Energy 145 (2018) 246–260

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A framework for real-time monitoring of energy efficiency of marine vessels

Hongtao Chi [a, *], Giulia Pedrielli [b], Szu Hui Ng [a], Thomas Kister [c], Stéphane Bressan [c]

[a] Department of Industrial Systems Engineering, National University of Singapore, 1 Engineering Drive 2, 117576, Singapore
[b] School of Computing Informatics & Decision Systems Engineering, Arizona State University, 699 S Mill Ave, Tempe, 85281, AZ, USA
[c] School of Computing, National University of Singapore, 13 Computing Drive, 117417, Singapore

A R T I C L E I N F O

Article history:
Available online 28 December 2017

Keywords:
Energy efficiency
Shipping
Real-time monitoring
Carbon dioxide emissions
Singapore Strait

A B S T R A C T

Sea shipping is one of the most widespread transport modes. Therefore, the improvement of energy efficiency and further curbing of Carbon Dioxide emissions by marine vessels is important both economically and environmentally. During the sixty ninth Marine Environment Protection Committee session in April 2016, the International Maritime Organization approved mandatory requirements for ships to report their fuel consumption, which is the first of the three-phase approach to derive a standardized measure for energy efficiency tracking of marine vessels. Under the International Maritime Organization Data Collection System, emphasis has been placed on verification of the collected fuel consumption data so that vessels' energy efficiency could be benchmarked and improved. To optimize the operational efficiency of marine vessels, this paper proposes the Real-Time Energy Efficiency Operating Index and the framework to implement it. The proposed scheme can be used to verify fuel consumption and carbon dioxide emission data reported by individual ships. It also provides an approach to automatically and remotely estimate the transport work in real time. The proposed architecture mainly relies on the Automated Identification System and a constructed vessel database. A proof of concept prototype is deployed that monitors the energy efficiency of vessels along the Singapore Strait.

1. Introduction and motivation

Although sea-transportation is the most fuel-efficient way of shipping goods, fuel consumption constitutes the major component in the operating costs of shipping line companies and for the maritime industry in general [1]. With increased transport demand, there is an increasing need to curb fuel consumption and Green House Gas (GHG) emission [2]. In this regard, the IMO has recently raised concerns on the need to further improve the energy efficiency of sea going vessels. To promote and sustain this need, several measures have been implemented targeting the design of new vessels. One prominent measure is the regulation of the Energy Efficiency Design Index (EEDI) for new ships [3]. The Ship Energy Efficiency Management Plan (SEEMP) is another important regulation for all ships to manage the ship's efficiency performance over time. In it, it also recommends the voluntary use of the Energy Efficiency Operating Index as a monitoring tool. With this need to reduce GHG emissions, several studies have been done on the additional technical and operational measures that can further improve the design and operational efficiency [4].

1.1. Relevant literature

The EEDI has had great impact in the definition of regulations and, as a result, it has boosted a significant amount of literature on the evaluation of such index for several categories of vessels. [5] analyzed the potential powering options for LNG carriers under the EEDI requirements, and [6] studied the effect of correction factors in the EEDI on the emissions of the general cargo vessels. Moreover [7], highlights the importance of accurate data in order to improve the effectiveness of the EEDI computation, and it proposes enhancements in the modeling of consumption due to the motion of vessels in real navigation conditions. The EEDI however is a static design based index that does not capture the operational efficiency performance over time. In this regard [8], analyzed the operational efficiency for inland river ships in order to understand the impact of the dynamic navigation environment (e.g., calm waters versus real

* Corresponding author.
E-mail address: chihongtao@u.nus.edu (H. Chi).

https://doi.org/10.1016/j.energy.2017.12.088
0360-5442/

List of abbreviations and acronyms

AER	Annual Efficiency Ratio
AIS	Automatic Identification System
ASSIST	Access Controlled Ship Identification Streams
CO_2	Carbon Dioxide
DCS	Data Collection System
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operating Index
EHS	Energy per Hour in Service
FORS	Fuel Oil Reduction Strategy
GHG	Green House Gas
GPS	Global Positioning System
GT	Gross Tonnage
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
ISPI	Individual Ship Performance Indicator
MARPOL	The International Convention for the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MMSI	Maritime Mobile Service Identity
MPA	Maritime Port Authority of Singapore
MRV	Measure Reduce Verify scheme
SEEMP	Ship Energy Efficiency Management Plan
STEAM	Ship Traffic Emission Assessment Model
SOLAS	Safety of Life At Sea convention
RT-EEOI	Real-Time Energy Efficiency Operating Index
VHF	Very High Frequency

time navigation conditions). Similarly [9], developed a model for the prediction of the fuel consumption and emission for large ships, and [10] proposed an innovative framework to evaluate ship air emissions based on Life Cycle Assessment. In addition to the evaluation of the design and operating efficiency indices, the literature has also focused on the effect of policies and operational measures on lowering emissions. [11] studies how the speed, size and slenderness in design reduces emissions and costs. [12] provides a comprehensive review of technical and operational measures and their emission reduction potentials, and [13] discusses the implementation of several technical measures on emissions. [14] studies the impact of route and port selection on reducing CO_2 emissions and [15] analyzes the impact of the use of LNG as an alternative fuel for propulsion.

In the current literature on operating emissions and efficiency, most are focused on retrospective yearly emission/efficiency measures, ignoring the real time behavior and the spatio-temporal dynamics of the emissions. Despite the indisputable importance of providing aggregate benchmark measures for periodic estimation of emissions, real-time monitoring is becoming increasingly relevant to ports as well as global authorities such as IMO and it can represent the basis to develop policies for efficiency optimization and emission minimization. In Ref. [16], a real time optimization of ship energy efficiency is proposed. However, the approach focuses on the optimization of the operations of a single vessel rather than global measures for fleet efficiency and benchmark for different vessels.

In the direction of obtaining estimates on fleets of vessels, especially in real-time, the availability of data becomes a key issue. The Automated Identification System (AIS) represents a promising source in this direction. In relation to AIS data, Gutierrez et al. [17] uses this source to provide a comprehensive analysis and comparison between various bottom-up approaches to estimate emission inventory and fuel consumption of ships. Smith et al. in Ref. [18] propose the application of AIS data to measure vessel energy efficiency employing both top-down and bottom-up approaches. In fact, while both contributions show the viability of employing AIS data for analysis of emissions retrospectively, and succeed in identifying clear patterns in the behavior of fleets and ship types with respect to CO_2 emission and energy efficiency, they do not allow for real time energy efficiency computation, thus hindering the possibility for the controlling bodies (either port or global organizations) to interact with the vessels and mandate improvement measures like speed adjustment [19].

1.2. Challenges to achieve real-time energy efficiency estimation

In fact, to enable automatic real-time tracking, additional methodologies and architectures are required.

A challenge for the implementation of such methodologies is the availability of data and an architecture to process and analyze them automatically [17]. In this direction, regulatory bodies like the European Union are actively promoting regulations for the shipping sector to report and verify vessel emissions and energy efficiency. However, the proposed Measure-Reduce-Verify (MRV) scheme is still based on data to be reported on a per-voyage or annual basis [20]. This hinders the potential to track and control vessel emissions in real time. Concerning data reporting and availability, during the 69th Marine Environment Protection Committee (MEPC) session in April 2016, IMO has approved mandatory requirements for ships to record and report their fuel consumption, which is intended to be the first step of the three-phase approach to derive a mandatory standard for energy efficiency tracking of marine vessels. Per this scheme, ships of 5000 gross tonnage and above will be required to collect consumption data for each type of fuel they use, as well as other specified data including proxies of the transport work [21]. These data can be collected retrospectively from shipping logs, but is tedious to compile and consolidate. In addition, to derive energy efficiency measures, data concerning the cargo mass being transported should be collected as well, but this is sensitive information that shipping companies do not want to publicly report. How to estimate this information without voluntary reporting by individual vessels is part of the challenge faced.

1.3. Contribution

In this paper, a novel software architecture which can gather real-time data from several sources including AIS is designed. And a new methodology is proposed for the fast computation of real-time energy efficiency of vessels which does not require any manually input information and can be done remotely on shore side. The resulting framework represents a first step towards a robust real-time system for vessels efficiency tracking. This is in line with IMO's agenda to enforce the Data Collection System (DCS) requirements in 2018 for benchmarking energy efficiency of marine vessels [21], and the framework proposed can enable independent verification of data submitted through DCS. In this contribution, the use of the framework is illustrated, while highlighting potential issues and limitations characterizing this first proposal.

