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Assessment of ship emissions in coastal waters using spatial projections of ship tracks, ship voyage and engine specification data

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A R T I C L E I N F O

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A B S T R A C T

To understand, mitigate and reduce the detrimental effects on human health and the environment from exhaust gas emissions from ships it is necessary to be able to estimate the quantity and location of these ship emissions in time.

Currently, the two most commonly used ship emission assessment methods sit on opposite ends of the spectrum – the *top-down* approach, which provides low resolution yet efficient aggregated results however is unable to account for specific shipping activities, and the *bottom-up* vessel-by-vessel approach, which provides near-instantaneous ship emissions production at a high resolution – yet is data and time intensive.

To address the market gap for a ship greenhouse emission estimation method that hybridises the best of both the *bottom-up* and *top-down* methods the novel Ship Emissions Assessment (SEA) method is proposed as an innovative hybrid solution.

It is a cost effective and resource efficient method, presenting spatial ship emissions utilising widely accessible data, and it is precise – fulfilling the requirements needed to evaluate ship emissions reduction measures.

Novel SEA method is the first in its endeavour to replace Automatic Identification System (AIS) Vessel-based raw data allocation, by using rapid analyses of readily available ship track density data and average voyage information. It combines obtained average voyage distance with voyage average speed to estimate ship activity for emission assessments - saving costs by reducing time and reliance on complex computations, especially when many ships need to be analysed simultaneously.

Using the novel SEA method, a series of containerships from geographically diverse ports were sampled and assessed for emissions with comparative results confirming the representations equivalent to the detailed and data demanding *bottom-up* method.

Subsequently, the novel SEA method was applied to containership traffic calling into the Port of Trieste, in the northern Adriatic Sea, where it demonstrated the ability to estimate and quantify historic emissions for the preceding 12 months while taking into account seasonal port traffic variations.

The novel SEA method showed to be an efficient, inexpensive and accurate, easy-to-use emission assessment tool based on widely accessible data. It can be used in day-to-day shipping operations by a variety of stakeholders including port operations managers, regional traffic operators, and those non-industry, while providing the required level of technical accuracy. In comparison, existing methods are not as time and cost effective, user-friendly, nor based on easy to interpret and readily accessible data.

The novel SEA method enables further global research of ship emissions, and for regional and international policy makers to effectively manage the measures needed to reach greenhouse gas emission reduction targets.

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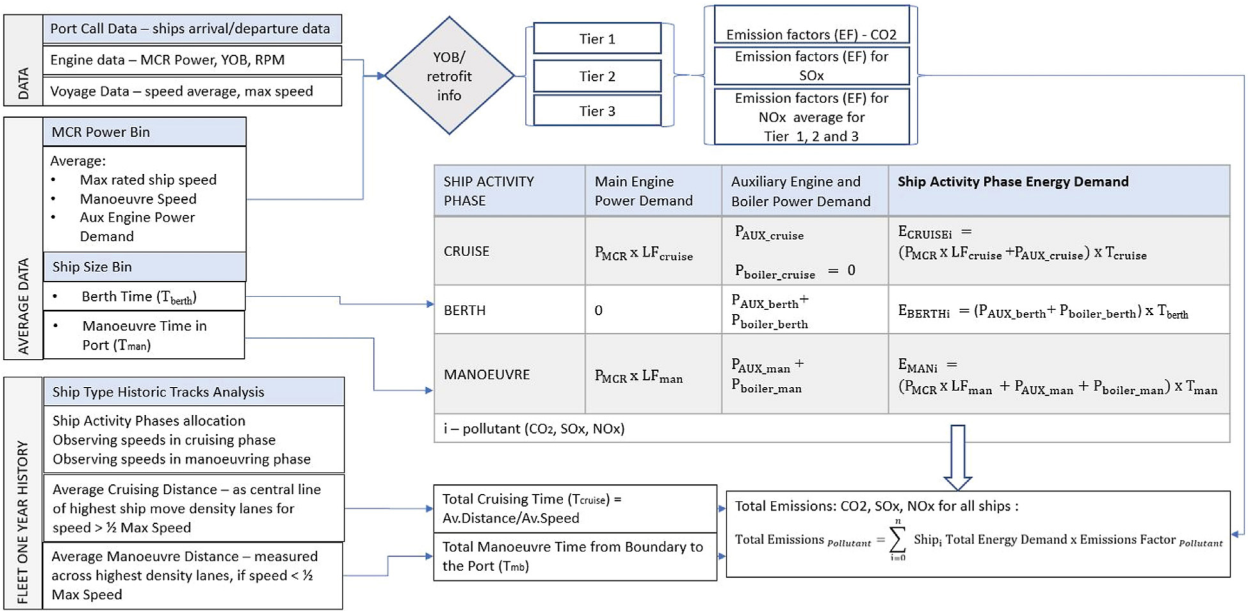


Fig. 1. Ship Emission Assessment Method (SEA) flow diagram.

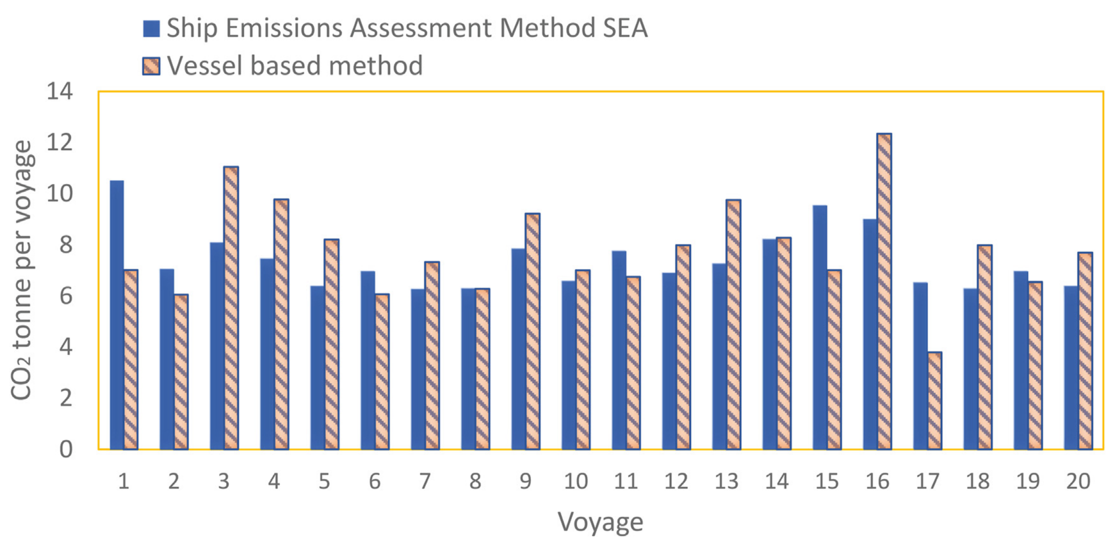
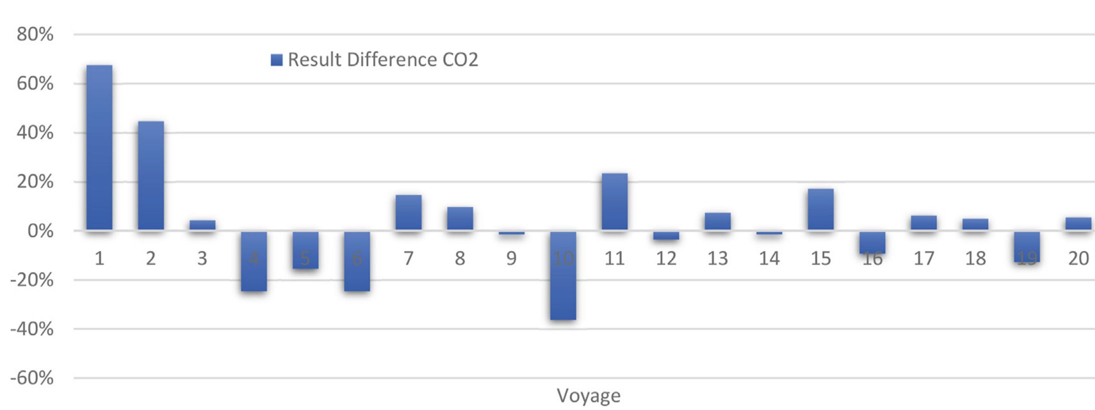


Fig. 2. Results compared between the Ship Emissions Assessment Method SEA and the Vessel-based Method.



