AN AIS-BASED FRAMEWORK FOR REAL TIME MONITORING OF VESSELS EFFICIENCY

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Abstract - **Maritime transport is one of the most energy efficient and one of the lowest CO_2 emitting modes of transport. Nonetheless, the industry's carbon footprint is significant. Stakeholders recognize the need for continuing efforts to curb CO_2 emissions. Such efforts require the ability to measure individual vessels' energy efficiency. To this end, several energy efficiency metrics/indices have been developed for tracking real time CO_2 emissions by marine vessels.**

We propose a new methodology to calculate and monitor individual vessel's energy efficiency and carbon emissions in real time through the Real-Time Energy Efficiency Operating Index (RT-EEOI). We demonstrate the practicality of the proposed methodology by presenting a software architecture implementing it. Specifically, by combining a vessel database with live data from the Automated Identification System (AIS), we calculate the RT-EEOI index. The system has been deployed to monitor traffic in the Southwest part of the port and strait of Singapore. We propose an example of implementation of the proposed framework in the Singapore waters to show how it can be deployed in the scenario of real time efficiency tracking.

Keywords - **energy efficiency operating index, real time monitoring, emissions, Singapore Strait.**

I. INTRODUCTION

Sea shipping accounts for 2.2% of the overall global CO_2 emissions [2]. Although a relatively energy efficient mode of transport, fuel still represents most of the operating costs for ship owners and operators. Besides, while shipping is not covered in the agenda of Intergovernmental Panel on Climate Change, the Internal Maritime Organization (IMO) is in charge of pushing for a standard metric for measuring vessel energy efficiency globally as part of its operational measures to curb CO_2 emissions. During the 59th Marine Environment Protection Committee (MEPC) session in July 2009, IMO proposed the Energy Efficiency Operating Index (EEOI) as part of Ship Energy Efficiency Management Plan (SEEMP) to improve operational energy efficiency of vessels [3]. The purpose of this study is to examine the feasibility of monitoring CO_2 emissions on a real time basis using a suitable measure.

Across different industries, there have been various proposals as to what constitutes the definition of an appropriate energy efficiency index. The consensus across different modes of transport is that such a metric index should capture CO_2 emissions with respect to transport work. While there has been extensive research on modeling the CO_2 emissions of marine vessels, this paper focuses on proposing a framework enabling the estimation of real time energy efficiency so as to perform online tracking/monitoring of marine vessels.

The current most appropriate technology to be applied for real-time monitoring of CO_2 emissions is the Automatic Identification System (AIS) [1,9].

The traditional terrestrial AIS system has been used for enhancing navigational security for a long time. A typical AIS message reports information like ship's identity by Maritime Mobile Service Identity (MMSI), type, position, course, speed, draught and timestamp of the message.

To ensure navigational safety and avoid collisions, the Safety of Life at Sea (SOLAS) Convention mandated that all vessels over 300 Gross Tonnage (GT) on international voyage must be fitted a Class A type AIS transceiver. Cargo ships of 500 GT and above engaged in domestic voyage and all passenger ships shall be provided with AIS also [9]. Due to the mandatory reporting of AIS messages, it is possible to explore the feasibility of tracking ship's energy efficiency real time in terms of Energy Efficiency Operating Index (EEOI) [2,3].

There have been studies on EEOI for various types of cargo vessels, most of which are retrospective in nature. For example, the International Council on Clean Transportation white paper submitted by Haifeng Wang and Nic Lutsey in [10], develops the ship stock turnover model to convert ship activity data captured by past AIS messages to the operational efficiency measure of EEOI. Their work represents one of the first studies in the area of satellite-AIS data, an emerging technology to complement the traditional on-shore AIS stations. While shore-based AIS stations can only transmit and receive messages within 50 nautical miles ([nm]) into the open ocean, satellite AIS, if pervasively deployed, could theoretically cover vast expansion of ocean areas. However, problems of poor signal detection in congested seaways as well as limited number of satellites hinder the spreading of such a technology.

In this paper, we ground on the shore-based AIS and develop an infrastructure for the real-time monitoring of the vessels efficiency evaluated through a real time version of the EEOI index, which we refer to as RT-EEOI.

Section II briefly presents the EEOI and justifies the choice of the authors to focus on this index and, consequently, its real-time version, the RT-EEOI providing the sufficient background to the present work. In section III, the novel software architecture for RT-EEOI tracking/monitoring is presented, which gathers real time data from several sources comprising the ASSIST system for AIS data collection [6]. Both the architecture and the calculation methodology were tested over the real time AIS data coming from the West Region of the Singapore Strait. Section IV provides an example of application of the proposed architecture. Section V summarizes the key observations, while section VI concludes the paper.

