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Green shipping: using AIS data to assess global emissions

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Abstract
Globalization and new environmental legislations lead to a rising need for new technological developments for the shipping industry, especially creating smart ports, smart waterways and smart ships. However, since these developments are on the horizon and thus not currently not state of the art, emphasis is on reducing emissions from shipping. To reduce the amount of CO_2 emitted by the maritime transport sector, the European Parliament introduced a regulation, which came into force in 2018, establishing a CO_2 emission Monitoring, Reporting, and Verification System. In order to measure and assess global ship emissions, an estimation model will be developed. Using AIS and environmental data, ship's resistance through water will be modelled. Based on the main engine used, the presumed fuel consumption of a voyage and thus the emissions can be indicated and hourly energy requirements for each ship worldwide quantified. Based on the knowledge gained from historical evaluations, a target/actual comparison enables the evaluation of the performance of a ship and thus the identification of emission reduction potentials.

Keywords Green Shipping · Emissions · AIS · CO_2 · Climate Change

Grüne Schifffahrt: Verwendung von AIS-Daten zur Bewertung globaler Emissionen

1 Introduction

Maritime transportation provides the most energy efficient means of transporting large quantities of goods over large distances. The central role of maritime transport in the world's logistic system is evident in the statistical estimates from International Maritime Organization (IMO): around 90% of world trade is carried by sea and the trade volume is still growing at a rate even faster than global economy (International Maritime Organisation 2017). Growth in world economy and trading translates into increasing demand for more ships with larger cargo capacity and higher travelling speed and highlights concerns in maritime safety and security.

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These positive developments have resulted in an increasing exchange of dioxides and thus emissions. As stated by the Third IMO Greenhouse Gas Study (International Maritime Organisation 2019) maritime transport emits around 940 million tons of CO_2 annually and is responsible for about 2.5% of global greenhouse gas (GHG) emission. The IMO expects this number to rise to up to 15% in 2050 if measures to reduce emissions are not taken quickly (International Maritime Organisation 2019).

In 2018, the International Panel on Climate Change (IPCC) published a report, explaining potential changes in the earth's system induced by an increase in the global mean temperature by 1.5 °C. These changes would include the passing of irreversible tipping points (e.g. melting of the Greenland ice shield) and the reinforcement of feedback loops (e.g. thawing of Siberian permafrost), which would further increase the GHG emissions (Stocker et al. 2014).

To reduce the amount of CO_2 emitted by the maritime transport sector, the European Parliament introduced a regulation, which came into force in 2018, establishing a CO_2 emission Monitoring, Reporting, and Verification (MRV) System (EU/2015/757). The MRV obliges all ship owners to report values for emitted CO_2 based on their fuel consumption. The MRV includes all voyages with start- and/or destination port in the European Union (EU). Nevertheless, how can global emissions be estimated and reported values be verified?

This paper presents a method to assess emissions of ships worldwide. By means of projections for the future voyage to the port of destination, nautical officers are to be shown very easily and comprehensibly how much fuel and thus CO_2 they could save with even a minimal reduction in speed. Based on historical ship movement data received from the Automatic Identification System (AIS) and weather data the ship's resistance through water will be assessed. Based on the main engine used, the presumed fuel consumption of a voyage can be indicated. In this way, the energy requirements for each ship worldwide are quantified. Based on the knowledge gained from historical evaluations, a target/actual comparison enables the evaluation of the performance of a ship and thus the identification of emission reduction potentials.

Based on a theoretical introduction on the estimation of emissions based on ship movement data, the method for assessing emissions and ship resistance is described and first results are presented in the subsequent section followed by a discussion and conclusion in the later sections.

2 Theory

In order to reduce marine CO_2 emissions, the EU introduced regulation 2015/757 establishing a "Monitoring, Reporting and Verification (MRV)" system for maritime transport emissions within European waters (European Union 2015). Regulation 2015/757 obliges all ship owners to monitor and report the CO_2 emissions of voyages of ships being larger than 5000 gross tonnages (GT) sailing within European waters.

