Estimation of worldwide ship emissions using AIS signals

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Abstract: *The reduction of emissions is one of the main common goals all over the globe. Shipping, as the main impact source of global emissions, plays a vital role and can perceptibly contribute to decarbonisation. The objective of EmissionSEA is to develop a methodology for the quantitative determination of CO_2 emissions from shipping. With the help of the data of the Automatic Identification System (AIS), motion information is set in relation to ship size, speed as well as meteorological and oceanographic environmental conditions. More than 300.000.000 daily AIS data records from hundreds of own and thousands of cooperative AIS base stations as well as detailed ship data including information on the main propulsion plant are conflated and allows a detailed target/actual comparison of ship emissions worldwide.*

ENC 2020 Topic:
Aviation & Marine Navigation
Challenges in safety and security of information, communication and navigation in relation to current emerging threats

1. Introduction

In order to reduce the major green house gas (GHG), the European Commission released a regulation which forces shipowner to report their ship's emissions by establishing a CO_2 emission Monitoring, Reporting and Verification (MRV) System (EU/2015/757). Since 01.01.2018, the obligation to report CO_2 emissions has been binding for ships traveling to and from Europe as well as for intra-European traffic[1]. In this context, the first emission report have been submitted to the European Union (EU) by 30 April 2019 and were released to the public by end of June 2019 [2]. For entire voyages made in the reporting period, from the port of departure (e.g. Hong Kong) via European ports (e.g. Hamburg) to the port of destination (e.g. New York), the amount of CO_2 emitted must be reported by every ship. Therefore, the International Maritime Organisation (IMO) has decided that emissions have to be determined on the basis of the amount of fuel consumed. Whereas the consumption on every ship is determined by tank soundings or through flow meters and recorded in the oil log in order to calculate the CO_2 emissions. On the other side the data-based application in the project EmissionSEA is an alternative method to the existing one and uses data from the ship-based Automatic Identification System (AIS). This project aims to synergise different maritime businesses and research institutions in order to assess ships emissions worldwide. Based on basic details about AIS and movement data a description of the resistance model is given in his paper and first results are presented.

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2020 European Navigation Conference (ENC) | 978-3-944976-27-3/20/$31.00 ©2020 10.23919/ENC48637.2020.9317402

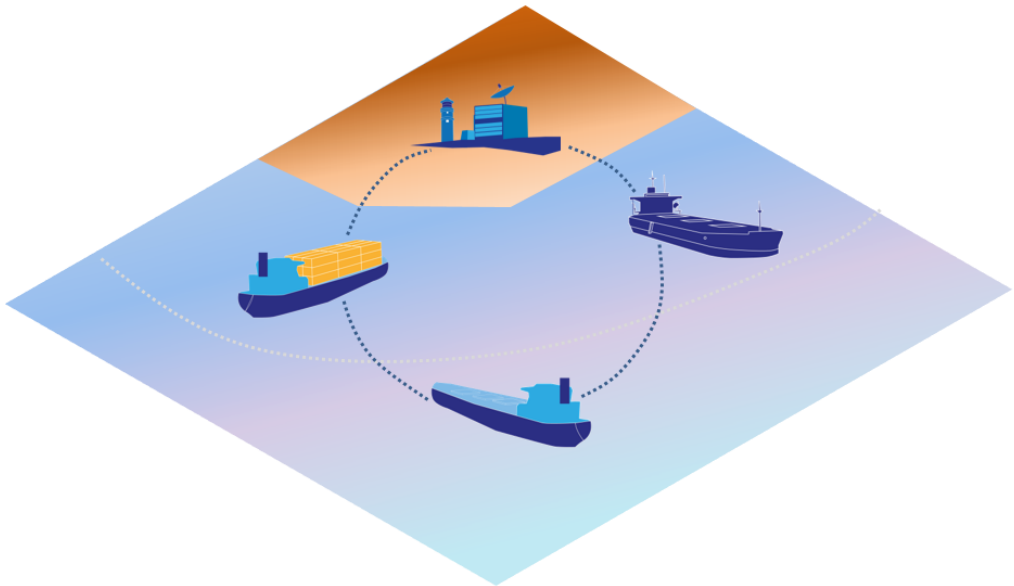

Figure 1: Sending and Receiving AIS data between ships and shore stations

2. AIS Data

The Automatic Identification System was introduced as navigation- and anti-collision-system on ships based on Very-High-Frequency radio waves (VHF). AIS has been mandatory for all commercial ships since 2000 and is designed to track, monitor and send vessel positions, as well as other static and dynamic ship's data. AIS data is received by shore stations all over the world directly and via satellite and then collected by a maritime intelligence provider, who processes and prepares the data in order to establish a semi-public vessel data collection [3]. This data collection is used for model-training. The developed application can therefore serve without additional technical installations on ships (e.g. gas flow measurements) as a shore based verification source. Additionally the emissions report collected by the EU can serve as mutual verification.