II. MARINE VESSELS EFFICIENCY MONITORING: A REVIEW AND CONTRIBUTION

The IMO Green House Gas Studies report represents one of the key references in the area of emissions in maritime traffic [2]. Motivated by these studies, several contributions focusing on the energy efficiency have been carried out on global as well as regional scale in the maritime research community. Jalkanen, et al. in [4] proposed a study on exhaust emissions in the Baltic Sea Area, while the University College London (UCL) extended the analysis to the global energy efficiency [9]. Both contributions provide a glimpse of how to use the Automatic Identification System (AIS) as data input to assess the energy efficiency of marine vessels retrospectively.

One of the main issues raised in these analyses is the challenge implied by the design of a comprehensive index to model the efficiency of vessels, which has lately received a remarkable attention.

The International Maritime Organization initially proposed the adoption of the Energy Efficiency Operating Index (EEOI) [3]. In particular, the EEOI is defined as the ratio of mass of CO_2 emitted per unit of transport work, which is calculated as the product of the cargo mass and the sailed distance, namely [3]:

$$EEOI = \frac{\sum_j FC_j \cdot c_{F_j}}{m_{\text{cargo}} \cdot D} \qquad (1)$$

Here, j is the fuel type; FC_j is the mass of consumed fuel of type j [tons]; c_{F_j} is the CO_2 mass conversion factor for fuel j; m_{cargo} is the cargo carried [tons], and D is the distance in nautical miles ([nm]) sailed under loading condition characterized by m_{cargo}.

A real-time extension of the index has been proposed. In particular, the EEOI has been translated into a time-varying measure which is referred to as RT-EEOI. The basic idea behind this indicator is to replace the distance D at the denominator by the instantaneous speed at ground of the vessel as well as the fuel consumption in the numerator by the instantaneous fuel consumption rate. The indicator results as follows:

$$RT - EEOI = \frac{\sum_j R_{FC_j} \cdot c_{F_j}}{m_{\text{cargo}} \cdot v} \qquad (2)$$

Here, v refers to the speed of the vessel, it is measured in [knots] and it results from the derivation of (1) with respect to time. R_{FC_j} is the rate of consumption of fuel type j, which follows a cubic relationship with vessel speed v, according to the brake fuel consumption model [4]. Also this term is obtained by computing the derivate of (1) with respect to time.

The index EEOI (and RT-EEOI as a consequence) has received some resistance due to the presence of sensitive data required to compute it such as the mass of cargo carried which is commercially too sensitive to be revealed.

As a result, several parties have set out to advocate alternative proposals to the EEOI.

Nevertheless, no agreement has been reached on the matter and the RT-EEOI still results the better index if the criteria of (C1) ease of adoption, (C2) feasibility of real-time monitoring, (C3) sensitivity to uncontrollable factors such as weather conditions, (C4) comparability across different modes of transport, and (C5) significance as energy efficiency indicator (with respect to the IMO and industry indications). Therefore, RT-EEOI is taken as a reference in this work and an architecture enabling the real time computation of such index relying on the Automated Identification System (AIS) technology is proposed in the next section.

III. REAL TIME VESSEL EFFICIENCY MONITORING INFRASTRUCTURE

A. Notation and Definitions

The main notations and definitions adopted in this paper are reported in Table I, where the main considered variables are defined together with the source from which the information is obtained. In fact, data can be derived: (1) from AIS due to the integration with ASSIST [6]. (2) from the Web due to the development of ad-hoc crawling scripts, and (3) derived within the framework through the proposed computation procedures.

TABLE I
MAIN DEFINITIONS ANS NOTATIONS IN VESSEL-DB

Name	Symbol	Unit	Source
Maritime Mobile Service Identity Number	MMSI	[-]	AIS, Web
Draught	δ	[m]	AIS
Nominal Draught	δ^N	[m]	Web
Real Time Draught	δ^{RT}	[m]	AIS
Ton Per Centimeter	TPC	[ton/cm]	Web
Deadweight	υ	[ton]	Web
Gross Tonnage	γ	[-]	Web
Net Tonnage	γ^N	[-]	Web

Name	Symbol	Unit	Source
Nominal Cargo Mass	μ^N	[ton]	Framework
Real Time Cargo Mass	μ^{RT}	[ton]	Framework

We will use the definitions below.