There are currently three main approaches for determining the exhaust gas values of ships. The first variant determines the CO_2 emissions with the help of sensors directly at the outlet of the exhaust gases. Although the process promises high accuracy due to the data collected for each individual vehicle, it has considerable disadvantages in terms of cost. Another method is the calculation of the CO_2 emission on the basis of the fuel consumption, which is calculated by means of information about the bunkered fuel and level measurements, e.g. by means of a flow meter. Based on the energy-based approach of (ECTA and CefiC 2011), emissions per voyage $CO \in \mathbb{R}$ can be calculated from the fuel consumption of a voyage $FC \in \mathbb{R}$ and the fuel emission conversion factor $CEF \in \mathbb{R}$:

$$CO = FC \cdot CEF \tag{1}$$

The carbon emission factor (CEF) represents the conversion factor for different types of fuel being used and can be found in Annex VI of regulation EU/601/2012 (European Commission 2012).

AIS data was used for the first time by Jalkanen et al. (Jalkanen et al. 2009) to calculate ship emissions. The "STEAM" model developed for the calculation was subsequently further developed (Jalkanen et al. 2012) and used for the analysis of emissions in the North Sea and Baltic Sea (Johansson et al. 2013; Jalkanen et al. 2014, 2016). For Danish waters, a study was carried out (Olesen et al. 2013) to investigate the influence of ship exhaust gases on air pollution (Olesen et al. 2013). Besides, a real-time AIS-based emission monitoring system was developed by with the aim of determining CO_2 and particulate matter emissions in the Strait of Gibraltar by means of a receiver specially installed for the project (Mabunda et al. 2014). Coello et al. (Coello et al. 2015) used AIS data to determine emissions from the UK fishing fleet. Based on the Energy Efficiency Operating Index (EEOI) (Chi et al. 2015) an application for real-time monitoring of ship emissions focusing on Singapore was developed. Brown and Aldridge (Olesen et al. 2013) compared models to estimate main engine (ME) power demands.

On the basis of AIS data, the UCL Energy Institute uses a method developed as part of the Third IMO GHG Study 2014 to estimate the emissions of five different types of ships and displays this on an interactive map for the movements of the global merchant fleet in 2012 (Energy Institute 2016). Further AIS-based emission calculations were carried out for Indonesia (Pitana et al. 2010), the Netherlands (Cotteleer et al. 2012) the Pearl River Delta (Lu et al. 2013; Ng et al. 2013), Hong Kong (Ng et al. 2013; Yau et al. 2012), Northern Germany (Diesch et al. 2013), Shanghai (Song 2014), the Arctic (Winther et al. 2014), Singapore (Rashidi and Koto 2014; Saputra et al. 2015), Australia (Goldsworthy and Goldsworthy 2015) and Tianjin (Chen et al. 2016).

The research works described before are limited to (very) small investigation areas, either carried out evaluations for the past or used significantly low resolutions of the ship positions. Different methodologies (e.g. EEOI) were used or the weather influence was only taken into account across the board. Thus, the work of the UCL Energy Institute (Energy Institute 2016) takes into account the influence of weather conditions in general with an increased fuel consumption of 15% for all seagoing ship types and 10% for coastal traffic. A more precise linkage of historical or current route and weather data, as planned in the project EmissionSEA, was not considered feasible due to the high level of detail of the data to be considered and the very high computing power required for application to the worldwide merchant fleet over a period of one year (International Maritime Organization

2019). In addition to Fraunhofer CML, which is developing the resistance model presented in this paper, Jakota Cruise Systems, Jakota Design Group, the Hochschule Wismar as well as the German Aerospace Center are participating in the project.

Despite existing approaches, which are briefly described above, currently, there exists no information platform that quantifies the global emissions of shipping and shows potential savings. All existing research work in the field of emission assessment have in common that they are either limited to small investigation areas, the evaluations were only carried out for the past, the resolution of ship positions were significantly lower or the influence of the weather was only considered on a general basis. The presented model is enhancing previous studies to a worldwide coverage, implying missing ship's characteristics as well as weather and environmental information.

3 Method

3.1 Data source

Data of the Automatic Identification System (AIS), which was introduced by the IMO to increase safety in shipping, provides the data basis for the following models. The data transferred by AIS transmitters for the exchange of nautically relevant information between different vessels and shore stations can be classified in static data, dynamic and voyage-related data. For details regarding the AIS, it is referred to the technical characteristics for an Automatic Identification System using time division multiple access in the VHF maritime mobile frequency band; Recommendation ITU-R M.1371-5 of the International Telecommunication Union (International Telecommunication Union 2014).