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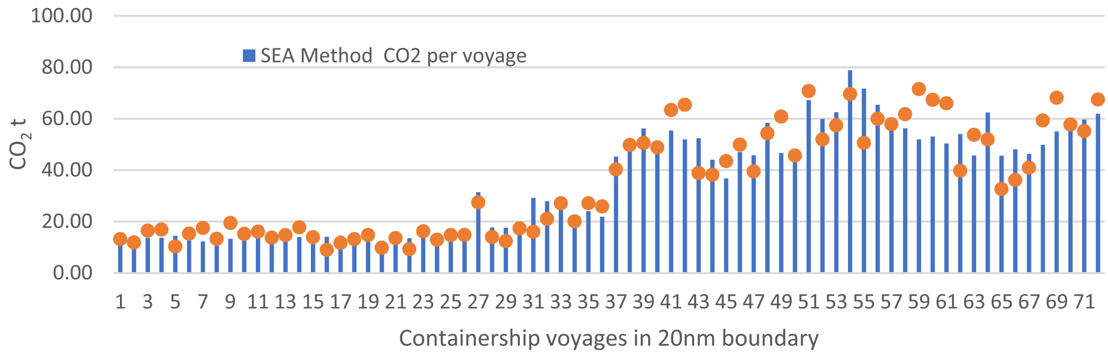

Fig. 4. Emissions of CO_2, comparison of method results btw. Ship Emission Assessment SEA and Vessel-based Method, for 71 containerships.

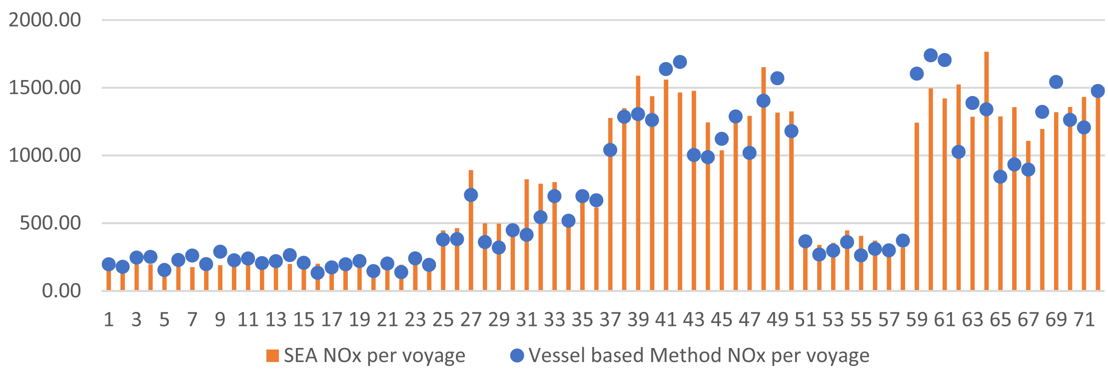

Fig. 5. Emissions of NOx, comparison of method results btw. Ship Emission Assessment SEA and Vessel based Method, for 71 containerships.

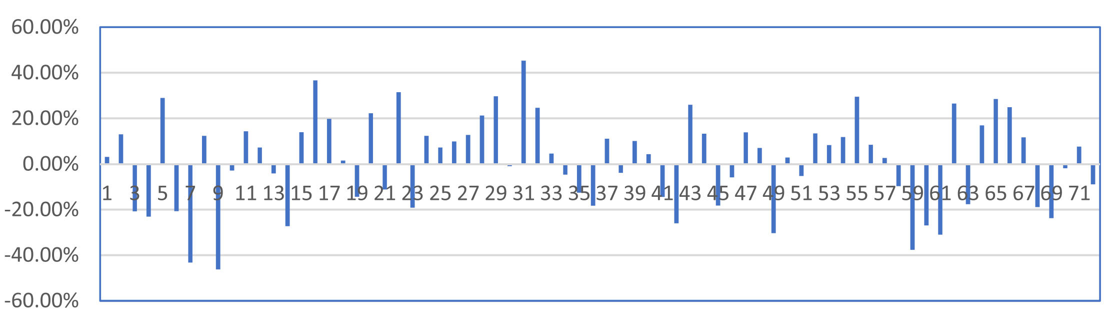

Fig. 6. Distribution of the two method results, difference in percentage, for CO_2.

1. Introduction

The fourth International Maritime Organization[1](IMO) Greenhouse Gas (GHG) Study (2020) projects by 2050 emissions from ships will surpass 2008 levels by 130 per cent if current shipping industry trends continue, namely, the increase in number of ships and subsequent fuel consumption. Emissions are now at 90 per cent of 2008 levels - achieved by reducing ship operating speeds and increasing their size. The IMO's global directive for the shipping industry is to meet the goal of reducing its GHG emissions to 50 per cent of 2008 levels by 2050, alongside other industries, to contain the global temperature increase to well below two degrees.

It is acknowledged that successful emission abatement and practicable policy development requires ship emissions data which (currently) is either limited or unavailable (Schim van der Loeff et al., 2018).

Currently, the two most common methods utilised for collecting and processing the direct and/or indirect data precursors of ship emissions are the *top-down* approach, *bottom-up* approach, or a combination of the two depending on the intended purpose.

A *top-down* approach is characterised by using highly aggregated information on a relevant shipping activity, e.g., total fuel consumption (or even sales) for a fleet of ships, over an extended period of time, relevant

[1] IMO: International Maritime OrganisationAIS: automatic identification system (an automatic tracking system using transceivers on ships) AUX: a ship's auxiliary power CO_2: carbon dioxideEF: emission factor GHG: greenhouse gases (mostly from anthropogenic combustion of fossil fuels) MCR: an engine's maximum rated power NECA: nitrogen oxides emission control areas NO_x: nitrogen oxides RPM: revolutions per minute (the number of times an engine's pistons turn the crankshaft around, with high RPMs delivering greater power but high fuel consumption and low RPMs resulting in fuel economy. SEA: ship emissions assessment (the novel methodology presented in this paper) SO_x: sulphur oxides SSD/MSD: slow speed diesel engine/medium speed diesel engine TEU: twenty-foot equivalent unit (the dimensions of one TEU is equal to a standard 20′ft shipping container) YoB: year of build (referring to a ship's engine production year).