The remainder of the paper is structured as follows: section 2 summarizes the main literature and state of the art concerning operational energy efficiency index and vessel information tracking. Section 3 presents our framework comprising of the developed software architecture and the proposed procedure to estimate the vessel real-time energy efficiency from AIS data. The proposed estimation procedures are also validated (refer to Appendix B). Section 4 provides a proof of concept aimed at showing how to implement the proposed infrastructure and verifying the obtained real-time index with benchmark calculated in Ref. [18]. The main considerations concerning the application of the framework are discussed in section 2, while section 5 concludes the paper.

2. Marine vessels energy efficiency monitoring: a review and contribution

The third IMO GHG report [22] represents one of the key references in maritime traffic emissions today. Motivated by such studies, several contributions within the maritime research community have focused on the energy efficiency evaluation at the global and regional scale. As mentioned in the introduction, the major problems encountered for the establishment of an effective and standardized indicator for energy efficiency, are the availability of data to compute the proposed metric, and technologies to gather and analyze the required data. As recognized in the Third IMO GHG report [22], three main categories of energy efficiency can be distinguished as: (1) Technical Efficiency, (2) Operational Efficiency, and (3) Nominal Efficiency (referred to as *normalized* efficiency in Ref. [6] which differs from (2) by using default values for capacity utilization).

2.1. Operational efficiency measurement

In this paper, the focus is on the operational efficiency, and more specifically, on the real-time indicator for this metric. A general definition of operational energy efficiency is the ratio between the actual CO_2 emissions and the actual transport work done, given by Equation (1) where C represents the CO_2 emission and S represents the transport work:

$$OE = \frac{C}{S} \tag{1}$$

The index is measured in $\left[\frac{g_{CO_2}}{ton \cdot nmi}\right]$. One of the more comprehensive index, proposed by IMO, is the Energy Efficiency Operating Index (EEOI) [18], defined as the ratio of mass of CO_2 emitted per unit of transport work, calculated as cargo mass multiplied by the sailed distance, given by Equation (2), where, j is the fuel type; FC_j is the mass [tons] of consumed fuel of type j; C_{F_j} is the CO_2 mass conversion factor for fuel j; m_{cargo} is the cargo carried (measured in [tons] or [TEU]) and D is the distance travelled in nautical miles ([nm]):

$$EEOI = \frac{C}{S} = \frac{\sum_j FC_j \cdot C_{F_j}}{m_{cargo} \cdot D} \tag{2}$$

Apart from EEOI, different indices for the evaluation of the operational efficiency of vessels have been proposed to address the highlighted issues of curbing CO_2 emissions for marine shipping. A comparison among various proposed energy efficiency indicators is included in Appendix A, and they mainly differ in the proxies used for the measurement of transport work. For example, the Annual Efficiency Ratio (AER) uses the deadweight, a proxy for total cargo capacity multiplied by the distance travelled [23], the Individual Ship Performance Indicator (ISPI) uses the distance travelled, and Energy per Hour in Service (EHS) uses the time at sea [24]. In this paper, EEOI is used, which most closely reflects the recommended energy efficiency indicator by International Energy Agency (IEA) [25] by tracking the actual transport work done. In particular, this indicator will be extended to illustrate the real-time monitoring framework for operational energy efficiency of vessels.

From equation (2), it is apparent how the estimation of the numerator and denominator are both critical tasks given the amount of required data to compute the four terms and difficulty in retrieving them through automated reporting [18]. Below, the main state of the art on the measurement of the components in (2) is presented.

2.1.1. Carbon dioxide emission computation

The difficulty of estimating vessels' CO_2 emission lies in estimating the fuel consumption FC_j, where j denotes the type of fuel being consumed. This is not a simple task as the instantaneous fuel consumption can be affected by several different input conditions, such as speed, engine type, engine power, hull structure, wave direction, wind intensity and type of fuel used etc. Such values are ship-specific and subject to environmental conditions. There are various methods proposed for predicting vessels' fuel consumptions [17]. This paper will focus on the Ship Traffic Emission Assessment Model (STEAM) [26]. STEAM assumes a constant fuel consumption rate with respect to the output power of the engine, and multiplies this rate with the estimated engine power. In his comparison of various emission models, Gutierrez [17] concludes that models like STEAM are the most realistic in estimating fuel consumption and CO_2 emission of vessel engines.

While STEAM utilizes the propeller law to arrive at the instantaneous fuel consumption rate, it is not particularly robust when the ship is at low speed maneuvering, mooring and anchoring. On the other hand, the Activity-based model categorizes ship's voyage into different statuses and it estimates fuel consumption using different load factors at each navigational status [27]. In the real-time setting of this paper, a refined fuel consumption model is presented which combines both STEAM and the Activity-based model to estimate the instantaneous fuel consumption rate of vessels under different statuses. With knowledge of the type of fuel used by the vessel engines, the real-time CO_2 emission rate can be computed by applying the carbon content factor C_{F_j} of the specific fuel type.

2.1.2. Transport work computation

Smith et al. in Ref. [18] presented one of the main approaches for the estimation of the *transport work* (denominator in (2)). In particular, m_{cargo} is derived, for each operating condition (e.g., loaded, ballast, in port, at anchor), as shown by Equation (3):

$$m_{cargo} = Dwt \cdot L\ [ton] \tag{3}$$

While the distance is:

$$D = d \cdot V \cdot 24\ [nmi]$$

where Dwt, L, d, V, refer to the deadweight (refer to Table 1 for the definition), the loading condition (a number between 0 and 1, where 1 refers to the fully loaded and 0 to the empty state), the days at sea and the average speed, respectively. Equation (3) is proposed as a yearly average in Ref. [18] to be adopted for aggregate studies. Moreover, the authors of [18] assumes that the loading condition is proportional to the ratio between the average vessel draft (information available from the AIS source) and the vessel deadweight. However, such a proportionality approach might not reflect the

Table 1
Main definitions and notations for data in VESSEL-DB.

Name	Symbol	Unit	Definition	Data source
Maritime Mobile Service Identity Number	MMSI	–	Nine-digit number which is sent in digital form over a radio frequency channel in order to uniquely identify a ship or a coastal radio station.	AIS, Web
Draft	δ	[m]	Distance between the vessel's waterline and the lowest point of the vessel, usually the keel. A larger deadweight corresponds to a larger value of δ.	AIS
Nominal Draft	δ^N	[m]	Nominal draft, or the Maximum static draft, is the maximum draft of a loaded ship when it is not moving.	Web
Real-Time Draft	δ^{RT}	[m]	Draft reported in dynamic AIS messages.	AIS
Ton Per Centimeter	TPC	[ton/cm]	Weight that must be loaded or discharged to change the ship's draft by 1 cm.	Web
Deadweight	Dwt	[ton]	Difference between the tons of water a vessel displaces "light" and the number of tons it displaces when submerged to the load line. It is the sum of weights of cargo, fuel, fresh water, ballast water, provisions, passengers and crew, if any.	AIS, Web
Gross Tonnage	γ	–	Unit-less index related to the ship's overall internal volume, divided by 100 cubic feet. The formula for its calculation is as follows: $\gamma = V \times (0.02 \times \log_{10}(V) + 0.2)$, where V is the ship's volume in m^3.	AIS, Web
Net Tonnage	γ^N	–	Gross tonnage minus the space occupied by accommodations of crew, by machinery, for navigation, by the engine room and fuel. In this report, a vessel's net tonnage expresses the space available for cargo stowage.	Web
Nominal Cargo Mass	μ^N	[ton]	Mass of the cargo carried when the draft reaches the maximum static draft.	Derived
Real-Time Cargo Mass	μ^{RT}	[ton]	Mass of the cargo carried in real time, when $\delta = \delta^{RT}$.	Derived

relationship between the change in draft and the change in load of a vessel (due to the density of the cargo). Furthermore, the loading factor used in the study is an average over the yearly activity of the vessel. All these hinders the ability to estimate transport work done by vessels in real time.

In this paper, a different approach is proposed for estimating the load of the vessel, explicitly accounting for the capacity and density of the cargo, and the data available to arrive at the real-time computation of transport work done.

2.2. Available technologies for vessel data monitoring

To prove the applicability of any of the metrics for energy efficiency monitoring, the technologies that can be harnessed towards this goal must be evaluated. In this regard, AIS technology is the most developed technology in the maritime environment and it has substantially enhanced navigation safety since its adoption [28]. It is based on the Very High Frequency (VHF) radio signal and it has been made mandatory by the IMO's Safety of Life at Sea (SOLAS) convention. To ensure navigational safety and avoid collisions, the SOLAS Convention mandated that all vessels over 300 Gross tonnage (GT) on international voyage must be fitted a "Class A" type AIS transceiver. In addition, cargo ships of 500 GT and above engaged in domestic voyage and all passenger ships must also be fitted with AIS transceivers [28].

