|---|---|
| D | Direct $CO_2$ emissions measurement |
| C | Flow meters for applicable combustion processes |
| B | Bunker fuel tank monitoring on-board |
| A | Bunker fuel delivery notes and periodic stocktakes of fuel tanks |

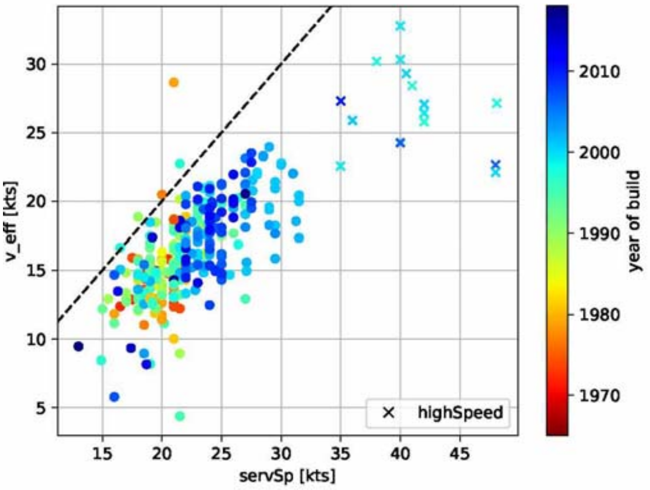


Fig. 2. Effective speed $v_{\mathrm{eff}}$ from Eq. 1 vs. service speed $v_{\mathrm{serv}}$, with marker colors relating to the year of build. High-speed Ro-Pax are shown as crosses; the 1:1 line is black and dashed.

mono-hulls, $F_n > 0.4$ corresponds to the transition to a semi-displacing regime [10]. Fig. 2 shows that such "high-speed" Ro-Pax vessels were all built around 2000 or later.

### C. Energy efficiency

The mean annual $CO_2$ emissions per distance sailed per passenger (EEOIpax) is georeferenced in Fig. 3. Some of the most efficient vessels with respect to this parameter operate in the British Isles, but also in the western Mediterranean and in the Adriatic sea.

EEOIpax is a quite sensitive indicator as, in the THETIS-MRV vessel population, it varies over five orders of magnitude. This spread likely reflects not just the various ferry sizes, but also propulsion features, age, and the various combinations of vehicles and passenger services (number of cabins, vehicles, entertainment facilities) in their payloads [11].

Fig. 4 shows how the EEOIpax relates to service speed, fuel type and the ratio of the number of beds to passengers (this ratio may exceed one, possibly because crew members are not included in the passenger count). There is some evidence that the logarithm of emission intensity increases with speed. The figure also suggests that there are at least three subpopulations (EEOIpax units are g $CO_2$/(pax·nmi) and $v_{\mathrm{serv}}$ kts):

*i)* $10^2 <$ EEOIpax $< 10^4$ and $v_{\mathrm{serv}} < 30$ : here most vessels with $n_B/n_P \approx 1$ are found;

*ii)* $10^3 <$ EEOIpax $< 10^4$ and $v_{\mathrm{serv}} > 35$ : these are the high speed ferries;

*iii)* EEOIpax $< 10^1$ and $v_{\mathrm{serv}} < 25$ : these vessels tend to have $n_B/n_P \approx 0.5$.

Fuel type can be any, apart from in cluster *ii)* which consists entirely of vessels using MDO as a bunker.

### D. Age

Year of build is shown in Fig. 5. There is no clear divide between northern and southern European sea vessels, with some of the oldest Ro-Pax in the northern Tyrrhenian and in the Adriatic sea, but also in the Baltic.

The upper histogram of Fig. 6 shows the distribution of the year of build. Given that the oldest ferries in service in 2018 were nearly 50 years old, the statistics indicate an expansive age pyramid, with a median age of about 20 years. Furthermore, the average vessel size (lower histogram in Fig. 6) shows that larger ferries are now being built.