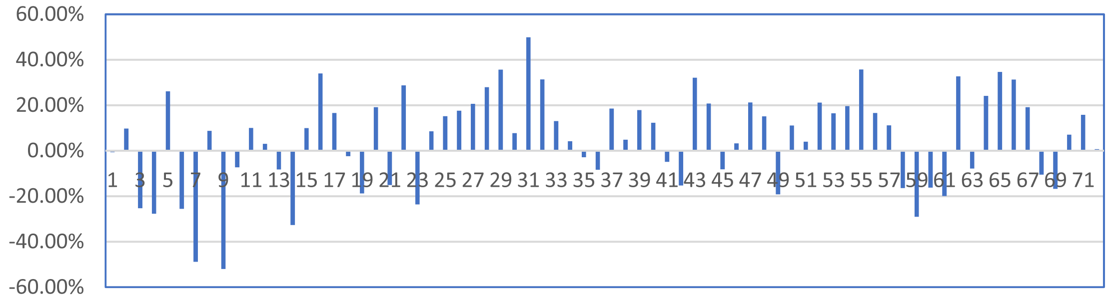

Fig. 7. Distribution of the two method results, difference in percentage, for NOx.

to a wide geographical region. The corresponding emission factors (EFs) are highly aggregated with averaged values, and do not take into account the specific conditions that lead to the instantaneous emission production in any given circumstance. So, although *a top-down* approach is relatively inexpensive (e.g., requires a small quantity of data) it is of low resolution (in time and space) and unable to accurately reflect emissions in response to specific shipping activities.

A *bottom-up* approach, on the other hand, typically estimates near-

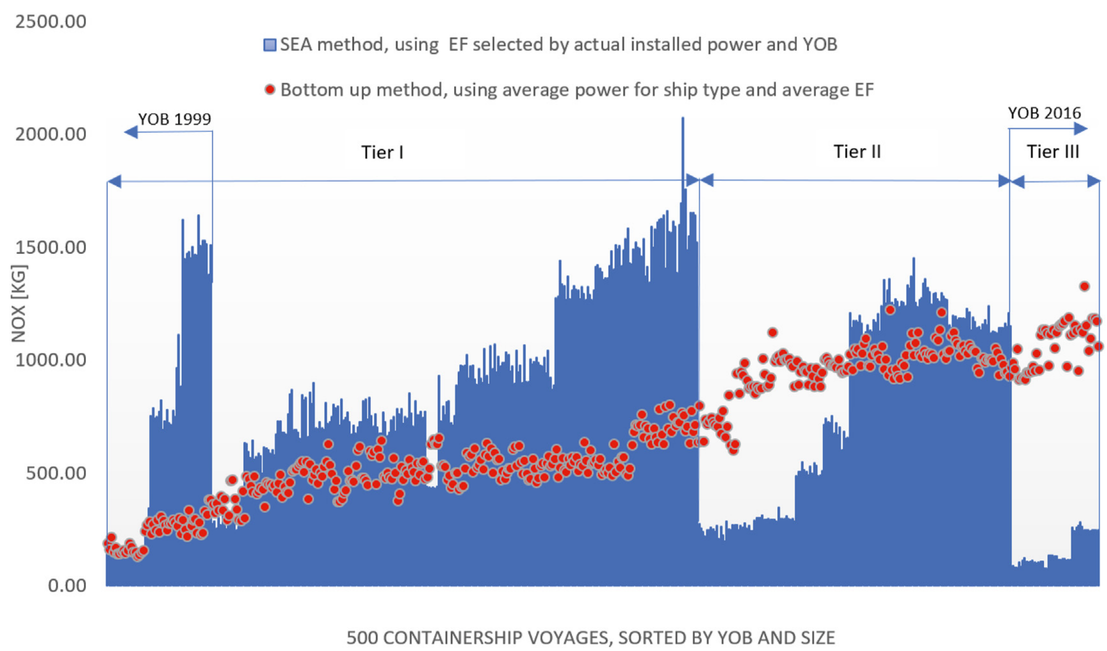

Fig. 8. Results of NOx emissions compared for the SEA method and the bottom-up method using average power and average EF.

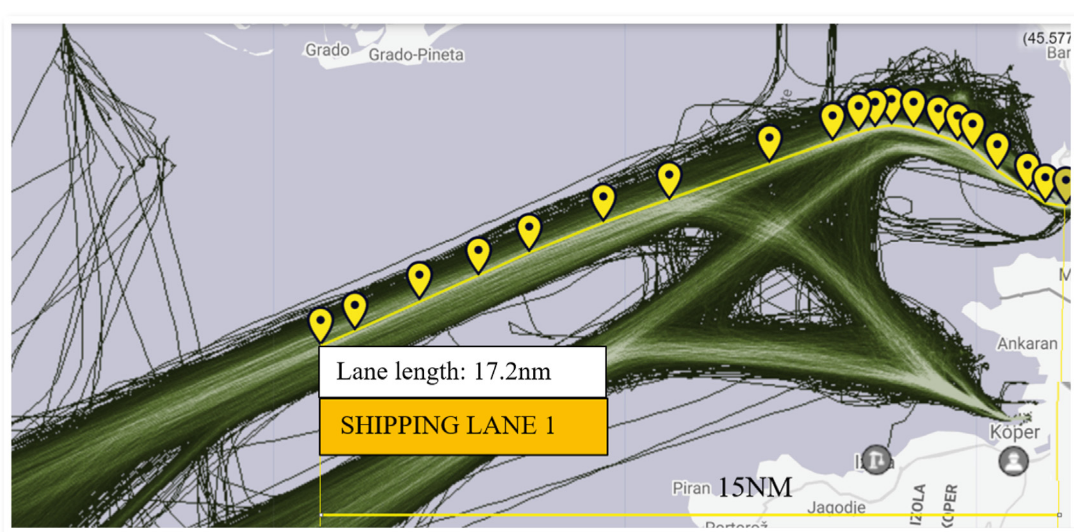

Fig. 9. Shipping Lane 1, 17.2 nm average length (Marine Traffic, 2020).

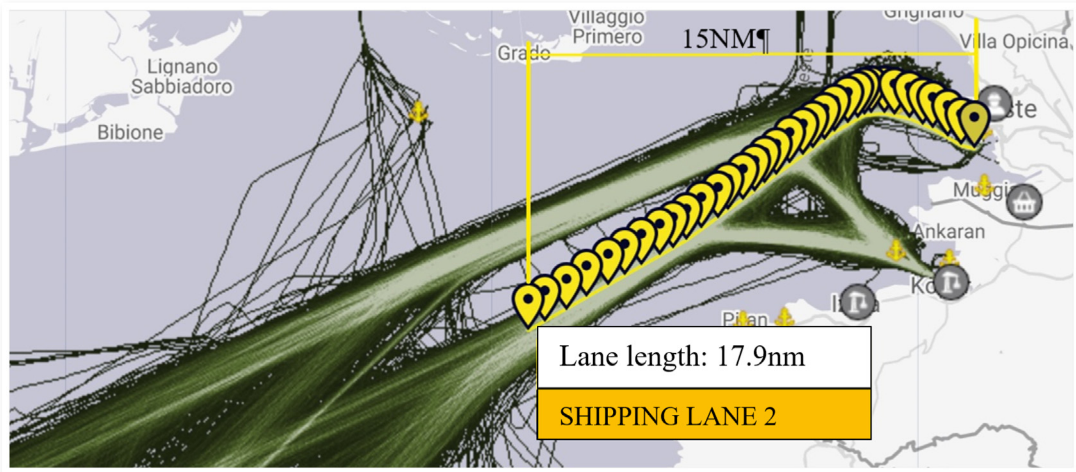

Fig. 10. Container ships shipping lane 2, length: 17.9 nm (Marine Traffic, 2020).