The following parameters are used for the resistance calculation:

- ShipID: In order to comply with data protection guidelines, each ship will be assigned an independent identification number (ID)
- ShipType: Integer in accordance with (International Telecommunication Union 2014)
- Length: The overall length of the vessel in meters
- Breadth: The breadth of the vessel in meters
- Draught: The maximum current draught in meters
- Latitude: latitude in 1/10,000 min (90°, north = positive (according to 2er-comple-ment), South = negative (according to 2er-complement))
- Longitude: longitude in 1/10,000 min (180°, east = positive (according to 2er-comple-ment), West = negative (according to 2er-complement))
- SOG: Speed over ground in 1/10 knots
- COG: Course over ground in 1/10 = (0–359°)
- TH: True Heading from 0 to 359°

In addition to ship movement data of the AIS, weather and environmental data is used for further analyses, such as the determination of the resistance of a ship, to estimate emissions:

- Wind speed [in m/s]
- Wind direction [in °]
- Primary wave direction [in °]
- Significant wave height [in m]

3.2 Resistance model

The development of a complex and innovative model to assess the resistance of the ship's hull is necessary for the reliable determination of emissions. The section described below comprises the development of a resistance model of the ship's hull based on the AIS, weather, environmental and static ship data described in Sect. 3.1.

Based on the position and motion information of the AIS, the temporal progression of the speed and the course over ground will be determined, followed by the speed and the course through water during a voyage, taking into account current environmental parameters. The influence of the wave and wind parameters leads to an increased resistance at a constant speed through water and thus to a higher drive power required to keep the speed constant. This allows the wave and wind influence to be represented by an increase in resistance. Often, however, no additional resistance is specified for a ship under certain environmental conditions, but a reduced speed with constant engine power is taken into account. In order to achieve a certain speed, the associated resistance or the required engine power must therefore be determined iteratively, taking into account the speed reduction.

3.2.1 Ship characteristics

The ship resistance on a voyage depends on different influencing variables. In particular, the characteristics of the ship are decisive. This means that speed, shape and size play an important role. The speed through water of the ship is a decisive factor in calculating the resistance. This is the speed of the ship relative to the water, i.e. changed by influences such as wind, current and waves. Since AIS data only indicates the speed over ground, i.e. relative to earth/GPS, this value is not sufficient for the calculation of the ship resistance. Therefore, the current given by weather data is included in the calculation and we get the speed with the charging by current. This is calculated as follows:

$$SOC_x = SOC \cdot \cos(\theta - \theta_c) \tag{2}$$

$$STW = SOG + SOC_x \tag{3}$$

With SOC being the current speed, the true heading of the ship θ, the direction of the current θ_c, the speed of the current relative to the movement of the ship SOC_x, the speed over ground SOG and the speed through water STW.

In the absence of comparative data, it is assumed here that the length overall LOA multiplied by a constant of 0.97 corresponds to the length of the waterline L_{WL}. Reynolds number Rn is essential for the determination of the ship's resistance. It describes the ratio of inertia forces to viscous forces and depends on the speed of the ship STW. The viscosity of the water υ is currently only determined by density and assumed for a water temperature of 17 °C.

$$Rn = \frac{STW \cdot L_{WL}}{\upsilon} \tag{4}$$

In addition to the Reynolds number, the Froude number, which describes the ratio of inertial force to gravity g, is used:

$$Fn = \frac{STW}{\sqrt{g \cdot L_{WL}}} \tag{5}$$

In order to determine the hydrodynamic properties of the ship in detail, the displaced mass is required. The draught T is important here, as the displacement is essentially dependent on it. The formula consists further of breadth B and Block Coefficient C_B.

$$V(t) = L_{WL} \cdot B \cdot T \cdot C_B \cdot \rho \tag{6}$$

With ρ representing the water density. One of the most important hull coefficients of a ship is the block coefficient C_B which has to be assessed examining by regression the number of containers TEU, gross tonnage GT, length of the water line L_{WL}, the breadth B and the current draught T.