The collection, analysis and provision of that AIS data is a central aspect in this project. There are approximately 230 billion raw motion records available from 2016 and 2017. The data set contains static and dynamic data, which include but is not limited to: timestamp, latitude, longitude, ship's name, Maritime Mobile Service Identity (MMSI), International Maritime Organization (IMO) number, callsign, length over all, width, draught, AIS type code, heading, course over ground and speed over ground [4]. To handle this raw data, a first step was to pseudonymize by assigning a newly created object ID to every ship. There are 3.6 million reports per hour that are afterwards compiled into trips between ports.

The AIS data sets are set in relation to ship size and type, speed as well as meteorological and oceanographic environmental conditions. In preparation for the development of the resistance model, the ships are clustered into type classes due to the large variety of ship types in order

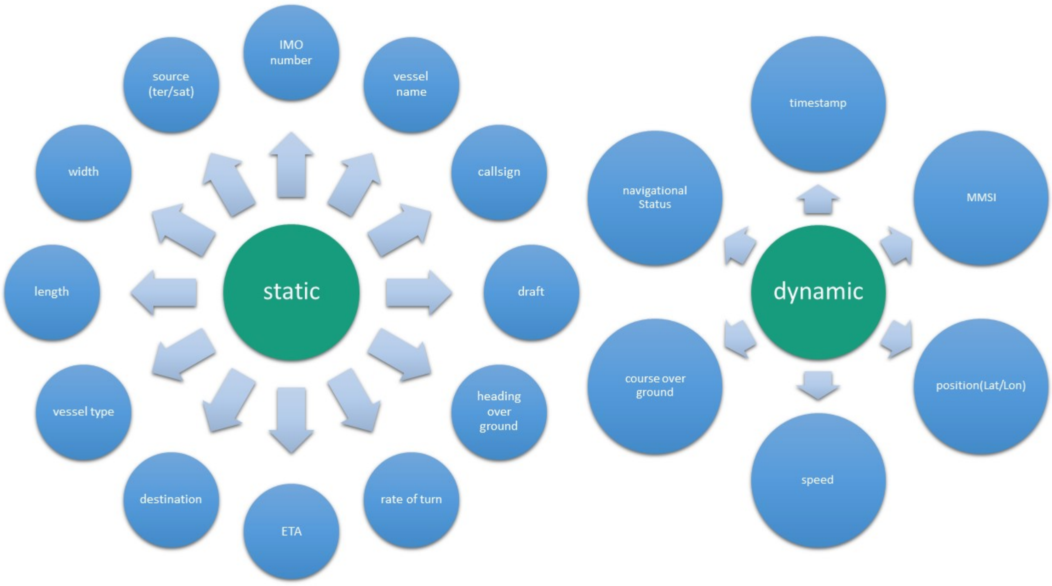

Figure 2: Static and dynamic AIS data

to determine the basic hydro-static relationships between similar ships. With the help of the existing AIS and other ship data, similarity structures in the data set are discovered using cluster analyses, then clusters are defined and the ships assigned to these clusters. The first step is to select the variables that are relevant for the type classification. These include mainly hull-describing variables like length, breadth, voyage-draft and speed. In a second step of the cluster analysis, the deviations of the variable values are determined in order to finally form corresponding - previously unknown - groups using the cluster method of machine learning. Both the partitioning k-Means algorithm or the density-based spatial clustering of applications with noise (DBSCAN) are used to counteract the fact that the number of clusters is unknown at the beginning.