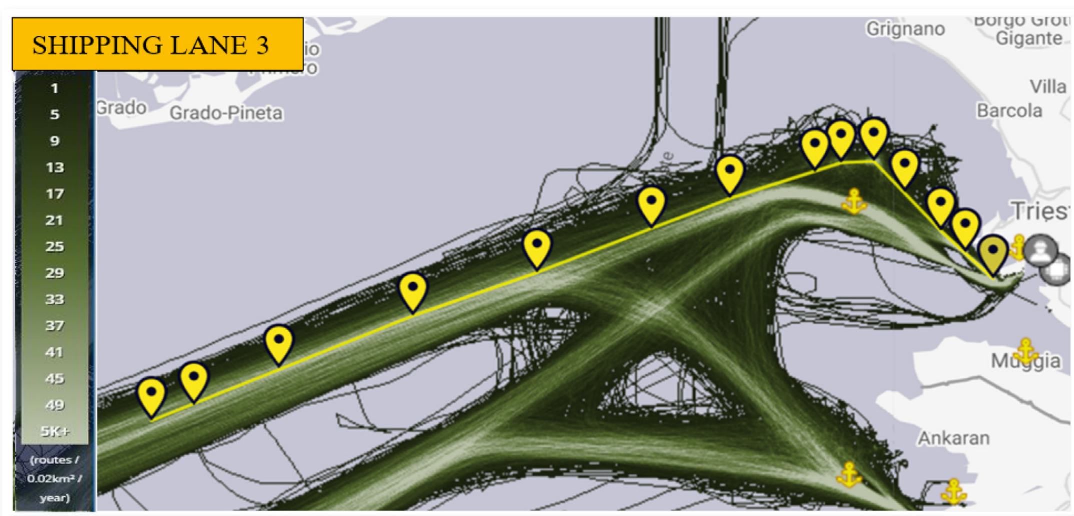

Fig. 11. Third route leading to the anchorage and further to the port (Marine Traffic, 2020).

instantaneous emission production on a vessel-by-vessel basis, at high resolution (in time and space). The EFs used can vary over the range of chosen operating conditions, for example, they could be continuously variable over the full range of engine power output. Although this approach is data intensive and, consequently, relatively expensive it can accurately reflect variations in emission productions at high resolution.

Methods to estimate emissions from ships based on Automatic identification System (AIS) rely on the *bottom-up*, Vessel-based approach - identifying ship speed over ground, course, and location to estimate the engine load and identify EFs for each type of ship activity.

This AIS data *bottom-up* Vessel-based approach (Goldsworthy and Goldsworthy, 2015), (Huang et al., 2017), is time intensive. Time is required to generate historic data-sets achieved by recording real-time AIS data, followed by complex data computations calculating ship movement trajectories, which are then applied to activity-based emissions estimations. To bridge some of this complexity a *bottom-up* Vessel-based assessment (Peng et al., 2020) uses a sampling technique where a certain number of ships represent emission quantity contributions for different types and sizes of ships.

However, these AIS *bottom-up* Vessel-based methods analyse emissions related to a ship type and its activity - they do not consider engine specification differences and their impact on emissions, particularly NO_x.

The third and fourth IMO GHG studies (2014, 2020) are detailed *bottom-up* high budget studies that provide global statistics and emission factor standards however to be practicable require the development of low-cost methods based on widely available resources.

As a result, it is evident there is a market gap for a ship GHG emission estimation model that hybridises the best of both the *bottom-up* and *top-down* methods.

And that is why the novel Ship Emissions Assessment (SEA) is proposed as an innovative hybrid solution.

Novel SEA method is cost effective, and resource efficient, presenting spatial ship emissions utilising widely accessible data, and it is precise – fulfilling the requirements needed to evaluate ship emissions reduction measures.

Novel SEA method is the first in its endeavour to replace AIS Vessel-based raw data allocation by using rapid analyses of readily available ship track density data and average voyage information. It combines obtained average voyage distance with voyage average speed to estimate ship activity for emission assessments - saving costs by reducing time and reliance on complex computations, especially when many ships need to be analysed simultaneously.

The proposed novel SEA method is introduced in its entirety in Section 2.

Fig. 12. Ship anchorage analysed using points of call historic spatial map (Clarkson's Research SEA/NET, 2020).

Fig. 13. Cruising distance determined by conventional IMO method (Marine Traffic, 2020).

Verifying novel SEA's results with empirical data was not possible due to limited data available from emissions measurements on board ships. Therefore, to confirm novel SEA's level of precision, the novel SEA method could only be verified by comparing it against existing methods' results.

Containerships were selected as the focus ship type due to it being the highest polluting vessel according to IMO statistics (2014, 2020).

Using the novel SEA method, a series of containerships from geographically diverse ports were sampled and assessed for emissions with results compared to the interpretation of the *bottom-up* IMO methodology (IMO, 2014). For this paper, representative samples were selected based on the containership's size and timing of port visits, with novel SEA method results confirming to compare well to the detailed and data demanding *bottom-up* method, presented in Section 3.

Subsequently, the novel SEA method was applied to containership traffic calling into the Port of Trieste, in the northern Adriatic Sea, and demonstrated its ability to estimate historic emissions for the preceding 12 months while taking into account seasonal port traffic variations. Emissions were quantified for CO_2, SO_x and NO_x pollutants, compared for compliance with the latest NO_x standard by IMO, Tier III, and presented on a spatial map for CO_2 emissions with the results presented in Section 4.

The novel SEA method is an efficient, inexpensive and accurate, easy-to-use emission assessment tool based on widely accessible data. It can be used in day-to-day shipping operations by a variety of stakeholders including port operations managers, regional traffic operators, and those non-industry, while providing the required level of technical accuracy. In comparison, existing methods are not as time and cost effective, user-friendly, or based on easy to interpret readily accessible data.

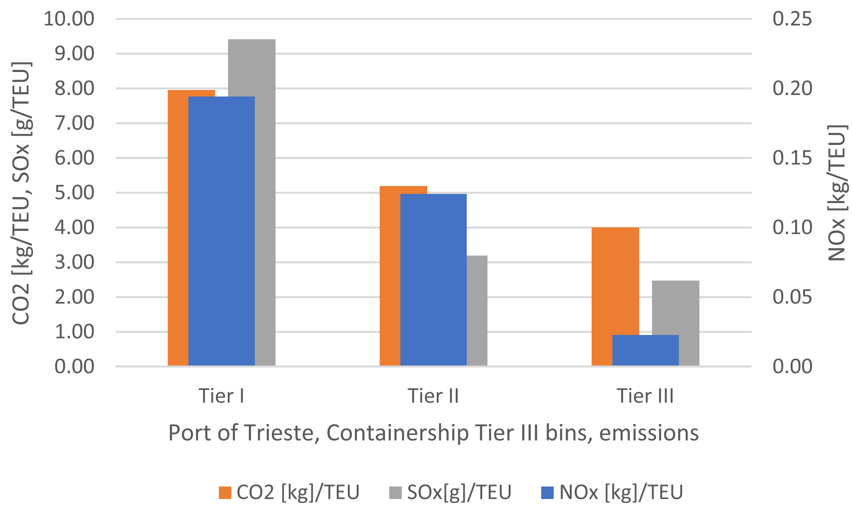

Fig. 14. Emissions by containerships, distributed in Tier III engine bins, in the Port of Trieste, 2019