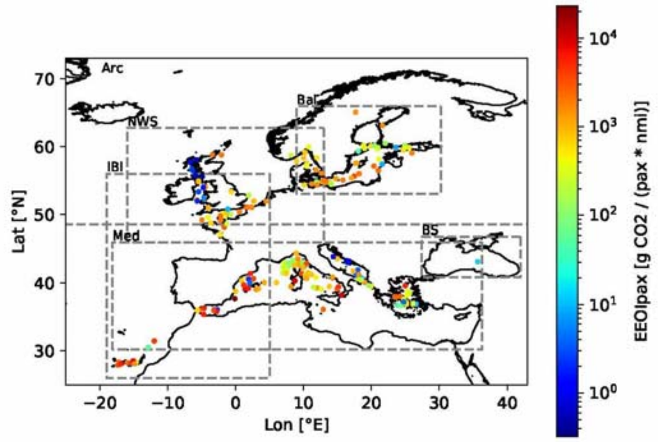


Fig. 3. $CO_2$ emissions per passenger per distance sailed (EEOIpax).

TABLE IV
EMISSION FACTORS ($CO_2$ BY FUEL MASS) USED IN THIS WORK

| | full name | $C_F$ (g/g) |
|---|---|---|
| MDO | Marine Diesel Oil | 3.206 |
| LFO | Light Fuel Oil | 3.151 |
| HFO | Heavy Fuel Oil | 3.114 |
| LNG | Liquefied Natural Gas | 2.750 |

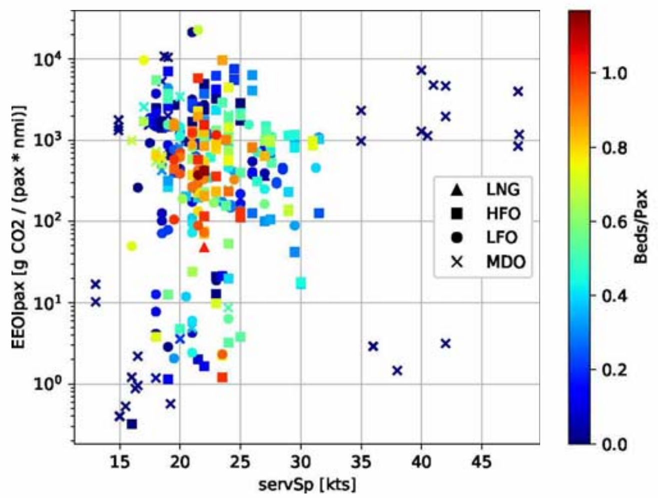


Fig. 4. EEOIpax vs. service speed with marker color given by number of beds per passenger and marker type given by fuel type (cf. Tab. IV).

The height of the bars in Fig. 6 represents the total emissions and mirrors the distribution of the number of vessels built per year. The average EEOIpax is used to colour this histogram. Given the great spread in values, a linear EEOIpax averaging would be dominated by the largest values. In order to mitigate this, the following averaging is applied:

$$\overline{\mathrm{EEOIpax}} = \exp\left(\overline{\log(\mathrm{EEOIpax})}\right) \tag{2}$$

Some of the highest emissions come from newer vessels (built in 2012).

### E. Sea state

The International Maritime Organization (IMO) recommends avoiding "rough seas and head currents". This is among the ten measures of the Ship Energy Efficiency Management Plan [12]. Therefore sea state (waves) can be relevant when considering carbon intensity [13]. Sea state can greatly change during a year, as the timescale of its variability depends on meteorological events. In wave spectra, wind waves can be differentiated from swell[14]. Fig. 7 reports the wind-wave component alone and shows an annual average $H_s \sim 1$ m in most domains, with higher values in western European seas, and lower values in the Adriatic and in the Aegean Sea.

The mean annual EESH (Fig. 8) shows a weak dependence on $H_s$ and this only for the smaller vessels (Pearson's R = 0.57 for LOA < 120 m). More time-resolved data (daily, at least) should highlight a clearer dependence of EEOI on sea state and even sea currents [13]. Fig. 8 shows that EESH increases with LOA, with larger vessels producing higher unit emissions per time. The emission intensity of high-speed ferries is comparable to that of much larger ferries.