The messages are broadcast on two VHF channels, AIS1 and AIS2, respectively 161.975 MHz and 162.025 MHz. The transponders transmit messages on only one channel at any given time. Fig. 1 provides details about the contents of a message sent in a slot. For example, an AIS message must report the following information: the ship's identity by its Maritime Mobile Service Identity (MMSI) number, ship type, position coordinates, course, speed over ground, draft and timestamp of the message. The detailed format of the data reported by AIS can be found in Ref. [29].

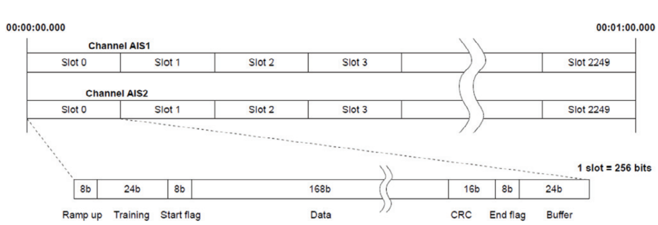

Fig. 1. AIS frames and Slots.

Due to the mandatory reporting and short update interval of AIS messages, it is possible to explore the feasibility of tracking ship's real-time energy efficiency in terms of RT-EEOI. There have been retrospective studies on the EEOI for various types of cargo vessels using historical AIS data. For example, the International Council on Clean Transportation white paper submitted by Wang. et al. [30], develops the ship stock turnover model to convert ship activity data captured by past AIS messages to the operational efficiency measure of EEOI. This also represented one of the first studies to analyze satellite-AIS data, an emerging technology to complement the traditional shore-based terrestrial AIS stations. While terrestrial AIS stations can only transmit and receive messages within 50 nm into the open ocean, satellite AIS, if pervasively deployed, could theoretically cover vast expanses of ocean areas. However, one issue characterizing traditional as well as satellite AIS technology is the unobserved time periods. In the third GHG study, it is reported that the average percentage of in-service ships observed by AIS is 83%. However, only 71% of the time a ship reports AIS data [22]. In this study, this is not a significant issue as the focus is on the real-time computation of energy efficiency, instead of retrospective analysis that needs to cover the whole period with estimation algorithms for vessel activities of unobserved time period.

With the mandatory reporting of AIS messages for vessel, vessel-tracking systems such as ASSIST [31] have been developed and are able to process data from AIS stations in real time. ASSIST monitors maritime traffic around the South West coast of Singapore from the shore-based AIS stations, located near Kent Ridge, Singapore [31]. In this paper, the real-time data of the ASSIST system, integrated with other static data sources, will be leveraged to track operational energy efficiency of marine vessels.

3. Real-time vessel efficiency monitoring framework

To facilitate real-time tracking, this paper proposes a real-time counterpart for the EEOI index, which can be referred to as RT-EEOI. This indicator will enable the monitoring of the energy efficiency when the input data are instantaneously received as dynamic AIS messages. The idea behind this indicator is to replace the distance D at the denominator in (2) with the instantaneous speed over ground of the vessel and the fuel consumption in the numerator with the instantaneous fuel consumption rate. The indicator is given by Equation (4):

$$RT - EEOI = \frac{\sum_j R_{FC_j} \times C_{F_j}}{m_{cargo} \times v} \tag{4}$$

As highlighted in section 2.1, this paper proposes innovative ways to facilitate the measurement of (4) by overcoming the challenges identified in the state of the art methodologies.

Section 3.1 gives the main notation and definitions used in the discussion, followed by the outline of the proposed architecture in section 3.2, while section 3.3 will elaborate on the procedure for the computation of the index in (4).

3.1. Notation and definitions

The main notations and definitions adopted in this paper are reported in Table 1. The main variables adopted in this work are defined together with the data source (if any) from which the information can be obtained.

3.2. Architecture

The real-time framework adopts two different input modules to compute the RT-EEOI. Fig. 2 gives an overview of the whole system, which consists of (a) a real-time vessel information tracking system using AIS and (b) a database to store vessel data. The architecture should be designed in such a way that when a dynamic AIS message is received by (a), the static information of that specific vessel can be queried from (b). With both the dynamic and static data sources, the vessel's energy efficiency can be derived in real time. To illustrate how this real-time framework can be implemented, the development of the prototype is described in detail below. For the dynamic vessel tracking data source (a), the framework adopts the ASSIST system, which processes the stream of real-time AIS messages received by an AIS station. ASSIST provides a web interface for easy visualization of vessels' AIS data on a map as well as a REST API that provides vessels' navigation data (via the Stream broadcaster), as shown in *Vessel_navigational_information* in Table 2. Concerning source (b), a vessel database is developed to store static information that is useful to characterize a given vessel. The static data fields are illustrated in the *Vessel_characteristics* table in Table 2. The framework uses third-party web resources as well as some fields of the AIS messages to populate the database, and these data sources are periodically updated if the database entry is older than a given threshold age.

In general, data stored from sources (a) and (b) have different availability. In this regard, in Tables 2 and 4, the column P(ay)/F(ree)

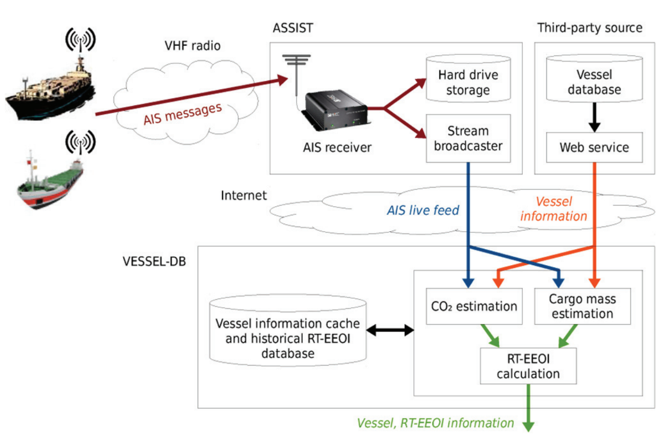

Fig. 2. Architecture diagram for real-time monitoring of RT-EEOI.

is added to distinguish the data that are available by paid subscription versus those that are freely available. In general, identification and physical properties are easily retrievable from several online vessel databases (e.g., www.marinetraffic.com, www.fleetmon.com, and www.vesselfinder.com). However, as remarked in Table 4, not all the technical specifications of the engines are freely available. The values reported in the ship register such as the engine detail data, net tonnage, nominal draft and TPC are not freely distributed. It is also noteworthy that, despite the information on the applicable fuel types being available retrospectively (not free), the real-time information on the fuel used is not available, neither for free nor paid. However, this can be estimated by the vessel's engine type and the region it is sailing on.

Data from both sources (a) and (b) are then integrated to form the VESSEL-DB, which is used to estimate the CO_2 emission and the cargo mass for each vessel in real time. These estimates are then used to compute RT-EEOI (in Equation (4)) for the given vessel. Estimations are updated every a new dynamic AIS message from a vessel is received. The set of computed values are then stored in the *Monitoring_information* table as shown in Table 3. The fields denoted with a (*) in Tables 2 and 4 are those required for the real-time computation of the index. The exact mechanism and computation procedures of this framework will be explained in the following sections.

3.3. Real-time energy efficiency operating index computation procedure

Given the possibility to store the information listed in the previous section, the procedures will be shown on how to use the stored data to derive the real-time energy efficiency of the tracked vessels, i.e., how to fill the *Monitoring_information* (Table 3).

3.3.1. Carbon dioxide emissions quantification

A first key task to compute Equation (4) is to derive the fuel consumption and, consequently, the CO_2 emission rate. A procedure is proposed which uses VESSEL-DB to derive the instantaneous fuel consumption rate and, consequently the CO_2 emission rate. Specifically, both the STEAM model and the Activity-based model will be used for the estimations of the main engine and auxiliary engine performance.

The main difference between the proposed method and the method in Ref. [17] resides in the fact that the proposed method directly uses the information contained in the AIS, i.e., the *navigation status*, and the *speed over ground*, to apply the appropriate formula of STEAM, without estimating the loading condition, which might lead to estimation error.