As we lack the C_B from AIS data, the maximum displacement is calculated depending on the ship type and either the gross tonnage GT or the amount of twenty-foot-equivalent-unit TEU. Regression formulas adapted by Papanikolaou (Papanikolaou 2014) are used.

$$\Delta_{\text{passenger}} = 0.606 * GT + 77.875 \tag{7}$$

$$\Delta_{\text{container}} = 15.06 * TEU + 1832.6 \tag{8}$$

$$\Delta_{\text{tanker}} = 2.253 * GT + 5368.409 \tag{9}$$

$$\Delta_{\text{generalcargo}} = 2.253 * GT + 5368.409 \tag{10}$$

3.2.2 Additional resistances

To model the total resistance, additional resistances have to be determined. According to the ITTC 1957 method (Conference ITT 2002) the total resistance coefficient C_T comprises of frictional resistance C_F, incremental resistance C_A, air resistance C_{AA} and appendages resistance C_{App}. The latter will not be part of this work. The coefficient of frictional resistance is calculated according to ITTC57 friction line:

$$C_F = \frac{0.075}{(\lg Rn - 2)^2} \tag{11}$$

The additional resistance due to surface roughness is calculated because of fouling and depends on the ship size:

$$C_A = \frac{0.5 \cdot \log(STW) - 0.1 * \log(STW)^2}{10{,}000} \tag{12}$$

A former project (Kristensen and Lützen 2013) did already regression analyses in order to find similarities for emission of ships. From this the findings on incremental resistance C_A and air resistance C_{AA} are implemented in this work, as well as the corrections for the residual resistance C_R in regards to the hull form, bulbous bow shape and size, as well as a deviation of B/T for different ship types. For the residual resistance in calm water the Harvald approach (Harvald 1983) is selected and therefore the diagrams, which are available only in paper form, were digitalized and made more interactive and responsive.

3.2.3 Total resistance

Afterwards the total resistance of the ship can be calculated. In this case, the sum of the minutely/hourly resistance coefficients results in the total resistance coefficient for one voyage.

$$C_T = C_F + C_A + C_{AA} + C_R \tag{13}$$

The total resistance coefficient can be combined with the water density, the wetted area and the speed through water:

$$R = \frac{1}{2} C_T \cdot \rho \cdot S \cdot STW^2 \tag{14}$$

with S being dependent on the ship type.

3.2.4 Environmental additional resistances

For specifying the resistance, the environmental factors wind and wave are included and resistances for each component are calculated.

3.3 Engine model

For the final estimation of emissions, it is necessary to determine the required engine power based on the ship's resistance from Sect. 3.2. Using detailed ship information, in particular on the main propulsion plant and thus information regarding the normal power level of the propulsion plant are used. The location (ports, approaches, anchorages) as well as the weather conditions (e.g. heavy sea) are indicators whether additional auxiliary power units are running. Information on the efficiency of different propulsion constellations is collected and stored in a database in accordance with the ship type classification. The changing load can be determined by the changing ship resistance.

3.4 Emission model

Existing methods for determining CO_2 emissions in sea, road and air transport are considered as the basis for a model for calculating emissions in order to transfer innovative methods and indicator systems. Using the appropriate identified emission determination method, these can be determined for each voyage. Sea charts provided by the Federal Maritime and Hydrographic Agency (BSH) with SECAs (Sulphur Emission Control Areas) combined with information on the ship allow conclusions to be drawn about the fuel used in order to further improve the accuracy of the model. The consumption is calculated from the available engine curves using the engine load (*EL*) and the fuel under consideration of incomplete combustion at high load changes and the CO_2 emissions are determined in the observation interval. For the CO_2 emission an carbon emission factor (*CEF*) of 3.144 kg emitted/kg of fuel for residual fuel oil (International Maritime Organization 2009) is used. In further advance of the project *CEF* for different fuel oils will be used.

4 Results

Fig. 1 describes the voyage of a container vessel traveling from Rotterdam to Hamburg. It includes STW, which is the activity data input of the model, and a resistance curve, which is the output of the resistance model. The STW is for the first half of the voyage just above 15 kn to then drop strongly because off the pilot point Elbe I as well as the tidal dependency in the river Elbe. Passing the river Elbe, the resistance stays high instead of the speed being smaller.

Fig. 2 depicts the areas with high resistance and low resistance depending on a given threshold *c* given by the average and standard deviation of resistances. Here, too, it becomes clear that at higher speeds, which occur after the acceleration phase, there are greater resistances and thus presumably emissions than at the beginning and end of the voyages.

Based on the resistance results for each ship, the effective power and the CO_2 emissions can be estimated. For three different sample ships the calculated values can be seen in Fig. 3.

The error between the calculated data and the reported data according to MRV can be seen for the three sample vessel in Table 1. Static and dynamic AIS data served as a data basis. The temporal scope included two days in the year 2018. The average details from the MRV table are based on annually reports.