Maritime Mobile Service Identity Number: nine digit numbers which are sent in digital form over a radio frequency channel in order to uniquely identify a ship or coast radio stations;

Draught: distance between the vessel waterline and the lowest point of the vessels, usually the keel. Larger weight corresponds to larger draught;

Nominal Draught: maximum static draught, is the maximum draught of a loaded ship when it is not moving;

Real Time Draught: draught reported in the real time AIS data;

Ton per Centimeter: weight that must be loaded or discharged in order to change the ship's draught by one centimeter;

Deadweight: difference between the number of tons of water a vessel displaces "light" and the number of tons it displaces when submerged to the load line;

Gross Tonnage: unit-less index related to ship's overall internal volume, divided by 100 cubic feet. The formula for its calculation is as follows: $\gamma = V \cdot \left(0.02 \cdot \log_{10} V + 0.2\right)$, where V is the ship volume in m^3;

Net Tonnage: gross tonnage minus the space occupied by accommodations of crew, by machinery for navigation, by the engine room and fuel. In this paper, a vessel's net tonnage represents the space available for cargo stowage;

Nominal Cargo Mass: mass of the cargo carried when the draught reaches the maximum static draught;

Real Time Cargo Mass: mass of the cargo carried when $\delta = \delta^{RT}$.

B. Architecture

ASSIST is a vessel tracking system that processes real time data streams of AIS messages received from the shore-based AIS station near National University of Singapore (School of Computing) and displays the vessel position around the South West coast of Singapore [6]. In this work, we use the ASSIST API to connect ASSIST to a newly developed module which crawls (RT-PYCRAWLER) real time position and static AIS messages to be stored in the database VESSEL-DB (the module is developed in Python language, whereas the database is managed using PostgreSQL relational database). In addition, online sources can access and feed VESSEL-DB. Specifically, for each vessel in VESSEL-DB, data such as design speed, engine information, ton per centimeter (TPC, see definition in section III.*A*), dimension, draught information, gross tonnage, net tonnage, deadweight, vessel type and density of cargo carried can be added to enrich the data base. Some of these data are also used to derive the cargo mass approximation and, eventually, the EEOI.

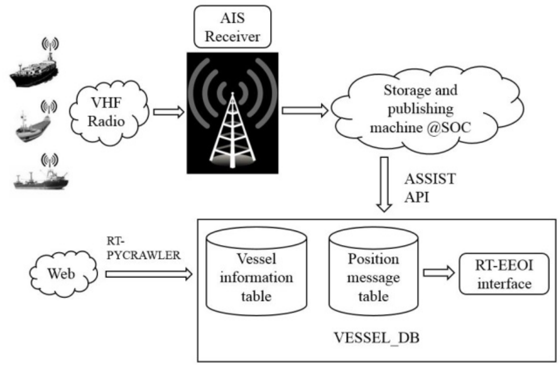

Fig. 1: Proposed Architecture

The architecture for data acquisition and modelling are illustrated in Fig. 1 and in TABLE II, respectively. Due to the ability of ASSIST to receive and stream AIS messages in real time, it is possible to store and process vessel data in real time, thereby enabling instantaneous modelling and tracking of energy efficiency in terms of RT-EEOI. This is realized by real-time computation of EEOI, saved in the **real_time_monitoring** table. To do this, every time a positional AIS message of a specific vessel (i.e., a specific pair *(mmsi, vessel_type)*) is received by ASSIST, the fields in the third column of TABLE II are saved as rows in the **position_msg** table, incase the pair *(mmsi, vessel_type)* is not key in the **vessel_info** table (TABLE II, first column) then a row is added also to this last table which contains the static information characterizing the vessel. Also the PY-CRAWLER is invoked in order to gather those data that are not in the AIS messages (refer to TABLE I). Afterwards, the joint information from the **vessel_info** table and that saved in the **position_msg** table defines the **real_time_monitoring** table with the tracking information.

TABLE II
RT-EEOI FRAMEWORK, MAIN INFORMATION

vessel_info	**position_msg**	**real_time_monitoring**
mmsi*	***mmsi****	***mmsi****
Vessel_type*	***Vessel_type****	***Vessel_type****
TPC	***Timestamp****	***Timestamp****
Cargo_density	Fuel_type	RT-EEOI
Engine_power	Current_speed	
Nominal_draft	Current_draft	
Net_tonnage		

Three tables are constructed for VESSEL_DB: **ship_info, position_msg**, and **real_time_monitoring**. In particular, the **position_msg** table stores positional AIS messages transmitted by AIS receivers and obtained in real time from ASSIST API while the **vessel_info** table contains entries of vessel information uniquely identified by *(mmsi, vessel_type)*.