3. Models

3.1. Existing Emission Models

Existing methods for determining CO_2 emissions in sea transport can be separated into three main approaches. The first idea is to use sensor data from the exhaust gas system on each ship. This seems to be the most accurate approach due to the data availability for each vessel, but lacks of a cost-efficient solution, as devices have to be installed on every ship. Another variant is the measurement of fuel consumption from on board installed flow meters or bunker reports and derivation of emissions from these. The third approach is an energy-based concept, where emissions per voyage are calculated from fuel consumption and a fuel conversion factor for different fuel types. For the first time AIS data was used to estimate ship emissions in the “STEAM” models by Jalkanen et.al. [5] [6] [7], which examined the North Sea and Baltic Sea.

Later, for other spatially limited areas studies for the development of emissions models were carried out, but either only past periods were observed or very low resolutions were achieved. In order to implement environmental influences several times a general percentage surcharge was made, without considering ship's exact response characteristics or local weather phenomenon [8]. A more precise or (near) real-time approach was considered to not feasible due to high computing power requirements [9]. A more precise calculation of emissions, as well as the integration of spatially relevant environmental influences is the aim of project EmissionSEA.

3.2. Resistance Model

The resistance model is developed on the data actually available. Therefore it is divided into three parts: (1) Ship Characteristics (2) Resistance Components (3) Environmental Effects. From these basic AIS datasets estimates are made in regard to hydrostatic variables. That means values for hull form, air resistance and wetted surface can be derived from ship type information. 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 the water during a voyage, taking into account the current and weather parameters. To specify the ship's (cluster) characteristics, general particulars needed for the resistance calculation, have to be estimated if not known from AIS data.

3.2. 1. Ship Characteristics

It is assumed that the length over all L_{OA} multiplied by a constant of 0.97 corresponds to the length of waterline L_{WL}, which remains constant for each draft in this calculation. The Reynolds number Rn is essential for determining the ship's resistance. It describes the ratio of inertia to viscous forces and depends on the speed of the ship V. The viscosity of the water v is currently determined by density and assumed for a water temperature of 17 ° C.

$$Rn = \frac{(V * L_{WL})}{v} \tag{1}$$

Furthermore, the Froude number Fn is an essential parameter in the calculation of ship resistance. It describes the ratio of inertial force to gravity. Its most important components are the ship speed and the length of the waterline.

$$Fn = \frac{V}{\sqrt{g * L}} = \frac{STW}{\sqrt{9.81 * L_{WL}}} \tag{2}$$

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

$$D = L_{WL} * B * T * C_B * \rho \tag{3}$$

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. The regression formulas from Papanikolaou [10] are used.

For passenger ships :

$$D_{passenger} = 0.606 * GT + 77.875 \tag{4}$$

For containerships:

$$D_{container} = 15.06 * TEU + 1832.6 \tag{5}$$

For tankers and general cargo ships:

$$D_{tanker} = 2.253 * GT - 5368.409 \tag{6}$$

The maximum displacement gives information about which C_B the ship can have fully loaded, in design condition.

$$C_B = \frac{D}{L_{WL} * B * T} \tag{7}$$

Each ship has an individual slenderness ratio that describes how the displacement and length of the waterline relate to each other. There are slender (naval) and full (tanker) ships.

$$SR = \frac{L_{WL}}{D^{\frac{1}{3}}} \tag{8}$$

3.2. 2. Resistance components

Without the results of towing tank tests, wind tunnel tests and exact modeling of each ships hydrodynamic behavior, a close estimation must be made. The existing AIS data sets give a broad basis for a calculation, but do not exactly provide all necessary data for a smooth resistance calculation, therefore the next step is to use the data by feature engineering (ship's characteristics) where variables are derived from existing ones to develop a resistance model.

Resistance models nowadays do not take all resistance components at one time into account. That means, either calm water situations are calculated or single coefficients for selected artificially arranged environmental conditions are investigated. The general resistance model for calm water consists of the total resistance coefficient C_T, the seawater density ρ, the wetted surface S and the squared velocity through the water V, which in this case is the speed through the water STW.

$$R_T = \frac{1}{2} * C_T * \rho * S * V^2 \tag{9}$$

From this, according to the ITTC 1957 method [11] 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.

$$C_T = C_F + C_A + C_{AA} \tag{10}$$

The frictional resistance coefficient is then defined by

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

A former approach [12] did already regression analyses in order to find similarities for emission of ships. From this the findings on incremental resistance and air resistance are implemented in this work, as well as the corrections for the hull form, bulbous bow shape and size, and the deviation of B/T for different ship types. For the resistance in calm water the Harvald approach [13] is selected and therefore the Harvald diagrams, which are available only in paper form, were digitized and made more interactive and responsive.