Detailing our procedure, the ship is categorized according to its navigation status (available from AIS data, see Table 2) defining four main states: *Cruising*, *Maneuver*, *At_Anchor* and *Moored*. Such a classification is derived directly from the AIS messages as follows:

- In case the navigation status is 0 (i.e., Under way using engine), 8 (i.e., Engaged in Fishing), or 15 (i.e., Default) considering the instantaneous speed v and the design speed v^D, the following rules are applied:
  - $v \geq 64.3\% v^D$, then the state is set to *Cruising*;
  - $v < 64.3\% v^D$, then the state is set to *Maneuver* and the same is done if the navigation status is 3 (i.e., restricted maneuverability).
- If the navigation status is 1, then the state is set to *At Anchor*.
- If the navigation status is 5, then the state is set to *Moored*.

The assignment of the state is particularly important for the computation of the consumption rate R_{FC_j} in equation (4). Rules in

Table 2
Vessel_characteristics table and *Vessel_navigational_information* table.

Vessel_characteristics				*Vessel_navigational_information*			
Field	Unit of Measure	Source	F(ree)/P(ay)	Field	Unit of Measure	Source	F(ree)/P(ay)
mmsi	–	AIS	F	Mmsi	–	AIS	F
Vessel_type (*)	–	AIS	F	timestamp	[date]	AIS	F
TPC (*)	[ton/cm]	web	P	Navigation_Status (*)	–	AIS	F
ρ (*)	[kg/m^3]	Table 16	F	v (*)	[knots]	AIS	F
δ^N (*)	[m]	web	F	Rate of Turn	[degrees/min]	AIS	F
γ^N (*)	–	web	F	Longitude	[degrees]	AIS	F
Beam	[m]	AIS	F	Latitude	[degrees]	AIS	F
Year Built	–	web	F	δ^{RT} (*)	[m]	AIS	F
Deadweight Dwt	[ton]	web	F				
γ	[ton]	web	F				
EngineType[a]	–	Table 4					

[a] *EngineType* is a complex property described in Table 4.

Table 3
Monitoring_information table.

Field	Unit of Measure	Source
mmsi	–	AIS
Vessel_type	–	AIS
timestamp	[date]	AIS
Rate of CO_2 Emissions	g_{CO2}/h	Derived
Rate of Fuel Consumption	[tons/h]	Derived
RT-EEOI	$\left[\frac{g_{CO_2}}{ton \cdot nmi}\right]$	Derived

Table 5
Rules for Consumption rate derivation.

Condition	State	Consumption rate
- (Navigation status = 0 or 8 or 15) and ($v \geq 64.3\% v^D$)	*Cruising*	$R_{FC_j} = R^{ME}_{FC_j} + R^{AE}_{FC_j}$ (5) $R^{ME}_{FC_j} \approx C_j^{ME} \cdot \left(\frac{v}{v^D}\right)^3 \cdot 0.75 \cdot P^{ME}$ (6) $R^{AE}_{FC_j} \approx C_j^{AE} \cdot \lambda_c^{AE} \cdot P^{AE}$ (7)
- (Navigation status = 0 or 8 or 15) and ($v < 64.3\% v^D$) - Navigation status = 3 - Navigation status = 1 - Navigation status = 5	*Maneuver* *At Anchor* *Moored*	$R_{FC_j} = R^{ME}_{FC_j} + R^{AE}_{FC_j}$ (8) $R^{ME}_{FC_j} \approx C_j^{ME} \cdot \lambda^{ME}_{man(moor,\ anc)} \cdot P^{ME}$ (9) $R^{AE}_{FC_j} \approx C_j^{AE} \cdot \lambda^{AE}_{man(moor,\ anc)} \cdot P^{AE}$ (10)

Table 5 are applied according to the Activity-based model [15]. More specifically, under Cruising state, a cubic scaling factor $0.75 \cdot \left(\frac{v}{v^D}\right)^3$ and the engine load factor λ_c^{AE} are applied to calculate the instantaneous fuel consumption rate of the main engine and the auxiliary engine ($R^{ME}_{FC_j}, R^{AE}_{FC_j}$) respectively. Under Maneuver, At Anchor or Moored states, respective engine load factors ($\lambda^{ME}, \lambda^{AE}$) under different states are applied, which are specified in Table 6. In this way, low speed scenarios where auxiliary engine contributes to most of the emission are taken into account since STEAM is less robust for estimating emissions of auxiliary engines under such scenarios.

At this development stage, for the values of the specific fuel consumption rate, (C_j^{ME}, C_j^{AE}), required by equations (5)–(10) in Table 5, this technical information is not publicly available for all ship types. To solve this issue, it is assumed that $(C_j^{ME}, C_j^{AE}) = (190, 215)$[g/KWh]. This approximation is in line with the IMO's reference calculation of the Energy Efficiency Design Index (EEDI) and refers to the Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO), respectively [18].

After calculating the rate of fuel consumption, it can be multiplied by the carbon dioxide conversion factor to arrive at the instantaneous CO_2 emission rate.

Table 7 shows the conversion factor c_{Fj} for different fuel types [27]. Using the same notation as in equation (2), the total emissions are:

Table 4
Engine characterization (Main Engine and Auxiliary engine).

EngineType Property							Description
Main Engine (ME)	Availability of Information		Auxiliary Engine (AE)	Availability of Information		Unit of Measure	
	Source	F(ree)/P(ay)		Source	F(ree)/P(ay)		
P^{ME} (*)	Web	P	P^{AE}	Ship registry	P	[kW]	Installed Power.
λ^{ME} (*)	(Table 6)	F	λ^{AE}	(Table 6)	F	[–]	Load Factor in the different navigation status.
n^{ME}	Web	P	n^{AE}	Web	P	[–]	Number of engines.
v^D (*)	Web	P	–	Web	P	[knot]	Design Speed.
J^{ME} (*)	Web	P	J^{AE}	Web	P	[–]	Set of Fuel types.
$c^{ME}_{F_j}$ (*)	(Table 7)	F	$c^{AE}_{F_j}$	(Table 7)	F	$\left[\frac{ton_{CO_2}}{ton_{fuel}}\right]$	Fuel consumption-CO_2 emissions conversion factor.
C_j^{ME} (*)[a]	Literature	F	C_j^{AE}	Literature	F	$\left[\frac{ton}{KWh}\right]$	Specific fuel consumption rate (according to STEAM [14]).

[a] C_j^{ME} is the Specific fuel consumption rate, a measure of the fuel efficiency of any prime mover that burns fuel and produces rotational or shaft power. It is typically used for comparing the efficiency of internal combustion engines with a shaft output. To calculate the actual efficiency of an engine requires the energy density of the fuel j being used. Different fuels have different energy densities defined by the fuel's heating value.

Table 6
Values of load factor λ for main and auxiliary engine under the different state for different ships types [15].

Ship Class	Cruising	Maneuver		At Anchor		Moored	
	λ^{AE} [%]	λ^{ME} [%]	λ^{AE} [%]	λ^{ME} [%]	λ^{AE} [%]	λ^{ME} [%]	λ^{AE} [%]
Oil tanker	30	20	40	5	30	20	60
Chemical tanker	30	20	40	5	30	0	60
Gas carrier	60	20	70	5	60	0	70
Ro/Ro cargo	30	20	40	5	30	0	70
Dry bulk carrier	30	20	40	5	30	0	10
General cargo	30	20	40	5	30	0	10
Container	50	20	60	5	50	0	20
Passenger	70	20	75	5	70	0	60
RoPax	70	20	75	5	70	10	70
Reefer	60	20	70	5	60	0	10
Other dry cargo	30	20	40	5	30	0	10
LNG	60	20	70	5	60	0	70

Table 7
Carbon conversion factor for common marine fuels, c_{Fj} [15].

Type	Carbon content	Conversion Factor [ton.CO_2/ton.fuel]
Diesel/Gas Oil	0.874	3.206
Light Fuel Oil (LFO)	0.86	3.151
Heavy Fuel Oil (HFO)	0.85	3.114
Liquefied Petroleum Gas (LPG)	0.818	3.000
Liquefied Natural Gas (LNG)	0.750	2.750

$$CO_2 = R_{FC_j} \cdot c_{Fj} \tag{11}$$

The proposed approach is validated with a test set of the AIS data for the category of Crude Oil Tankers on Feb 23rd, 2015, 12pm-7pm from the Southwest side of the Singapore Strait. By comparing the estimated hourly emission rate with the data reported in the Third IMO GHG report [22], it can be shown that our model is reasonable, and our results are statistically comparable with the estimates in Ref. [22] (refer to Appendix B.1 for the detailed validation results).

3.3.2. Transport work estimation

According to equation (4), the denominator of $RT - EEOI = \frac{\sum_j R_{FC_j} \times c_{F_j}}{m_{cargo} \times v}$ equals the mass of the cargo carried multiplied by the instantaneous speed of the vessel. The key to estimating the transport work in the denominator resides in estimating the cargo mass. In this section, a novel way to overcome this problem with the objective of estimating RT-EEOI is presented.