### F. Fuel types

Fuel type can be inferred for most THETIS-MRV Ro-Pax vessels, but the $g_2$) set of Sect. II-B2. Fig. 9 shows

[14]http://bit.ly/ECMWFwaves

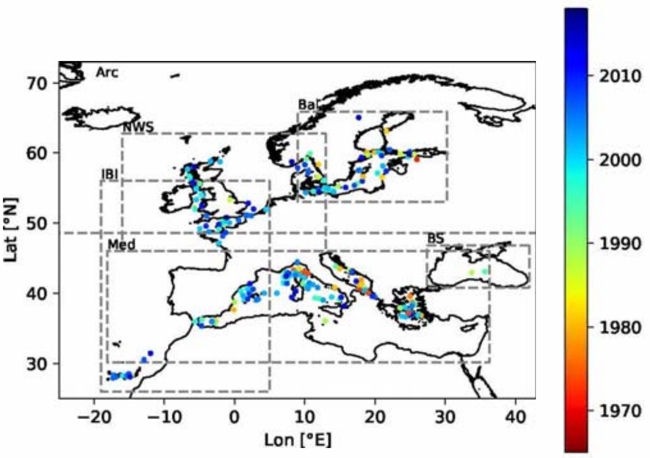


Fig. 5. Ro-Pax vessels' year of build.

$CO_2$

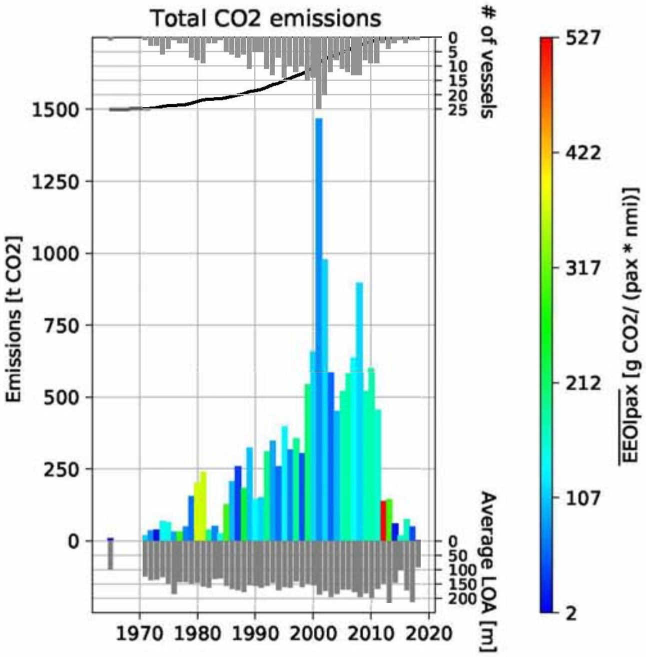


Fig. 6. Total emissions by year of build of the vessels, with bar color given by $\overline{\mathrm{EEOIpax}}$ from Eq. 2. The number and cumulative distribution of vessels built in each year are given in the upper histogram and the average LOA in the lower one (both as grey columns).

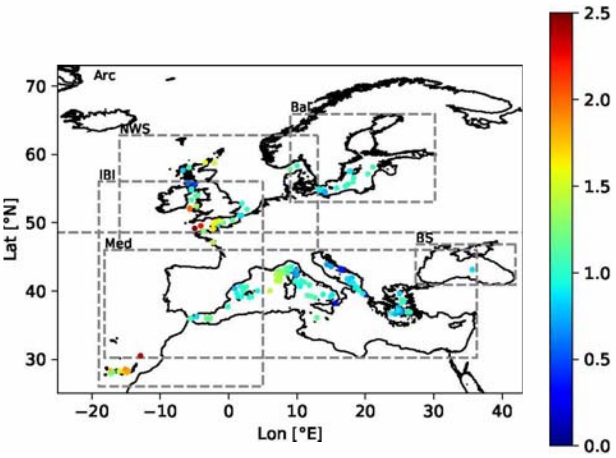


Fig. 7. 2018 mean annual significant wave height $H_s$ from the sea state model outputs of Tab. I interpolated at the representative vessel locations. $f_5$ criterium applied.

their distribution in the various European sea domains. HFO is dominant in both the Mediterranean and the NWS. LFO dominates in the Baltic. LNG is used for NWS and Baltic ferries only. MDO is relevant in the NWS and in the Baltic and, to a lesser extent, in the Mediterranean too. Fig. 9 also highlights that the Mediterranean alone accounts for nearly as many Ro-Pax emissions (6.9 Mton $CO_2$) as all other European seas combined (7.1 Mton $CO_2$).