The influence of the wave and wind parameters lead to an increased resistance at a constant speed through the 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 machine line must therefore be determined iteratively, taking into account the speed reduction.

3.2. 3. Environmental Effects

With the help of worldwide historical AIS and environmental data, data of individual selected sample ships including their loading condition from specific ship clusters, the local weather influence on the ship resistance is analyzed and a correlation is derived and implemented. After training the developed resistance model including the parameters current, wind and wave, but

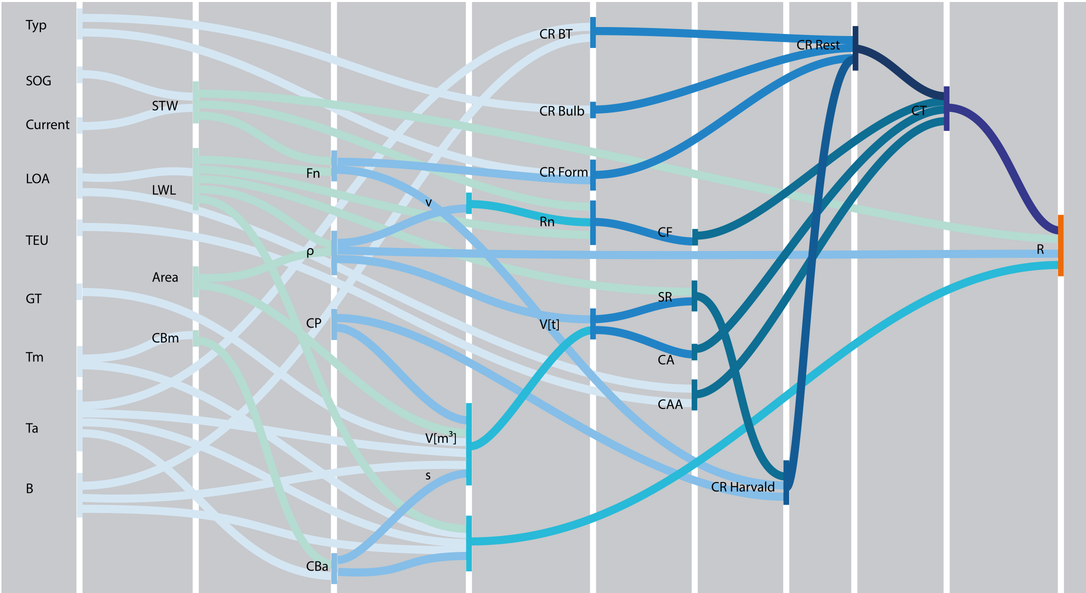

Figure 3: Initial process to receive calm water resistance from AIS variables

also seawater temperature, salinity, water density and water depth (squat and bank effect) as well as the ship type class (hull shape), the course of resistance during a voyage can be calculated. This serves as an input variable for the hereafter developed engine and emission model as well as for the performance evaluation. For a random voyage of a ship between Rotterdam and Hamburg one can see here the differences in the calculation of resistance with and without the environmental influences.