As stated, the cargo mass is not reported in the AIS data and, in general, the information is not shared by the shipping companies and thus difficult to provide in real time (section 0). Nevertheless, it is important to design a procedure which can take as input the AIS data and estimates the cargo mass to make the computation of RT-EEOI feasible. In this paper, an alternative method to equation (3) is proposed to estimate the transport work. Equation (3) assumes a linear relationship between the cargo mass and the draft, which can lead to inaccuracy in the final estimation due to the non-linearity introduced by the cargo density. The idea proposed in this paper is to instead use the TPC and the nominal cargo mass μ^N to calculate the real-time cargo mass μ^{RT} (i.e., m_{cargo}), namely:

$$m_{cargo} = \mu^{RT} = \Delta\delta \cdot TPC + \mu^N \tag{12}$$

Here it is assumed that vessels are well balanced and maintain constant load of ballast water. Hence, when the real-time draft deviates from the nominal draft, it is due to the difference in the amount of cargo carried. By multiplying $\Delta\delta$ (the difference between the real-time draft and the nominal draft, δ^{RT} and δ^N, respectively), with the TPC value of the vessel (refer to Table 1 for the definitions), the deviation of μ^{RT} from the nominal cargo mass μ^N is derived. As previously explained, the TPC of a vessel is usually available from the ship register data when the vessel is built.

The nominal cargo mass μ^N can be approximated by multiplying the net tonnage of the vessel γ^N with the density of the cargo ρ^c as follows:

$$\mu^N = \gamma^N \cdot c_\gamma \cdot \rho^c \tag{13}$$

Where $c_\gamma = 2.83168$ is the conversion factor to transform the unit of net tonnage into [m^3]. Here, it should be noted that the nominal cargo mass μ^N of a vessel is the design capacity of cargo the vessel can carry. The nominal mass cannot be directly employed due to the fact that, in real-time settings, vessels may not carry cargo at their full capacity. Equation (13) shows the need to have the cargo density ρ^c. This can represent an issue since usually vessels carry mixed cargo. In the scope of this paper a table of the cargo densities was constructed offline, considering a specific sample of tanker vessels which was used for validation purposes. The adopted cargo density values for the proof of concept are reported in Table 17.

The estimation of the real-time cargo mass, as part of the computation procedure of RT-EEOI is illustrated in Fig. 3. A retrospective approach was adopted to validate the proposed procedure for the estimation of cargo mass. In particular, the estimated cargo mass was compared against the data for the specific category of Crude Oil Tankers for the year 2014 published by the Maritime Port Authority (MPA) of Singapore. These data are publicly available at www.mpa.gov.sg [32] and the validation shows rather accurate estimation results (the detailed results are provided in Appendix B.2.).

Fig. 4 illustrates the overall framework for the computation of the RT-EEOI index.

4. Real-time energy efficiency operating index framework: proof of concept

In this section, a test application of the described framework for RT-EEOI monitoring in the Singapore Strait is presented. A prototype of VESSEL-DB is developed in Python using PostgreSQL as the Relational Database Management System. A logical view of VESSEL-DB is presented in Fig. 5. The database tables were previously described in Tables 2 and 3

The prototype was executed from 12:00PM to 7:00PM on February 23rd, 2015, receiving and analyzing messages from the AIS receiver located in the School of Computing in the National University of Singapore. These receivers cover the Southwest side of the Singapore Strait as shown in Fig. 6. Within this time window,

Algorithm 1: Generic Procedure for Real Time Monitoring of RT–EEOI

Data Collection: Connect to web source through PY-crawler and connect to ASSIST;
Monitoring State =1 ;
while *Monitoring State == 1* **do**
    if $msgType = 1 \cup 2 \cup 3 \cup 18 \cup 19$ **then**
        record `Position_msg`
        Use the `Navigation_status` and apply Table 5
        Return R_{FC_j} and the Emission Rate $R_{FC_j} \cdot C_{F_j}$;
        Compute $\Delta\delta = \delta^{RT} - \delta^N$;
        Compute $\gamma^N \leftarrow \gamma^N \cdot c_\gamma$;
        Compute $\mu^N = \gamma^N \cdot \rho^c$;
        $m_{cargo} = \mu^N + TPC \cdot \Delta\delta$;
        $RT - EEOI = \frac{R_{FC_j} \cdot C_{F_j}}{v \cdot m_{cargo}}$
    end
end

Fig. 3. Algorithm1.

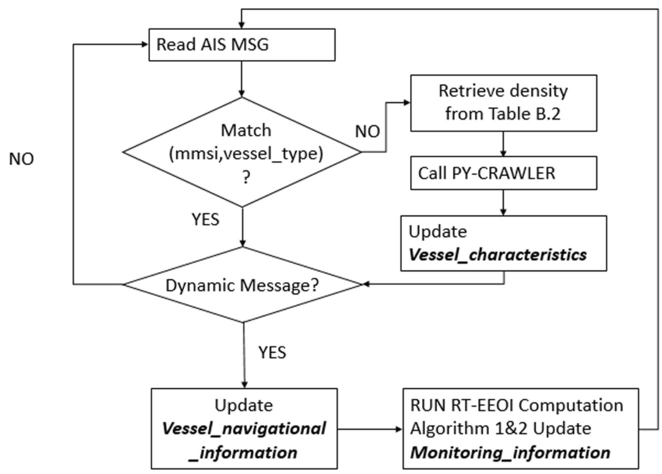

Fig. 4. Main flow chart for RT-EEOI computation.

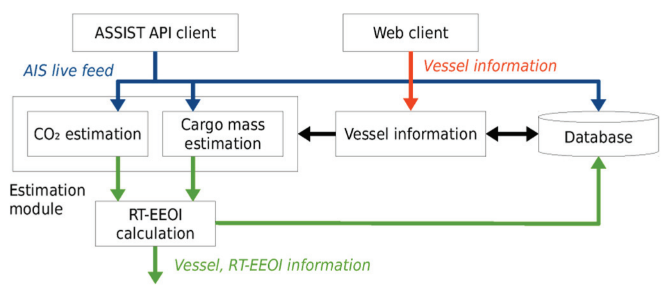

Fig. 5. Logical view of VESSEL-DB.

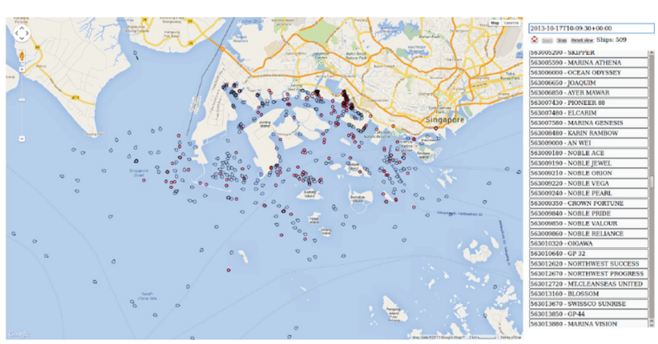

Fig. 6. A snapshot from ASSIST.

Table 8
Example of an entry in *Vessel_navigational_information* table.

Data Type	Data Value	Unit Measure	Source
mmsi	373638000	–	AIS
Vessel_Type	Crude Oil Tanker	–	AIS
Time Stamp	2015-May-29/29/05/2015/ 01:44:05	[year-month-day /dd/mo/yyy/ hh:mm:ss]	AIS
Navigation_status	0	–	AIS
v	3.2	[knot]	AIS
δ^{RT}	12	[m]	AIS

Table 9
Example of an entry in *Vessel_characteristics* table.

Data Type	Data Value	Unit Measure	Data Origin
mmsi	373638000	–	AIS
Vessel_Type	Crude Oil Tanker	–	AIS
v^D	12.8	[knots]	www.marinetraffic.com
TPC	91	[ton/cm]	www.marinetraffic.com
P^{ME}	12800	[KW]	www.marinetraffic.com
γ^N	31829	[100 ft^3]	AIS
δ^N	12	[m]	www.marinetraffic.com
Fuel Type	Marine Diesel Oil	–	www.marinetraffic.com
Cargo Density	0.81	[ton/m^3]	Table 17
Deadweight Dwt	107113	[ton]	www.marinetraffic.com

Table 10
Example of *Monitoring_information* table.