The comparison states the mean speed through water (*stw_mean*), fuel consumption per nautical mile (*foc/nm*), emissions per nautical mile (*emissions*), the average fuel oil consumption (*average foc/nm MRV*) and emissions per

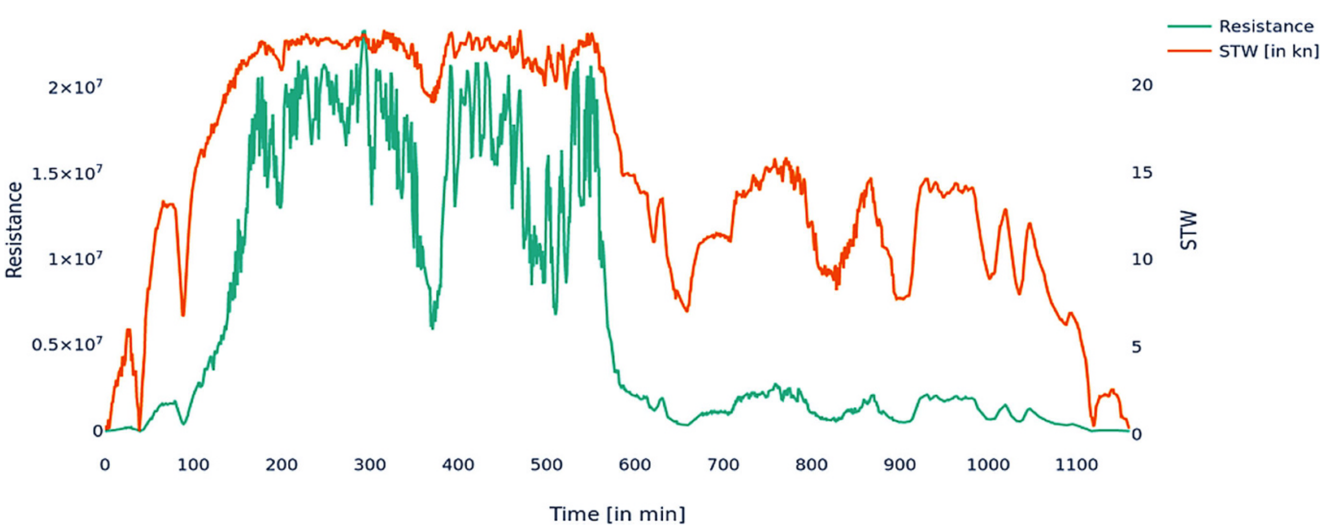

Fig. 1 Resistance and speed through water (STW) for a test voyage from Rotterdam to Hamburg

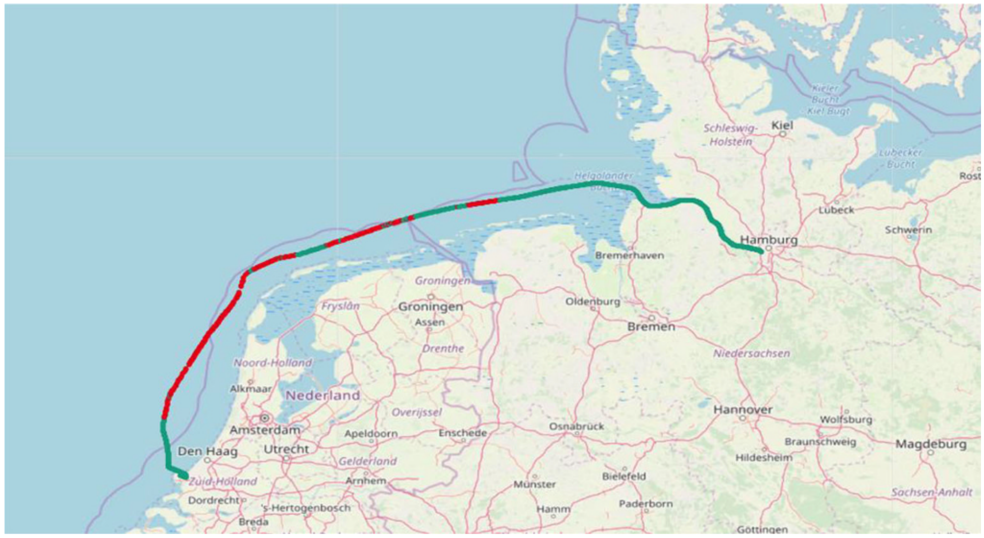

Fig. 2 Representation of resistance values in dependence of a threshold. Red dots represent a higher and green dots a lower value

nautical mile (*average emissions MRV)* based on MRV data from 2018 and the error for fuel oil consumption (*error foc*) and emissions (*error emissions*). The very limited time period in this evaluation compared to the averages sampled over one year is one reason, why the model calculations show a variation of error. Another influence are the low mean speeds, which are to be explained with extensive laytime periods of the ships during the observation period. It is assumed, that with ongoing project work and a broader data base, as well as real-time ship consumptions, the uncertainty can be drastically reduced.