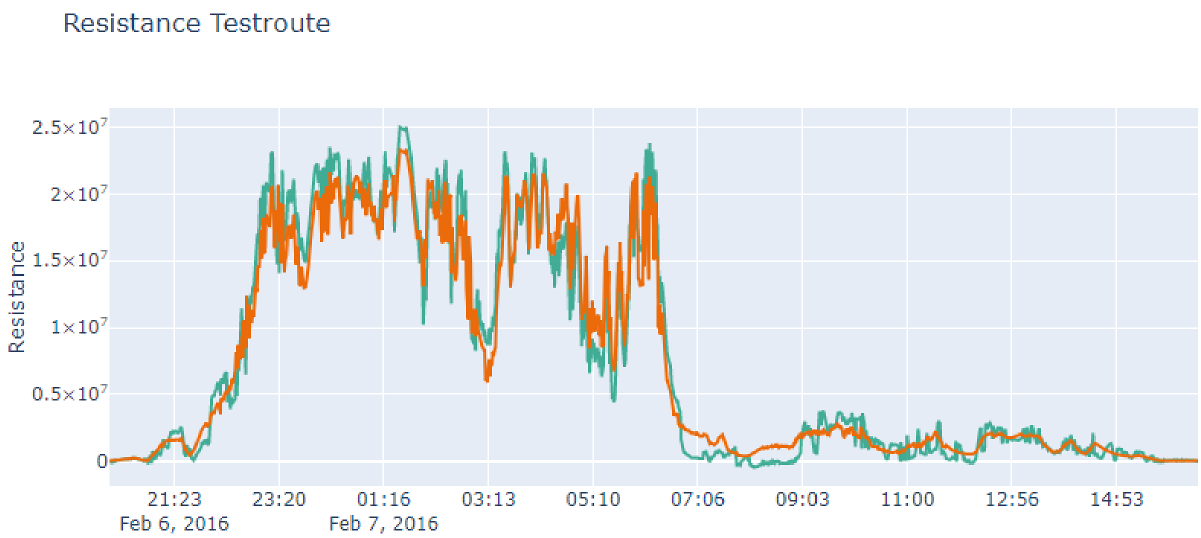

Figure 4: Resistance for a 376-m Containership on route between Rotterdam and Hamburg with (green) and without (orange) environmental effects

On a map the standard deviation from mean resistance on this test voyage can be seen and an overview of all sections of calm water resistance is presented.