Data Type	Data Value	Unit Measure	Source
mmsi	373638000	[–]	AIS
Vessel_Type	Crude Oil Tanker	[–]	AIS
Time Stamp	2015-May-29/29/05/2015/1:44:05	[year-month-day/ dd/mo/yyy/hh:mm:ss]	AIS
R_{FC}	486.4	[kg/h]	–
$CO_2 = R_{FC} \cdot c_F$	1559.3984	[kgCO$_2$/h]	–
RT-EEOI	10.2499	[kgCO$_2$/ton.nm]	–

Table 11
RT-EEOI characterization for vessels observed on the Southwest side of the Singapore Strait on Feb 23rd, 2015.

Type (MARPOL 73/78)	RT-EEOI statistics [gCO$_2$/ton.nm]				
	Average	min	max	Number of ships	Number of data points
Crude Oil Tanker	37.83	0.1544	328.0	10	22
Product Tanker	32.114	7.996	58.09	4	15
LPG Tanker	448.98	229.7	599.2	3	6
Chemical Tanker	29.7864	11.09	272.52	5	10

several vessels were tracked, to demonstrate the feasibility of monitoring the RT-EEOI. The detailed flow for the RT-EEOI computation for the first Crude Oil tanker detected with MMSI 373638000 is provided in Tables 8–10. The aggregated analysis for the remaining tracked vessels is provided in Table 11 and it is compared with the results in Ref. [18]. The detailed observations and computational results are reported can be referred in Table 12.

First, the ASSIST API client connects to ASSIST's REST API and continuously pulls AIS messages. Each message is in JSON format and contains the AIS message itself together with a timestamp. Since most AIS messages do not contain useful time information, ASSIST uses a GPS receiver for a precise timekeeping, with the generated timestamps having the granularity of 1 s. Assume that an AIS message for a vessel of MMSI 373638000 and type “Crude Oil Tanker” is received. This message is sent to the estimation module and saved in the *Vessel_navigational_information* table, as shown in Table 8.

Next, the estimation module queries the vessel information module (*Vessel_characteristics* table) for all the missing vessel information needed to perform the estimations. Assume the pair (373638000, “Crude Oil Tanker”) does not have any match in the *Vessel_characteristics* table. As outlined in Fig. 4, the value of Cargo Density is retrieved from Table 17, while the web client crawls www.marinetraffic.com to collect the remaining information. An example of the resulting *Vessel_characteristics* entry is reported in Table 9.

As stated in section 3, not all the information is available for free. At this development stage of the framework, only the information publicly available on www.marinetraffic.com is used. In particular, auxiliary engine emission is not considered due to unavailability of data. However, these data are contained in the ship registry, and mandatory reporting of this data would further improve the

Table 12
Detailed results for the proof of concept example, rate of CO2 emission calculation $R_{FC}^{ME} \times C_F$ [kgCO$_2$/h].

Vessel name	dwt	Vessel_ type	Navigation_ status	v (knots)	v^D (knots)	$\frac{v}{v^D}$	State	λ^{ME}	P^{ME} (kW)	$R_{FC}^{ME} \times C_F$ (kg/h)
Chemtrans Rouen[a]	34860	Crude Oil Tanker	1	0.1	12.3	0.0081	At Anchor	0.05	7150	217.77
Chemtrans Rugen	34861	Crude Oil Tanker	0	5.6	12.6	0.4444	Maneuver	0.20	7150	871.07
Chemtrans Rugen	34861	Crude Oil Tanker	0	7.4	12.6	0.5873	Maneuver	0.20	7150	871.07
Chemtrans Rugen	34861	Crude Oil Tanker	0	10.9	12.6	0.8651	Cruising	0.30	7150	2114.72
Chemtrans Rugen[b]	34861	Crude Oil Tanker	0	11.4	12.6	0.9048	Cruising	0.30	7150	2419.29
CS Pioneer	34930	Crude Oil Tanker	1	0.1	12.6	0.0079	At Anchor	0.05	25485	776.20
Chemtrans Petri	47228	Crude Oil Tanker	0	0.2	12.9	0.0155	At Anchor	0.05	8562	260.77
Concertina	96835	Crude Oil Tanker	0	7.4	10.0	0.7400	Cruising	0.30	580	107.37
Concertina	96835	Crude Oil Tanker	0	7.1	10.0	0.7100	Cruising	0.30	580	94.84
Concertina	96835	Crude Oil Tanker	0	7	10.0	0.7000	Cruising	0.30	580	90.89
Aframax Riviera[c]	107113	Crude Oil Tanker	0	0.1	12.8	0.0078	Maneuver	0.20	12800	1559.40
Aframax Riviera	107113	Crude Oil Tanker	0	0.3	12.8	0.0234	Maneuver	0.20	12800	1559.40
Aframax Riviera	107113	Crude Oil Tanker	0	0.5	12.8	0.0391	Maneuver	0.20	12800	1559.40
Aframax Riviera	107113	Crude Oil Tanker	0	3.2	12.8	0.2500	Maneuver	0.20	12800	1559.40
Aframax Riviera	107113	Crude Oil Tanker	0	3.4	12.8	0.2656	Maneuver	0.20	12800	1559.40
Aframax Riviera	107113	Crude Oil Tanker	0	5.1	12.8	0.3984	Maneuver	0.20	12800	1559.40
Cap Lara	159000	Crude Oil Tanker	1	0.1	8.9	0.0112	At Anchor	0.05	950	28.93

[a] Data point 1 used as an illustration in Section 4.1.
[b] Data point 2 used as an illustration in Section 4.1.
[c] Data point 3 used as an illustration in Section 4.1.

Table 13
Detailed results for the proof of concept example, RT-EEOI calculation [gCO2/ton-nm].

Vessel name	δ^N(m)	δ^{RT}(m)	$\Delta\delta$ (cm)	TPC	γ^N	μ^N (ton)	μ^{RT} (ton)	v (knots)	RT-EEOI (gCO$_2$/ton-nm)
Chemtrans Rouen	5.5	7.2	170	41.5	7640	17523.6	24578.6	0.1	88.60
Chemtrans Rugen	5.5	7.9	240	41.5	9470	21721	31681	5.6	4.91
Chemtrans Rugen	5.5	7.9	240	41.5	9470	21721	31681	7.4	3.72
Chemtrans Rugen	5.5	7.9	240	41.5	9470	21721	31681	10.9	6.12
Chemtrans Rugen	5.5	7.9	240	41.5	9470	21721	31681	11.4	6.70
CS Pioneer	20.08	17.5	−258	179.5	80521	184688	138377	0.1	56.09
Chemtrans Petri	4.54	8.0	346	50.2	12369	28370.3	45739.5	0.2	28.51
Concertina	6.3	8.0	170	87.9	30153	69160.8	84103.8	7.4	0.17
Concertina	6.3	8.0	170	87.9	30153	69160.8	84103.8	7.1	0.16
Concertina	6.3	8.0	170	87.9	30153	69160.8	84103.8	7	0.15
Aframax Riviera	14.798	12.0	−279.8	91.0	31829	73004.9	47543.1	0.1	328.00
Aframax Riviera	14.798	12.0	−279.8	91.0	31829	73004.9	47543.1	0.3	109.33
Aframax Riviera	14.798	12.0	−279.8	91.0	31829	73004.9	47543.1	0.5	65.60
Aframax Riviera	14.798	12.0	−279.8	91.0	31829	73004.9	47543.1	3.2	10.25
Aframax Riviera	14.798	12.0	−279.8	91.0	31829	73004.9	47543.1	3.4	9.65
Aframax Riviera	14.798	12.0	−279.8	91.0	31829	73004.9	47543.1	5.1	6.43
Cap Lara	14.9	9.2	−570	119.0	50927	116809	48979.3	0.1	5.91

Table 14
Comparison among energy efficiency indicators.

Indicator	Source	C1	C2	C3	C4	C5
EEOI (RT-EEOI)	International Maritime Organisation (MEPC.1/ Circ.684) [21]	Hindered by confidential information	Hindered by the real-time tracking of the cargo mass	Weather conditions as well as economic conditions might lead to external variability in cargo load and distance travelled	High comparability across different mode of transport	High
EHS	United States (MEPC.64/5/19) [22]	Relatively easy to adopt within certain countries (USA)	Hindered by non-standard definition of "hour in service"	Not applicable	Low comparability across different mode of transport	High
ISPI	European Maritime Safety Agency (MEPC 66/4/6) [22]	Hindered by the need to estimate EIV	Difficult to monitor "distance travelled" as it requires information on the route which is not available in real time	Weather conditions as well as economic conditions might lead to external variability in distance travelled	Low comparability across different mode of transport	High
FORS	Germany (MEPC 66/4/6) [22]	Easy to adopt	Feasible to monitor in real time with AIS data	Not applicable	High comparability across different mode of transport	Low, as it does not consider transport work
AER	Japan (MEPC 66/4/6) [11]	Relatively easy to adopt	Feasible to monitor in real time due to the use of deadweight as a proxy to total cargo capacity	Weather conditions as well as economic conditions might lead to external variability in distance travelled	High comparability across different mode of transport	Low, as it does not capture capacity utilization

Table 15
Prediction interval based on third IMO GHG report [22].