It can be argued that an entry in the ship information table has an optional one-to-many relationship with respect to positional messages. More specifically, one vessel entry can have multiple positional messages broadcasted and received. It is also possible for a vessel entry to have no positional message received during the specified time period. However, one positional message must be related to one and only one vessel identifiable by the mmsi.

C. RT-EEOI Computation Procedure

The issue related to equation (2) defining the RT-EEOI index resides in the difficulty of estimating the cargo mass. In this section, we present a novel way to overcome this problem under the objective to further foster the applicability of the index. We briefly recall the definition of the index:

$$RT - EEOI = \frac{\sum_j R_{FC_j} \cdot c_{F_j}}{m_{\text{cargo}} \cdot v}$$

Here, the denominator is the mass of the carried cargo [ton] multiplied by the instantaneous speed of the vessel v, which is monitored through the AIS messages. If the speed over ground value reported in AIS message is zero, we assume the vessel is not sailing and, therefore, no RT-EEOI is computed. As already stated, the cargo mass is not reported in the AIS data, and, more in general, this information is not readily available. Nevertheless, it is fundamental to design a procedure which can take as input the AIS data and estimate the cargo mass in order to make the application of RT-EEOI feasible, i.e., we need to estimate the cargo mass from the data we have about the vessel being monitored (in TABLE II).

The basic idea we propose is to use the TPC and the nominal cargo mass μ^N to calculate the real time cargo mass μ^{RT}, according to the following:

$$\Delta\delta = \delta^{RT} - \delta^N \text{ , } m_{\text{cargo}} = \mu^{RT} = \Delta\delta \cdot TPC + \mu^N \qquad (3)$$

Here, we assume that vessels are well balanced and not carrying ballast water such that when the real time draught deviates from nominal draught, it is due to the different amount of cargo carried. By multiplying $\Delta\delta$ with the TPC value of the vessel, we arrive at the deviation of μ^{RT} with μ^N.

The nominal draught δ^N is retrieved in VESSEL-DB, while δ^{RT} comes from AIS sources (TABLE I). However, the nominal cargo mass μ^N is not readily available in neither of the aforementioned sources, hence it needs to be approximated. The nominal cargo mass can be approximated by multiplying the net tonnage of the vessel γ^N with density of the cargo ρ^c, as follows:

$$\mu^N = \gamma^N \cdot c_\gamma \cdot \rho^c \text{ .}$$

Where $c_\gamma = 2.83168$ is the conversion factor to transform the net tonnage into [m^3]. The approximation stands in the fact that ρ^c is assumed unique for an entire vessel and derived based on the information on the vessel type contained in the AIS messages (TABLE II).

The estimation of the current cargo mass, as part of the computation procedure of *RT-EEOI* can be illustrated by the flowchart in Fig. 2.

Algorithm 1: Generic Procedure for Real Time Monitoring of RT-EEOI	
1	Data Collection: Connect to the web source through PY-crawler and to AIS through ASSIST
2	Monitoring State =1
3	**While** Monitoring State ==1
4	**If** _msgType == $1 \cup 2 \cup 3 \cup 18 \cup 19$
5	Record `Position_msg`
6	Use the `Navigation_status` and apply Li [2013]
7	Return R_{FC_j} and the emission rate $R_{FC_j} \cdot C_{F_j}$
8	Compute $\Delta\delta \leftarrow \delta^{RT} - \delta^N; \gamma^N \leftarrow \gamma^N \cdot c_\gamma;$ $\mu^N \leftarrow \gamma^N \cdot \rho^c; m_{cargo} \leftarrow \mu^N + TPC \cdot \Delta\delta$,
9	Derive $RT - EEOI = \frac{R_{FC_j} \cdot C_{F_j}}{v \cdot m_{cargo}}$
10	**end**
11	**end**

Fig. 2: RT-EEOI Computation Procedure

IV. ARCHITECTURE APPLICATION

In this section, we propose an example of application of the proposed infrastructure to the tracking and of the efficiency of a tanker. For tankers, we use the net tonnage as the volume of the cargo held. This maximum volume for cargo stowage, multiplied by the density of the cargo being carried, gives the nominal cargo mass. For cargo density, a list of the adopted densities for each type of tanker is shown in Table III.