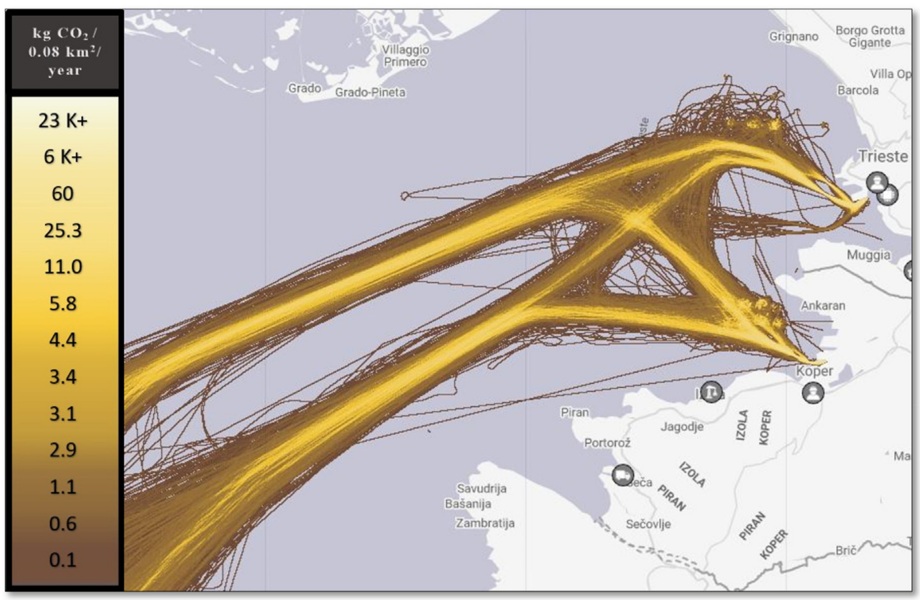

Fig. 15. CO_2 emissions by containerships in the Port of Trieste in 2019.

2. Methodology and data

The proposed novel SEA method applies IMO (2014) emission factors (EFs) and generates emissions estimates results with the precision required to assess the efficacy of new IMO GHG standards and directives. Thus, enabling users to calculate energy demand and apply engine specific emission factors in their estimates of emissions for different pollutants.

2.1. IMO standards for NO_x emissions

New IMO regulations reduced the allowable sulphur content in ship fuel oil from 3.5 per cent to 0.5 per cent by mass as of January 1, 2020, (IMO, 2020, 2016). This regulation reduces the production of sulphur oxides (SO_x); however, it has little effect on the formation of nitrogen oxides (NO_x), which form after the combustion process, and among other factors depend on the combustion temperatures within the engine (McCaffery et al., 2021; Trodden et al., 2015).

Presently, NO_x is regulated by the IMO Tier III set of standards, which are expected to reduce NO_x emissions by 80 per cent from Tier I level. It is taking a 75 per cent cut in NO_x emissions to move from Tier II to Tier III limits. However, Tier III NO_x limits apply only to vessels operating in NO_x Emission Control Areas (NECA). Outside such areas Tier II limits apply (IMO, 2020, 2014).

2.2. Novel ship emissions assessment method (SEA)

Different methodologies, (Goldsworthy and Goldsworthy, 2015a) (ENTEC, 2010), classify the emission factor by ship engine type (SSD/MSD), fuel type, and operating mode. However, none of the existing methods show the impact of emerging ship emission reduction measures against Tier III standard compliance. Emissions of NO_x would correlate with the number of ships fitted with NO_x Tier II and Tier III compliant machinery (IMO, 2014).

Classification of engines according to NO_x regulations by IMO Tier III standards presented in Table 1.

The novel SEA method provides the solution for identified gaps in existing methods, i.e., inability to identify impact of ship emissions measures and high 'costs' in data acquisition and time. It possesses the precision to differentiate ships according to the level of emission

Table 1
Engines classified according to IMO NOx engine Tier III standard.

Engine Tier	Maximum Rated Power	Year of Built
Tier 1	MCR>130 kW	2000–2010
Tier 2	MCR>130 kW	2011–2015
Tier 3	MCR>130 kW	2016 – today

Table 2
Ship activity phases allocation using Vsog by the IMO bottom-up method, compared to the novel SEA method using averaged speed values.

Method	IMO *bottom-up method* Vessel-based	Novel SEA method Voyage-based
Ship Activity Phase	Input: speed over ground	Input: voyage average speed
Berth	0-3kn	0
Manoeuvring	3kn< V_{sog} < $V_{MCR}/2$	$V_{man\text{-}average} = 0.3^* V_{sea\ speed\ average}$
Cruising	$V_{sog} > V_{MCR}/2$	$V_{voyage\text{-}average}$

Legend: V_{sog} – speed over ground (obtained from AIS) $V_{man\text{-}average}$ - average manoeuvring speed.

Table 3
Differences and similarities between the two methods table.

	LF MAIN ENGINE	TIME AT BERTH	TIME IN ACTIVITY PHASE	AVERAGE DISTANCE CRUISE	CRUISE SPEED	MAN. SPEED
SEA method	Eq. 8	Port calls data	T_{cruise}, Eq.6 T_{man}, Eq.7	Input from Historic Ship Tracks (Section 4.2.1.1.)	$V_{voyage-average}$	$V_{man-average}$
Vessel- based method	$(V_{SOG}/V_{MCR})^{3.5}$	T_{birth_AIS}	$T_{cruise\ i}, T_{man\ i} = \sum (\frac{d_i}{V_{SOGi}})$	$\sum d_i$	$\sum V_{SOGi}$	$\sum V_{SOGi}$

Legend: d - distance between two nearest AIS points of call V_{SOG} – speed over ground at the AIS point of call.

Table 4
The Ship Emissions Assessment SEA Method results compared to the Vessel-based Method results.

	SEA Method	Vessel- based Method	Result Difference (tonnes CO_2)	Result difference %
Total Emissions all voyages [tonnes of CO_2]	148.31	156.07	7.75	4.97%

Table 5
Ship Emissions for 75 voyages of containerships in the 20 nm port boundary, the Ship Emissions Assessment SEA method compared to the Vessel-based Method.

Vessel-based Method	SEA	Vessel-based Method	SEA	Difference CO_2	Difference NO_x
CO_2	**CO_2**	**NO_x**	**NO_x**	**%**	**%**
2172 t	2213 t	44,7 t	49,1 t	1.87%	8.94%

reduction measures by Tier III standards and enables savings in time and resources needed to identify a ship's past activity.

Current methodologies for ship emission assessments rely on estimates of the installed power (averages from engine installed power statistics based on ship size and type).

The proposed novel SEA method requires knowledge of the installed engine's data, which can be accessed using existing readily available commercial platforms as outlined in Section 2.3.2.

Emission inventory results, presented in Section 4, by the novel SEA method provide quantification and comparison of emissions between ships, classified by ship type, size and compliance with Tier III standards.

Although the acquisition of ship engine details increases the 'cost' in time, of the SEA method, novelty in rapid ship activity data acquisition, is balancing the time score and enables rapid processing.

The method reduces computational resources required for processing of AIS raw data, by using one-year ship track density maps, for aggregated cruising and manoeuvring distance estimates.