Ship type	Size category (dwt)	Number of active vessels (AIS)	Average days at sea	Average fuel consumption - main engine ('000 ton/year)	Average fuel consumption - auxiliary engine ('000 ton/year)	Mean CO_2 emission rate (kg/hour)	Lower limit of predicted CO_2 emission rate (kg/hour)[a]	Upper limit of predicted CO_2 emission rate (kg/hour)[a]
Oil tanker	0–4999	1419	145	0.8	0.6	258.88	152.32	365.43
	5000–9999	529	155	1.3	1	398.16	296.71	499.62
	10,000–19,999	172	159	2	1.6	608.27	453.28	763.25
	20,000–59,999	623	169	4.1	2	955.63	693.41	1217.9
	60,000–79,999	356	177	5.9	1.9	1154.3	860.20	1448.4
	80,000–119,999	795	180	6.2	2.6	1289.1	960.62	1617.5
	120,000–199,999	380	206	9.2	3.1	1565.7	1166.8	1964.7
	200,000 − +	534	222	15.8	3.7	2285.1	1702.8	2867.3

[a] Based on normality assumption and standard deviation estimates in Ref. [10] page 245.

Table 16
Emission model validation against prediction interval based on third IMO GHG report [22].

Size category (dwt)	Sample size in proof of concept	Average estimated hourly CO_2 emission rate in proof of concept (kg/hour)	Lower limit of prediction interval based on IMO report (kg/hour)	Upper limit of prediction interval based on IMO report (kg/hour)
20,000–59,999	7	1075.8	693.41	1217.9
80,000–119,999	9	1072.2	960.62	1617.5
120,000–199,999	1	28.934	1166.8	1964.7

Table 17
Type of tankers tracked, cargo carried and cargo density assumed.

Vessel Type	Cargo carried	Density of cargo
Asphalt/Bitumen tanker	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 tanker	Petrochemical products	0.81 ton/m^3
Bunkering tanker	Heavy fuel oil	0.93 ton/m^3

accuracy of the estimation. Nevertheless, since no more than 20% of the installed main engine power is allowed for auxiliary engine output, and auxiliary engine usage is insignificant during normal cruising [26], the underestimation effect is negligible in many situations. For fuel type and main engine power, data on www.marinetraffic.com were considered.

After updating the database, the vessel information module reports back to the estimation module the missing information for the current vessel. The latter computes the CO_2 emissions and cargo mass estimations and forwards them to the next module which finally computes the RT-EEOI. The CO_2 emissions and RT-EEOI are saved in the *Monitoring_information* table, as shown in Table 10.

This result estimates that the considered tanker is consuming 10.25 [gCO_2] for each nautical mile carrying 1 ton of cargo. Table 11 extends the results to the entire sample in the test period and it characterizes the RT-EEOI for each vessel type (according to MARPOL 73/78, which is consistent with [18]).

From Table 11, it can be observed that crude oil tankers and Product Tankers are less efficient in general compared to chemical tankers. This result is in line with those in Ref. [18] (Table 31, page 59). To derive the results, following the recommendation in Ref. [18], only those vessels with a cargo mass larger than 33% of its deadweight are included, which is considered to be approximation of the carried ballast water, i.e., the empty condition.

4.1. Detailed results for crude oil tankers

Here, the AIS data collected and estimates computed to monitor Crude Oil Tankers on the Southwest side of the Singapore Strait on February 23rd, 2015, from 12pm to 7pm is presented to further explain results obtained with the proposed methodology in Section 3. There are multiple entries for some vessels if multiple messages of the same vessel with different vessels status (navigational status, speed) are received at different timestamps. It is shown in Section 3 that when the vessel's navigational status or speed changes, its hourly emission rate and thus RT-EEOI can change, resulting in different energy efficiency estimates at different times. Table 12 shows the detailed calculation for the CO_2 emission rate using the estimation model proposed in section 3.3.1. To clarify the approach, the following illustrates the detailed computation and provides explanations for the consumption results for a selected subset of vessels in Table 12. Specifically, three examples are proposed: Chemtrans Rouen at speed 0.1 knots, Chemtrans Rugen at speed 11.4 knots, and Aframax Riviera at speed 0.1 knots.

1. *Chemtrans Rouen (0.1 knots)*
First, the state of the vessels has to be determined as either *Cruising*, *Maneuver*, *At Anchor* or *Moored*. Based on the activity-based model in Ref. [27], the state classifications have been summarized in Table 5. According to Table 5, since this vessel data point has a navigation status of 1, it is classified *At Anchor* state. Therefore, Equation (9) can be applied to calculate the instantaneous fuel consumption rate of its main engine. For this, Table 6 is referred to for engine load factor $\lambda^{ME}_{man(moor,\,anc)}$ of Oil Tanker under *At Anchor* state, which is 5%. After applying the specific fuel consumption rate, C_j^{ME} of 190 g/kWh, P^{ME} of 7150 kW, Carbon Conversion factor of 3.206 for Diesel/Gas Oil and engine load factor of 0.05, the CO_2 emission rate of 217.77 kg/h is obtained.
2. *Chemtrans Rugen (11.4 knots)*
Again, refer to Table 5 for assigning the state of the vessel. Since the navigational status is 0, and the instantaneous speed is 90.5% of the design speed (12.6 knots), the vessel state at this point is classified as *Cruising*. Therefore, Equation (6) is applied to calculate the instantaneous fuel consumption rate of its main engine. In this case, a cubic factor to the ratio of instantaneous speed and design speed is applied. Using the specific fuel consumption rate, C_j^{ME} of 190 g/kWh, P^{ME} of 7150 kW, Carbon Conversion factor of 3.206 for Diesel/Gas Oil and $(0.905)^3 \cdot 0.75$, a CO_2 emission rate of 2419.29 kg/h is obtained.

3. Aframax Riviera (0.1 knots)
As this vessel has a navigational status of 0 at this point, and its instantaneous speed is less than 64.3% of its design speed (which is 12.8 knots), this vessels is classified in *Maneuver* state. Therefore, Equation (9) is applied to calculate its instantaneous fuel consumption rate. Similar to the first data point, Table 6 is used to derive $\lambda^{ME}_{man(moor,\ anc)}$, which is 20% for Oil Tanker under *Maneuver* state. Therefore, using the specific fuel consumption rate, C^{ME}_{j} of 190 g/kWh, P^{ME} of 12800 kW, Carbon Conversion factor of 3.206 for Diesel/Gas Oil and engine load factor of 0.2, a CO_2 emission rate of 1559.4 kg/h is obtained.

This proposed approach considers the different vessel states, *Maneuver, Cruising, At Anchor* or *Moored* and combines the STEAM [2] and the activity-based model [3] to account for the interactions between various factors like navigational status, instantaneous speed and engine power to determine the CO_2 emission rate for vessels at any time point. To further illustrate this combined approach, we compare the data point 1 and 3 above. It can be observed that although both vessels have the same low speed over ground of 0.1 knots, data point 3 has a significantly larger instantaneous CO_2 emission rate. This is because the data point 1 has a navigational status of 1, which classifies it as *At Anchor*, whereas, data point 3 has navigational status of 0 and is classified as *Maneuver*. When maneuvering (including turning), more fuel is consumed and hence, more CO_2 is emitted by the vessel corresponding to the data point 3. Furthermore, data point 3 (vessel name: Aframax Riviera, speed: 0.1 knots, main engine power: 12500 kW) has a larger main engine power than data point 1 (vessel name: Chemtrans Rouen, speed: 0.1 knots, main engine power: 7150 kW), further adding to the high emission rate. Considering data point 2 (vessel name: Chemtrans Rugen, speed: 11.4 knots, main engine power: 7150 kW), as it is Cruising, its instantaneous CO_2 emission rate is then cubically related to the ratio between its instantaneous speed and its design speed (see Table 5), resulting in high emission rate.

From the computations of the real-time emission rates in Table 12 and the transport mass estimation detailed in Section 3.3.1, the RT-EEOI index can be obtained for Crude Oil Tankers as shown in Table 13.