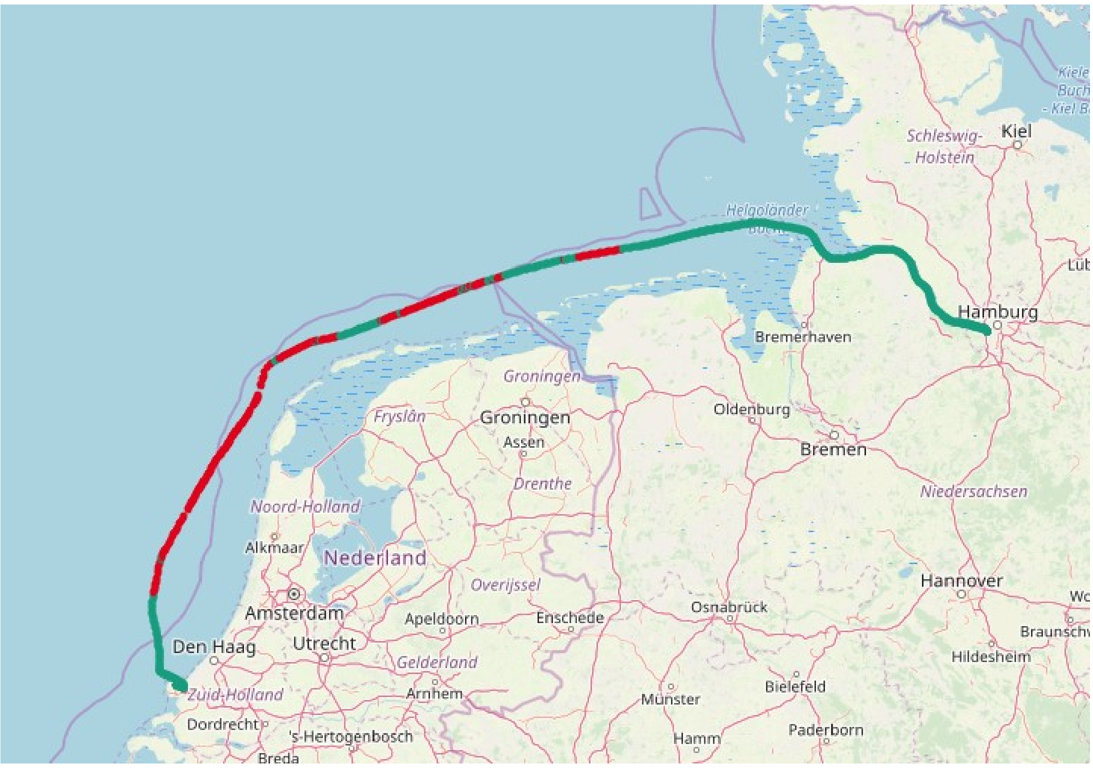

Figure 5: Trip between Rotterdam and Hamburg

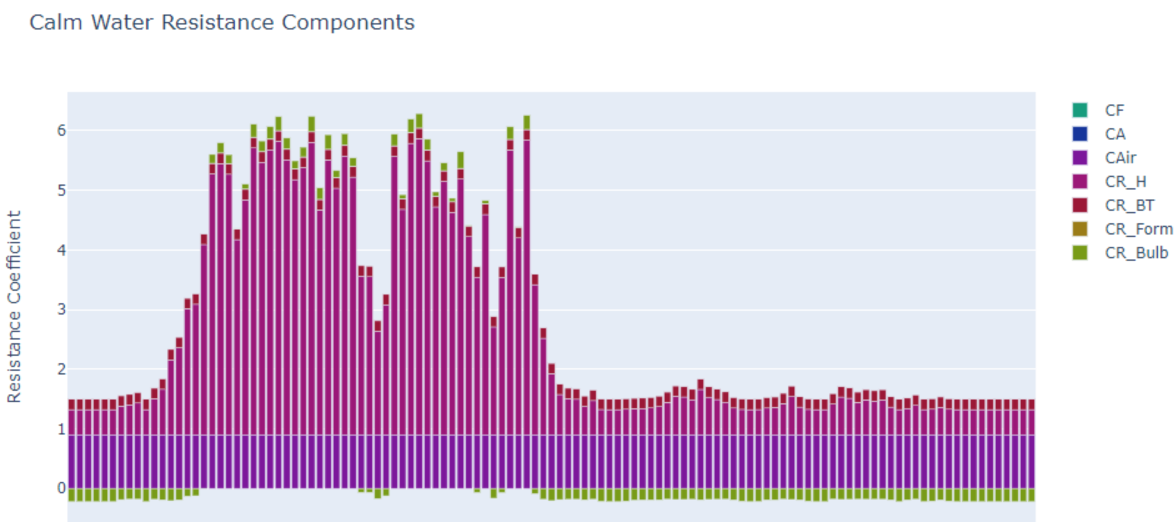

Figure 6: Partitions of calm water resistance calculation

3.3. Engine Model

Using an engine model the fuel consumption is extrapolated and the CO_2 emissions are determined. With the application to be developed, a possibility is to be created to comply with the aforementioned obligation to report CO_2 emissions from ships sailing in European waters. With the additional implementation of an optimization algorithm, improvement and reduction potentials can be identified by comparing historical and optimal movement data and emissions. By using the identified potentials by means of optimised ship voyages and arrival time forecasts, the application can make a contribution to emission reduction and avoidance. The evaluation of ship voyages in real time also enables shipping companies to analyse and monitor performance and to compare their own fleet with other ships. By quantifying, evaluating and potentially reducing emissions, EmissionSEA contributes to the realisation of sustainable mobility systems in the maritime sector. Especially for coastal regions, the prognostic model to be developed should quantify the CO_2 emissions in a detailed, dynamic and comprehensible way. This will make it possible to better assess the effects and adjustments in the use of coastal regions by maritime transport, in order to achieve a more sustainable and digital future for maritime transport.

Due to the well-known main engine of many tens of thousands of ships, one main engine or one cluster can be assigned for each of the before created ship clusters. 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 the project database in accordance with the ship type classification. The changing load can be determined by the changing ship resistance.

4. Outlook

After an initial assessment of resistance outputs, route sections of very high resistance are detected, which will result in large CO_2 emission. The next stage after developing the resistance model and the internal verification is to simultaneously develop the engine model and carrying out a verification procedure. The aim is to analyse the accuracy of the resistance and engine model. For this purpose, the results will be compared with existing historical data from recent years in order to determine possible deviations and improve the prediction quality. Known consumption and/or emissions are then set in relation to calculated emissions under different weather conditions or trade lanes.

In addition recommendations concerning optimised routes will be made, so that ship's personnel as well as operators ashore can easily monitor and adjust ship's routes to reduce resistance, fuel consumption and consequently CO_2 emissions. Furthermore it help to asses a ship's and fleet's performance by comparing their historical tracks. Not only the en-route emission reduction is part of the project, but it additionally focuses on the connection to hinterland transport by improving an arrival time algorithm, which enables shore-sided personnel and stakeholders to reduce waiting and idling times for all transport sectors.

5. Acknowledgements

The EmissionSEA project leading to these results receives funding from the Federal Ministry of Transport and Digital Infrastructure under support code 19F2062C.

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