The one-year ship track density maps are newly available historic data in the graphical form.

Analysis of the one-year ship tracks density maps, shows that merchant ships use narrow shipping lanes, especially at entry and exit to ports. To simultaneously estimate emissions of multiple ships the high-resolution data which identifies distance between AIS points of call for each ship can be replaced with an averaged cruising distance obtained from the previous 12-month ship tracks density maps.

The novel SEA method comprises:

- data acquisition
- main assumptions
- energy demand estimate
- application of emissions factors and emissions estimate

The novel SEA method flow diagram is presented in Fig. 1, with each step explained in Sections 2.3 to 2.6.

Table 6
Conversion table for spatial map legend, from ship tracks to CO2 per area.

SHIP TRACKS/0.08 KM^2	CO_2 [KG/0.08 KM^2]
200,000	22,920.0
50,000	5730.0
521	59.7
221	25.3
96	11.0
51	5.8
38	4.4
30	3.4
27	3.1
25	2.9
10	1.1
5	0.6
1	0.1

2.3. Data acquisition

2.3.1. Port calls data

The port calls dataset can be obtained directly from the port or from commercial AIS portals, e.g., Clarkson's System or Marine Traffic. Ships need to be classified by ship type as each ship type is processed independently.

Port calls data includes:

- times of arrival and departure of ships
- time in berth
- ship names
- containership maximum capacity (TEU)

2.3.2. Engine data

Engine specific information is obtained from Clarkson's system alongside Year of Build (YoB) and retrofit information. This then enables categorisation of the ship in-line with Tier standard bins: Tier I, Tier II or Tier III which will be relevant to the EFs selection later in the process.

Engine data includes:

- year of build (YoB) and retrofit information (SO_x or NO_x scrubber)
- installed main engine power (MCR)
- revolutions per minute (RPM)

2.3.3. Voyage data

Voyage data is a data set that has only recently become widely available which can be used to save time estimating a ship's average cruising distance, and it is inexpensive as it has become a standard inclusion in port calls (ships arrival and departure) data. Voyage speed average ($V_{voyage\text{-}average}$), another new addition to the port calls dataset, is an individual ship's average speed between the last two ports. As speeds differ for the same ship on each of its visits to the port the $V_{voyage\text{-}average}$ is used as a speed proxy, and provides a level of accuracy comparable to more detailed methods presented in Section 3.

Average sea speed and average maximum rated speed are obtained from statistics of world containership population (IMO, 2014). These values are easily accessible from averaged empirical data in IMO statistics by ship types, as they are not available in ship data sets. This simplifies the data needed to run the novel SEA method and enables quick processing of large numbers of ships.

Voyage data includes:

- voyage speed average ($V_{voyage\text{-}average}$), obtained from Marine Traffic System
- averaged sea speed for containership capacity size bins ($V_{sea\ speed\ average}$)
- maximum rated speed (V_{MCR})

2.4. Activity data

Twelve-months of consecutive ship tracks density maps need to be analysed for ship activity areas, as demonstrated in Section 4.1, with the below listed lengths measured along the central line of the ship tracks highest density:

- averaged distance of cruising tracks from entry to exit of the port's boundary
- average manoeuvring track length, within the port's boundary

2.5. Assumptions and estimates

2.5.1. Auxiliary engines power demand

Power demand for auxiliary engines and boilers is assumed using statistical average values based on empirical trials for different ship activity phases (IMO, 2014).

2.5.2. Engine load

It is assumed the main engine is the only engine used for propulsion and that auxiliary engines are at a low load during cruising phase, high load during manoeuvring, and medium load in port, as presented in Fig. 1.

2.6. Energy demand for ship activity phase

The proposed novel SEA approach estimates the ship's total energy demand in kWh per voyage. The ship's total energy demand, Equation (1), is directly linked to fuel consumption and can be further used to calculate the emissions for individual pollutants, presented in Equation (2).

$$\text{Ship Total Energy Demand:} \quad E_{TOTAL} = \mathrm{E_{CRUISE}} + \mathrm{E_{MAN}} + \mathrm{E_{BERTH}} \tag{1}$$

$$\text{Total Emissions}_{Pollutant} = \sum_{i=0}^{n} \text{Ship}_i \ \text{Total Energy Demand x EF}_{Pollutant} \tag{2}$$

To estimate emissions, the total energy demand calculated by Equation (1), is multiplied by emission factors for each pollutant as presented in Equation (2).

The method is simplified by assuming that auxiliary engines are only used for electricity production and that the propulsion engine is the main engine.

For the auxiliary engines and boilers, power demand is based on existing statistics by IMO (2014).

Ship activity is defined by the speed of the ship, as presented in the Table 2. For ship speeds in each of the activity phases the novel SEA method is compared with the IMO *bottom-up* method (IMO 2014).

The novel SEA method is based on estimates per each voyage. For this method a voyage event is defined as a ship's singular visit to the port. Voyage speed average ($V_{voyage\text{-}average}$) is input from the voyage dataset, where distance of the voyage is calculated between the last two ports of call.

Energy demand for each ship activity phase is estimated, for main engines, auxiliary engines and boilers, as presented in Section 2.7; Equation (3), Equation (4), and Equation 5

$$E_{CRUISE} = P_{MCR} \ x T_{cruise} \ x LF_{cruise} \tag{3}$$

$$E_{MAN} = (P_{MCR} \ x LF_{man} + P_{AUX\_man} + P_{bolier\_man}) \ x \ T_{man} \tag{4}$$

$$E_{BERTH} = (P_{AUX\_berth} + P_{bolier\_berth}) \times T_{berth} \tag{5}$$

P_{MCR} – main engine maximum rated power
P_{AUX} – auxiliary engine, average power demand for ship activity phase
P_{bolier} – auxiliary boiler, average power demand for ship activity phase
LF_{man} – main engine, assumed load factor, per voyage, during the manoeuvring activity phase

Pollutant emission factors for CO_2, SO_x and NO_x, are expressed in g/kWh according to the Third IMO GHG Study, (2014). For NO_x, emission factors are different for engine tier bins: Tier I, II and III.

Engines identified as retrofitted with scrubbers for NO_x, were also considered as Tier III engines.

Time for cruising (T_{cruise}) is calculated using Equation (6).

$$T_{cruise} = \frac{Average \ \ Distance_{cruise}}{V_{voyage-average}} \tag{6}$$

Where Average Cruising Distance is obtained from Ship Historic Tracks Map, as explained in Section 4, Voyage Speed Average is obtained from Voyage Data, as explained in Section 2.3.3.

Time manoeuvring (T_{man}) is calculated using Equation (7).

$$T_{man} = \frac{Average \ \ Distance_{man}}{V_{Sea \ Speed \ Average} \ \ x \ \ 0.3} \tag{7}$$

Time at berth (T_{berth}) is retrieved from port calls data. Coefficient 0.3 is the speed adjustment factor assumed for manoeuvring phase, as presented in Table 1.

Main engine load in cruising (LF_{cruise}) and manoeuvring (LF_{man}) activity phase is estimated using Equation (8) where "n" for containerships is assumed to be 3.5, as suggested by (MAN Diesel and Turbo, 2013).

$$LF_{cruise} = \left(\frac{V_{Sea \ Speed \ Average}}{V_{MCR}}\right)^n \tag{8}$$

At the time this research was completed there were limited test results available for emissions from engine loads lower than 25 per cent. The experimental study on Tier II containership vessel by McCaffery (2021) states that during berth entry and exit manoeuvres the main engine power is reduced to 25–30 per cent per cent load. Main engine load in the manoeuvring phase LF_{man} is assumed to be 0.3, as in this study it presents average main engine load for acceleration and deceleration in the manoeuvring phase.