TABLE III
EXAMPLE DESCRIPTION

Tanker	Cargo carried	Cargo Density
Asphalt/Bitumen	Asphalt	1.04 ton/m^3
Crude Oil tanker	Crude oil	0.81 ton/m^3
LPG tanker	Liquefied Petroleum Gasoline	0.58 ton/m^3
Chemical/Oil Products	Petrochemical products	0.81 ton/m^3
Bunkering tanker	Heavy fuel oil	0.93 ton/m^3

A flowchart illustration on the use of infrastructure explained is represented in Fig. 3. Experiments on real data were also performed, but they are not reported for space reasons. In the example, a message with key (525015249,Asphalt/Bitumen) is retrieved by ASSIST. Since this is a new pair, the **vessel_info** table in VESSEL-DB on a local machine is updated with all the relevant *static* information, PY-CRAWLER is activated and information as the TPC retrieved (7.6 in this case). Dynamic information such as *navigation status*, *speed over ground*, *current draught*, *time_stamp* together with

(525015249,Asphalt/Bitumen), are used to update the **position_msg** table in the local VESSEL-DB.

Subsequently, a SQL join operation is performed on the two tables on the condition of equal (*MMSI,vessel_type*) key. The joined table is then used to calculate and update real time EEOI saved the **real_time_monitoring** table. In the next section we discuss the main future directions and challenges with respect to the proposed framework. To do this the procedure in [5] is used to derive the c_{F_j} as well as R_{FC_j} in (1), resulting in 161.17844[kgCO$_2$/hour]. The m_{cargo} is derived with (3) and the RT-EEOI is computed from (2) and saved in **real_time_monitoring**.

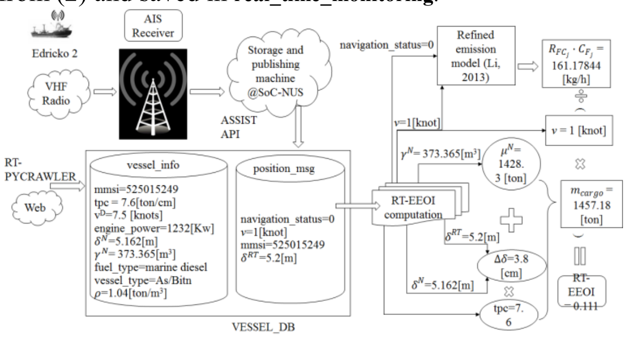

Fig. 3: RT-EEOI Calculation Flow Chart

V. DISCUSSION

We propose a first step towards a framework for the real time monitoring of vessels efficiency. RT-EEOI represents individual vessel's carbon emissions in real time. The Cloud-based software architecture implementing it combines a vessel database with live data from the AIS as collected and managed by the ASSIST system. While actual cargo mass is not publicly available for commercial confidence reasons, we show that it is possible to estimate cargo mass from the vessel draft that is communicated by AIS. With vessel-specific information such as TPC data made available, it is possible to apply the full methodology discussed in this paper to virtually all vessels transmitting over AIS. The approach and architecture is no longer limited by the short range (~20 nautical miles) of VHF-based AIS. Satellite-AIS creates the opportunity for global monitoring, historical recording and analytics of vessels' activities. Commercial companies are launching satellites, mostly micro- and nano-satellites, with AIS payload. Wider geographical coverage and improved latency for Satellite AIS tracking coupled with data streaming systems similar to ASSIST and RT-EEOI-based real-time interfaces, energy efficiency and CO_2 emission of marine vessels can be monitored globally and in real time.

VI. CONCLUSION

We propose the Real-Time Energy Efficiency Operating Index (RT-EEOI) to calculate individual vessel's energy efficiency and carbon emissions in real time. We present a software architecture combining a vessel database with live AIS data, to calculate and monitor the RT-EEOI index. The system monitors traffic in the Southwest part of the port and strait of Singapore. An example on real time data extracted in the Singapore strait show the application of the approach. The advent of satellite-AIS technology and the Cloud-based design of the software architecture make it possible for our approach to scale. At a global scale, however, the 4V characteristics of Big Data, namely volume (several hundreds of thousands of vessels emitting every 3 minutes to 2 seconds), velocity (satellite-AIS, internet and collection systems latency), variety (more vessel types being equipped) and veracity (accuracy and truthfulness of transmitted data), need further consideration.

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