5 Conclusion and outlook

This paper presented a method to estimate global emissions based on AIS and environmental data and presented first results of the resistance model. In a next step, the algorithm, which currently consists of determining the resistance through water as accurately as possible, is combined with machine data to determine global emissions. An initial analysis revealed areas of high speed and high resistance in particular, which will result in a large output of CO_2.

In addition to the emission determinations, an integrated approach of resistance and engine model will be used to determine optimized routes taking into account weather and environmental conditions as well as ships characteristics and route information. This model enables a target/actual comparison between the calculated optimized and actual performance, which also forms the basis for further fuel and emission reductions. Besides, the performance model will be used as an example to verify the results and to enable an estimation of the benefits. For the further analysis of the benefit it is suitable that the method allows ex-post analyses of past voyages using historical voyage data (AIS) and weather data instead of weather forecasts. It can be used to show how much a particular ship has performed in relation to others, or a comparative fleet, in terms of transport performance.

Apart from the further development of an emission and routing algorithm, predicted arrival times also improve the possibilities of emission reduction and extending the planning horizon of maritime stakeholders: the waiting times of ships at anchorage can be minimized, waiting times of ships at pilot points can be reduced, berths can be allocated more efficiently, waiting times for the hinterland transport can be shortened and fuel costs and emissions can be reduced using slow steaming.

The following assumption is made for an exemplary estimation of the broad impact: According to (Conference ITT 2002), approximately 50,000 international cargo ships are currently active with a total lifting capacity of 308.1 million tonnes. A cargo ship engaged in international voyages travels about 75,000 nautical miles (nm) per year. About 4% of the worldwide ships have a payload of approx. 12,000,000 tons. In addition, a container ship on international voyages requires about 0.0002 t of fuel per 60 nm per ton of payload at 20 kn and emits about 3 t of CO_2 per 1 t of heavy oil. This results in the following CO_2 emissions per year for 1000 ships:

$$1000\,\text{ships} \cdot 75{,}000\,\frac{\text{NM}}{\text{year}} \cdot 12{,}000{,}000 \cdot \frac{\text{t load capacity}}{\text{ships}} \cdot \frac{0.00002\,\text{t}}{60\,\text{NM}} \cdot 3\text{t}\,CO_2 = 4{,}500{,}000{,}000\,\frac{\text{t}\,CO_2}{\text{year}} \tag{15}$$

If the speed of these ships can be reduced by 1 kn (from 20 to 19 knots) by making well-founded forecasts and performance analyses at ¼ for the voyages of these ships and