3. Methods comparison

The novel SEA method requires testing to establish results accuracy. Due to the limited ability to access representative research samples from on-board Ship Performance Monitoring systems (IMO, 2020), the proposed new method was validated by comparing results to the more detailed Vessel-based, *bottom*-up method. A computational model, an interpretation of the Third IMO GHG Study (2014) methodology, was established. The Vessel-based method is more detailed and was therefore used as a baseline to compare, validate and refine outputs of the novel SEA method.

Both the novel SEA and Vessel-based *bottom-up* methods used EFs from the Third IMO GHG Study (2014).

Auxiliary boiler power usage and emissions were not considered when comparing results, as that part of the estimate remains constant in both methods and therefore does not impact on the method's results.

The differences and similarities between the two methods are listed in Table 3.

3.1. First sample: 20 container ship voyages 15 nm port boundary

The first research sample analysed a total of 20 voyages from two different vessels to the same port over a one-year period, with the port boundary distance set to 15 nm. Using the novel SEA method and the Vessel-based method CO_2 emissions estimate results were compared for individual voyages, and aggregated voyage data results.

In this series of tests identical EFs were used for both methods, however, the result differences were due to voyage parameters: cruising and manoeuvring distance, time spent in each ship activity (cruise, maneuver, anchor/berth), and speed. The results of the total emissions are compared in Fig. 2.

It can be observed that for a single ship voyage, emission estimates using the novel SEA method could differ from the Vessel-based method, typically depending on deviation of ship cruising distance from average mean cruising distance.

When Vessel-based method results are aggregated the emissions per voyage variations that are scattered equally on both positive and negative sides of the mean (Fig. 3) will cancel out.

Results for the novel SEA method, compare well to the Vessel-based method once both methods results are aggregated for all voyages, i.e., individual ships.

When the novel SEA method's outcomes (total emissions for all voyages considered) are summed up and the results that cancel each other out accounted for, there is less than five per cent difference between the Vessel-based method and novel SEA, as presented in Table 4.

3.2. Second sample: 100 container ship voyages, 20 nm port boundary

A second research set was conducted to test how voyage-based parameters would compare to the Vessel-based method, using a larger sample, presenting containerships of all sizes and engine powers. Again, the emission factors were kept identical to identify any impact on results differences based on voyage data parameters.

The sample was again taken from one year's worth of voyages to the same port. Several ships in each size bin were selected, and additionally, ships with the highest number of voyages from small, medium, and large bins, were prioritised, to establish and understand the standard deviation in speeds by vessels that repeat the same routes throughout the year.

Out of the 100 selected voyages, 95 had sufficient data to complete the novel SEA method estimate, while 75 had sufficient data to perform the Vessel-based method. Uncertainty was found in four voyages by not matching AIS and port report data, i.e., ships were anchoring within the boundary, but only berth time was recorded. Methods were further compared for 71 voyages as presented in Figs. 4 and 5.

Aggregated result differences will fall equally in positive and negative directions from the mean value as can be seen in Figs. 6 and 7.

For each pollutant, aggregated results were compared in Table 5.

The results show that differences between the two methods in individual ship voyage results would scatter equally in positive and negative direction and then eventually cancel out. Consequently, aggregated emission results compare well, with a less than two per cent result difference for CO_2 and under nine per cent difference for NO_x. It can be concluded that for the second sample, which is nearly four times larger than the first sample, results for CO_2 emissions compared better.

3.3. Novel SAE method compared to bottom-up method using average installed power and emissions factor

Results of the novel SEA method were further compared to the interpretation of the *bottom-up* method to estimate regional ship emission inventories (Peng et al., 2020) using a constant EF for all ships, assuming most ships use MSD engines and FSC fuel with 0.2 per cent sulphur content as a mean value.

The comparison of 500 containership emissions over one year is presented in Fig. 8. Results of the *bottom-up* method estimates do not consider fluctuations in emissions due to the engine type and compliance to engine emission standards.

This chart clearly shows how the novel SEA method provides results that more accurately reflect the differentiation of NOx emission by engine type, and according to the latest IMO Tier III emissions factors standards. There is still some uncertainty to what extent ships in operating conditions are compliant to named standards. This uncertainty is the limitation of all emission estimation methodologies and can only be thoroughly resolved using the on-board measurements in coastal areas and harbours. Subsequently, comparison of spatial ship emissions estimates to atmospheric air quality measurements (Mao et al., 2020), and coastal air quality modelling (Merico et al., 2017), could help understand to what extend ships are responsible for coastal air quality pollution compared to other industrial sources.

4. Results and discussion

4.1. Application of the novel SEA method to containerships calling into the Port of Trieste

Based on the novel SEA method's comparative results, an analysis of existing historic ship tracks is presented in this Section focusing on containership emissions and their impact in the northern Adriatic Sea. The Adriatic Sea lies in a north-east oriented elongated basin which is closed to intakes of fresh sea water apart from the narrow Otranto Strait where it connects to the Mediterranean Sea.

Port of Trieste was chosen because containerships entering through the Otranto Strait must cruise the length of the basin before reaching this northernmost positioned port - the last waterway stop to reach European railway and road transportation routes- and the narrowness of the sea basin highly impacts coastal areas and ecosystems within the entire Adriatic region.

$$\text{Emissions per ship track} = \frac{\text{total emissions(pollutant)}}{\text{number of voyages} * \text{number of tracks in the voyage}} \quad (9)$$

4.2. Application of ship historic tracks in assessment of emissions from ships

Apart from fishing boats and pleasure yachts, most merchant ship types have route patterns, therefore, it is possible to understand ship movements and the distances of ship cruising and manoeuvring lanes, using historic ship track maps. Due to its geographic location, enclosed and in the far northern Adriatic, the Port of Trieste lacks transposing traffic – qualifying that all containerships entering the bay of Trieste are registered to the Port of Trieste thereby providing identifiable historic tracks.

4.2.1. How the novel SEA method was applied for the Port of Trieste

STEP 1

One years' worth of ships calling to the Port of Trieste, from October 2018 until October 2019, were selected from the port calls dataset with repetitive occurrences and identical date and time sequences filtered out.

STEP 2

Ships in this one-year sample are listed with their capacity bins (TEU) and linked to the voyage data and port calls data, as described in the Section 2.3.

STEP 3

Ship Historic Tracks, also known as ship density maps, are analysed within the research boundary. In this case, the study boundary was set to 15 nm from the containership berth.

Traffic lanes with the highest density of containership moves per square kilometre were identified. Vessels using lanes were then analysed to understand patterns in containership navigation and ship activity phase locations along the lanes.

Two lanes were identified and measured along the central line of highest congestion, as shown in Figs. 9 and 10.

The first two lanes were added together as an averaged voyage distance, one was assumed as the entry lane and the other as the berth and port exit lane.

A third shipping route, Fig. 11, is measured from boundary edge to the anchorage zone. This route is measured to the approximated central point of the anchorage zone.

The anchorage zone is better analysed, if ship points of call are observed, Fig. 12, as dots rather than lines between the points of call.