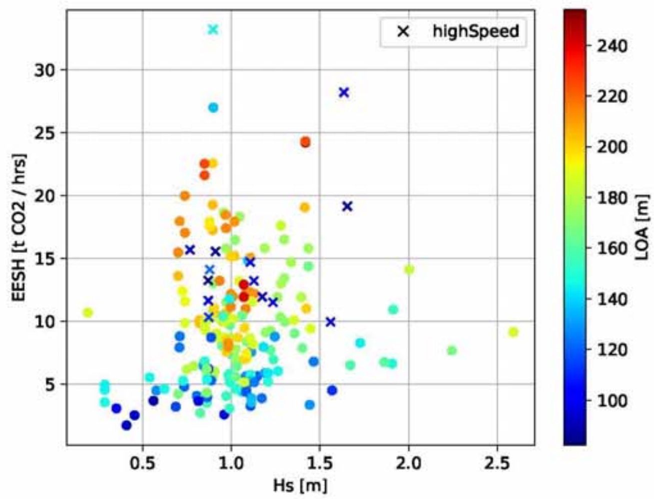


Fig. 8. Energy efficiency per service hour (EESH) vs. mean annual $H_s$, with marker color given by vessel LOA. Crosses represent high-speed ferries.

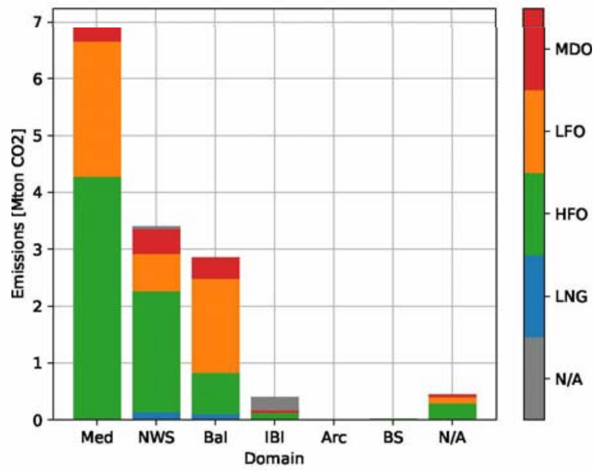


Fig. 9. Total Ro-Pax emissions in the various European sea basins; the fractions due to the various fuel types are highlighted. The total emissions in 2018 were 14.0 Mton $CO_2$. Colorbar's N/A is due to the $g_2$ set, the N/A column to the $f_4$ set.

## IV. Conclusions

This paper reports the first ever publication of ship-distinctive $CO_2$ annual emission data (EU-MRV) from Ro-Pax vessels in the EEA.

Some noisy geographic patterns were found and can be summarized as: multiple $CO_2$ monitoring methods used in northern European seas, newer vessels in western European seas, weak dependence on mean annual sea state, and half of the EEA emissions stemming from the Mediterranean Sea. The latter fact is in line with findings from a bottom-up inventory [14].

Although our georeferencing procedure provides a rough attribution of emissions to specific sea basins and a visualization of continental patterns, it could be improved by integrating more detailed tracking data, such as the ports of calls of each voyage or the full AIS data.

On the other hand, the non-spatial information shows that the energy efficiency is quite diverse within the Ro-Pax population, reflecting service speed, fuel type, size, and, possibly, type of payload. High-speed ferries stand out when it comes to the relationship between energy efficiency and speed or size.

Dataset augmentation was key for both the spatial and non-spatial part of this analysis. Due to the annual temporal aggregation, it was not possible to clearly assess if sea state affects the energy efficiency. Also, a more refined clustering may help refine the dependence of the energy efficiency on the other vessel parameters considered here. This would enable comparisons among similar vessels, assessing their potential for decarbonization, and facilitate a credibility test of the reported data. As mentioned in the preamble of [2] this would simplify the EU-MRV verification process.

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