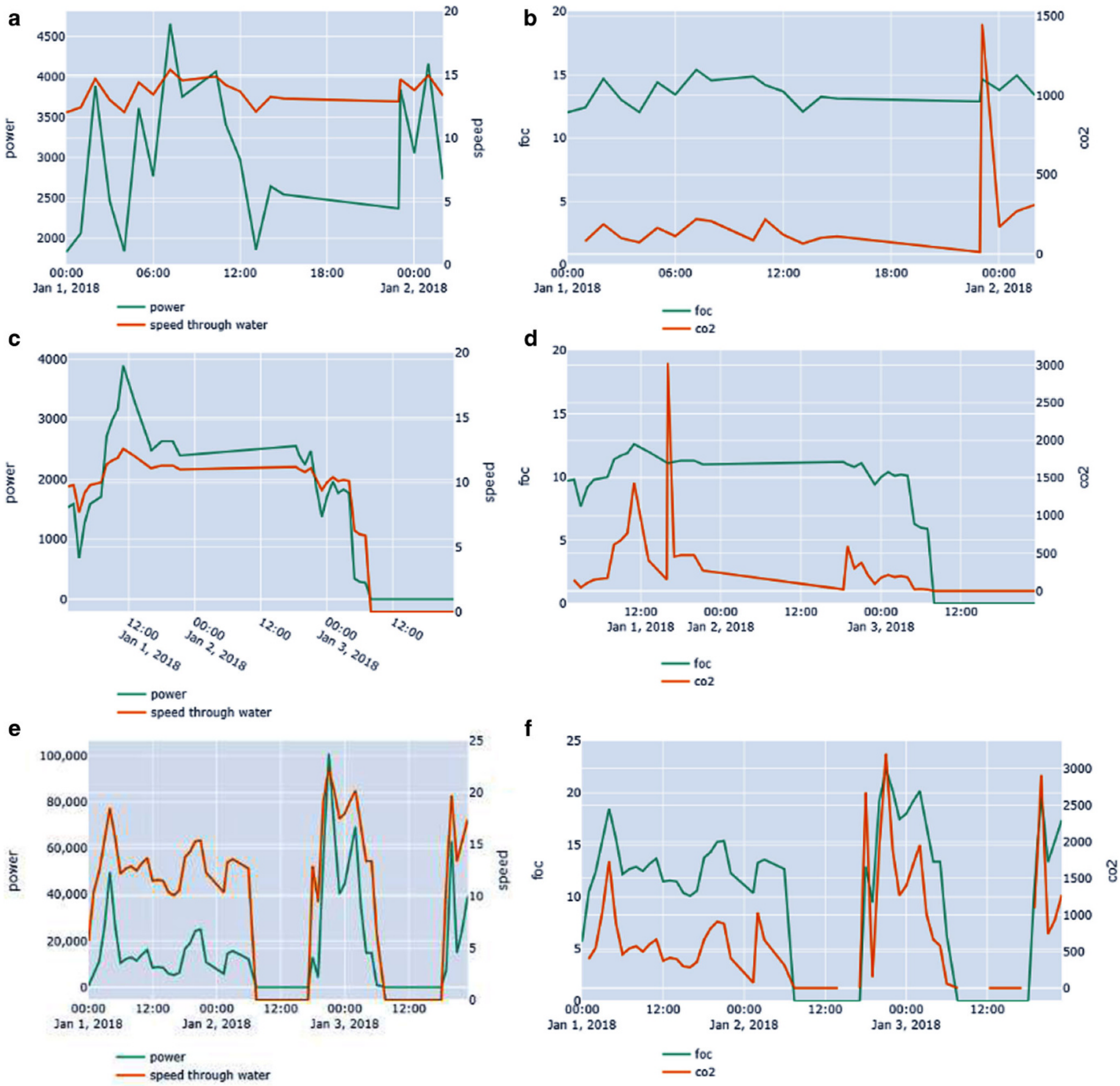

Fig. 3 Sample vessels relation speed through water to power and fuel oil consumption to emissions. **a**, **b** Vessel 1 (Container vessel, L = 118 m, B = 18 m, D = 6.7 m); **c**, **d** Vessel 2 (General Cargo, L = 145 m, B = 24 m, D = 7.3 m); **e**, **f** Vessel 3 (Passenger, L = 272 m, B = 32 m, D = 8.4 m)

Table 1 Comparison of three sample ships during a period of two days in 2018

Index	stw_mean	foc/nm	Emissions	Average foc/nm (MRV)	Average Emissions (MRV)	Error foc	Error Emissions
1	13.65	68.39	214.07	58.41	184.50	0.17	0.16
2	6.88	84.17	263.45	67.92	215.37	0.24	0.22
3	9.52	219.19	686.06	384.23	1202.15	0.43	0.43

better estimations of times of arrivals, this will result in a saving of 0.00003 t per 60 nm per ton load. Assuming that ships use a corresponding module for optimization, the CO_2 savings is at

$$1000\,\text{ships} \cdot 75{,}000\,\frac{\text{NM}}{\text{year}} \cdot 12{,}000{,}000 \cdot \frac{\text{t load capacity}}{\text{ships}} \cdot \frac{0.00003\,\text{t}}{60\,\text{NM}} \cdot 3\text{t}\,CO_2 = 337{,}500{,}000 \frac{\text{t}\,CO_2}{\text{year}} \tag{16}$$

Future project work will include an extended temporal and spatial database, which will refine the results. It is expected that the error can be minimized with more evaluation data.

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Conflict of interest T. Hensel, C. Ugé and C. Jahn declare that they have no competing interests.

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