Ships from the database were selected according to the length of time spent in the port. Ships taking more than 24 h for time in por, were assigned Lane 3 distance, as it was assumed those ships were anchored. For regular analysis of similar ports, further research is needed to analyse the typical port processing time for different containership capacity bins.

The point where speed becomes less than half of the average sea speed for the area is assumed to be the start of the manoeuvring phase, as explained earlier in Section 3, Table 3. Manoeuvring distance is subtracted from the averaged voyage distance to get averaged cruising distance.

4.3. Comparison with conventional IMO method application

To perform a conventional *bottom-up* method for emission assessment, voyage information (actual speed for each point of call, course, time and location of call), is determined through AIS.

Voyage distance is estimated by calculating the distance between each AIS point of call, with eventual gaps filled by interpolation and extrapolation (Goldsworthy and Goldsworthy, 2015b), (Scarbrough et al., 2017) of the given lines to form a curve of the most probable ship route.

Fig. 13 presents a visualisation of cruising and manoeuvring distance, obtained by calculation of distances, between AIS points of call. The conventional Vessel-based method would require approximately 17 AIS points of call as presented by the numbers and yellow location marks in Fig. 13.

Actual speed over ground is received for each point of call. The green colour represents cruising speed, while yellow shades in the ship track represent manoeuvring activity, in this case, deceleration distance, and the warmer red shades represent very slow speed, under three nautical knots.

Using the conventional method, the dataset for the equivalent of one voyage would require 2 × 17 data lines, with an additional dataset to account for every three to 5 min between calls for time in Port - resulting in approximately 100–300 lines per voyage.

To compare data requirements for 500 voyages:

SEA method = 500 lines of dataconventional *bottom-up*, Vessel-based method = 50.000 to 150.000 lines of historic ship data.

The novel SEA methodology is the first attempt to replace conventional AIS based *bottom-up* methods using a hybrid, voyage-based method using widely available, aggregated historic ship track data in combination with actual ship engine technical information for individual ships.

Thus, for single ship activity analysis Vessel-based methods using AIS data provide accuracy that can only be bettered by measurements done on board ships. However, if aggregated results are required to estimate emissions in ports, regional or global areas, the current complex and resource demanding, ship-by-ship based estimates have a simpler, inexpensive and less computationally demanding alternative in the form of the novel SEA method.

4.4. Emissions spatial distribution

Emissions were calculated for a period of 12 months (October 2018 to October 2019), for containerships calling to the Port of Trieste. In 544 voyages, each voyage represented ship activities from entry to exit of the boundary. The distribution of CO_2, SO_x and NO_x emissions per container transported, and engine Tier III standard is presented in Fig. 14.

4.5. Spatial emission representation

Emissions from containerships are presented spatially, for the Bay of Trieste. The advantage of the novel SEA methodology is that it recalculates existing historic ship tracks that are interconnected with the wider regional area. Ship track density is converted to spatial emissions distribution – providing a general understanding of the impact on the wider area than the original boundary, subject to the unchanged vessels and ship track density remaining of coherent density.

It can be seen in the Fig. 15, that shipping tracks density remains similar in distribution in the whole regional area of the Port of Trieste bay, therefore providing an estimate of emissions for the port boundary area and wider region.

Ship tracks, also referred to as routes, are divided by the grid of squares in size of 0.08 km^2. The legend (Table 6) presents the number of ship tracks per square kilometre and conversion to CO_2 in [kg/0.08 km^2].

To understand the emissions distribution per ship track segment, the total quantity of CO_2 pollutant is divided by the number of voyages. Assumption is made that each ship track spans the lengths of the grid sides.

To obtain CO_2 emissions per area [kg/0.08 km^2], emissions per ship track (obtained in Equation (9)) are multiplied by the number of tracks in the historic ship tracks legend (Table 6).

Due to the complexity of the formation of NO_x in the combustion process, those emissions cannot be presented in linear dependency of the voyage average distance. For emissions of NO_x the production of emissions could be higher for low engine loads (Jahangiri et al., 2018) but more depends on the time ships spend manoeuvring, and in the port. As these challenges require a substantive focus, which is not in the scope of the current paper, it will be presented in a future publication.

5. Conclusion

The proposed novel ship emissions assessment (SEA) method saves data resourcing costs and processing time while providing emission results that distinguish ships based on engine production age and emission standards compliance.

The IMO's development of new stricter standards for emissions has positively impacted on engine technical emissions reduction measures, fuel sulphur content regulations, and regional regulations for emission control.

In its' third and fourth GHG Studies, the IMO established ship fuel consumption and emission factors for different ships types, sizes and the specific age and types of engines. Existing emission assessment methodologies, however, use averaged emission factors values based on different fuel and ship types. Stricter IMO fuel sulphur content regulations, commencing January 2020, forced ship owners to regulate SO_x emissions by switching to low-level sulphur fuel or using SO_x scrubbers (technical reduction measures), prioritising, in an emissions assessment, the understanding of a ship's technical ability to comply with nitrogen oxides emissions limits.

Essentially, forward thinking countries have imposed NO_x Emission Control Areas (NECA) which regulate NO_x levels and force all ships operating in NECAs to comply with the highest IMO Tier III standards. Outside those areas however, 80 per cent less stringent Tier II regulation apply, allowing ships to emit hazardous NO_x in the vicinity of populated areas and in ports. This situation requires better monitoring and an assessment method that fills the gap between rapid *top-down* methods, which provide data quickly yet of low-resolution accuracy, and the data exhaustive and time intensive *bottom-up* methods.

The novel SEA method proposes a simplified and timely process of AIS data acquisition using newly available one-year ship tracks maps and averaged voyage data. The novel SEA method analyses emissions for ship types in regional areas and presents it in a spatial map with tables of quantified emissions per pollutant.

Results of the novel SEA method distinguish individual ship technical measures and emission standard compliance - enabling an understanding of the efficacy of policy emission measures. Simultaneously, the novel SEA method fosters accuracy in technical emission reduction measures screening while shortening data acquisition and processing times. Each individual ship has its own engine specification and accompanying line of aggregated voyage data which potentially could be used as a unit of measure – namely 'data cost'. When comparing the amount of data required to generate ship emission assessment outcomes, the novel SEA method requires one line of data per single ship visit to the port (voyage), while the conventional *bottom-up* method requires anywhere from a few hundred lines of data to a few thousand lines of data depending on the AIS data resolution. However, the aggregated emission results compared well, and it was observed that result differences decreased as the comparative sample size increased, i.e., the greater the number of ships assessed for emissions the better the results of the novel SEA method compared to the more detailed *bottom-up* Vessel-based method.

It can be concluded the novel SEA method covers the gap between the two extreme ends of the accuracy results scale. The novel SEA method concentrates on individual ship power and engine production date assessment, while scanning for emission reduction measures on ships, to accurately classify ships to their compliance with IMO Tier III standard for NO_x reduction. The SEA method uses newly available, inexpensive aggregated historic ship datasets plotted as historic ship tracks on the global map. The conversion of one-years' historic ship tracks with spatial presentation of emissions per voyage as presented in the case study conducted for containership traffic to the Port of Trieste. Results of emissions from containerships were presented spatially for the regional Trieste bay area and quantified by different types of ship engines.

The novel SEA method is a ship emission assessment methodology that is applicable to all regional seas and to ports, requiring less data resources than existing methods, and rapidly yet accurately enables understanding of the effectiveness of ship emission reduction measures.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2021.100089.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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