4.2. Validation and verification for real-time energy efficiency operating index calculations

This section contains the validation and verification of the RT-EEOI calculations for various types of tankers obtained in the proof of concept. Fig. 7 shows the comparison of the aggregated results across different deadweight categories of *product tankers* against the average EEOI estimation per deadweight category obtained in the UCL study [18] and IMO Third GHG Study [22]. In Refs. [18,22], product tankers are categorized into five categories according to the increasing deadweight of the vessel. These are 0–5000 (not inclusive) tonnes, 5000 to 10000 (not inclusive) tonnes, 10000 to 20000 (not inclusive) tonnes, 20000 to 60000 (not inclusive) tonnes, 60000 and above (not inclusive) tonnes. These are labeled as category 1–5 respectively. For each category [18,22], have estimated the average operational efficiency by retrospectively calculating the EEOI of vessels' annual voyages. In Fig. 7, the average RT-EEOI calculations of the same tanker type (*product tankers*) are plotted against estimations in Refs. [18,22] across increasing deadweight categories. Here, the estimations by Ref. [18] is referred to as UCL-Operational Efficiency (UCL-OE) and estimations by Ref. [22] as IMO-Operational Efficiency (IMO-OE) respectively.

From Fig. 7, a substantial consistency between the three estimates can be observed. For smaller vessels (i.e., for smaller values of the ship deadweight), a lower level of efficiency is reached, both in the case of RT-EEOI evaluation as well as for the UCL-OE and IMO-OE. On the contrary, larger vessels might reach higher efficiency levels. It is interesting to note that there are larger discrepancies associated with either very small or very large vessels due to the outliers in the sample size over the test period.

Figs. 8–11 plots all the results obtained for the different vessel types according to MARPOL 73/74 in a log-log scale. Here, the estimated RT-EEOI is plotted against deadweight. For all ship types observed in the trial run period used, there is decreasing trend between RT-EEOI and deadweight. Such a trend agrees with the results discussed above. Nevertheless, it is observed that there are outliers to this trend such as very large vessels with low efficiency for *Product Tanker* and *Chemical Tanker* (the extreme right points in Figs. 8 and 9) or medium vessels having very high efficiency for Crude Oil Tanker (points well below the trend line in Fig. 10).

In summary, the difference between the other estimates like UCL-OE, IMO-OE with the RT-EEOI can be attributed to: 1) the real-time measurements are subject to a wide range of variation, whereas the UCL and IMO measure represents a mean over a large number of vessels over an extended period of time across the globe, thus leading to a substantial smoothing effect; 2) data in the UCL and IMO estimates are from 2011 to 2012, whereas a sample from 2015 was used for the proposed proof of concept; 3) the

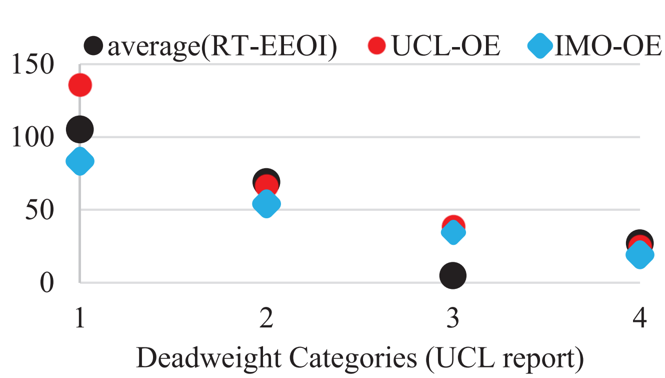

Fig. 7. Average RT-EEOI per deadweight category against the estimated UCL-OE for Product Tankers.

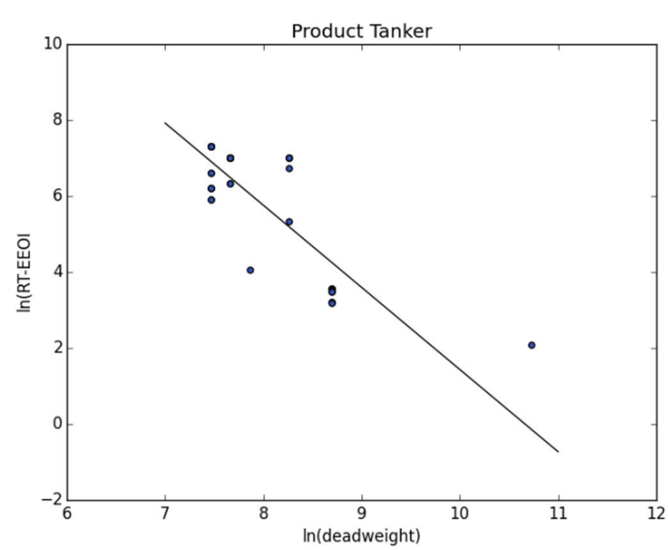

Fig. 8. RT-EEOI against the deadweight for *Product Tankers*.

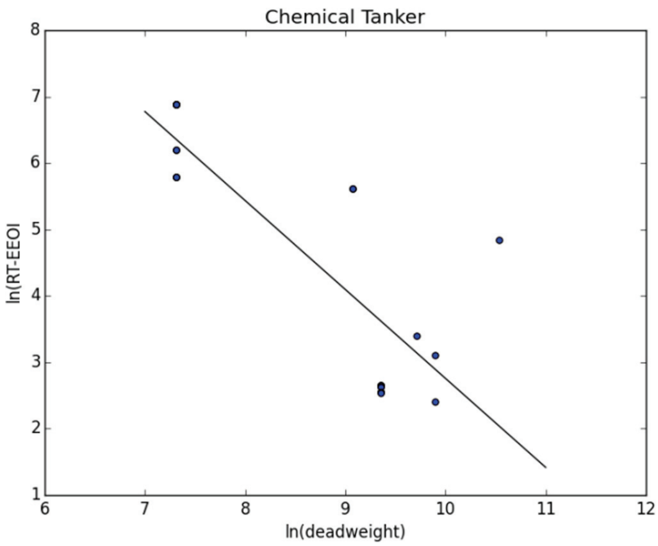

Fig. 9. RT-EEOI against the deadweight for *Chemical Tankers.*

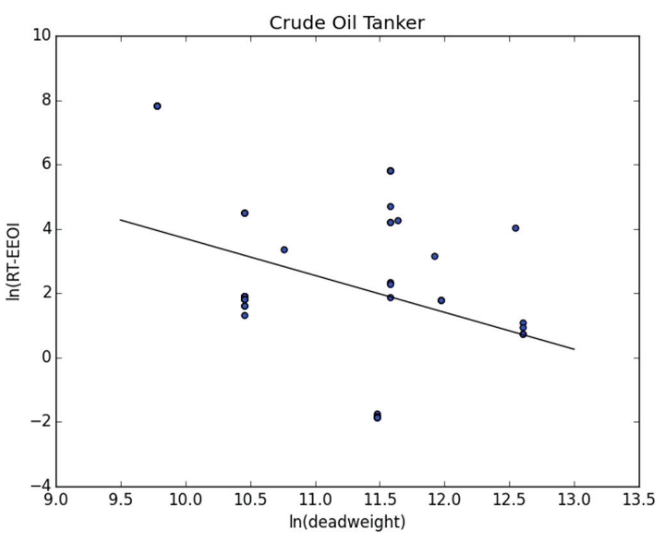

Fig. 10. RT-EEOI against deadweight for *Crude Oil Tankers.*

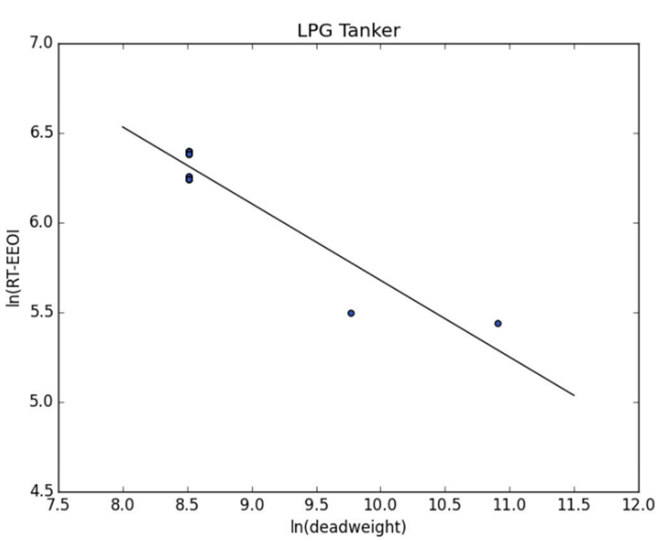

Fig. 11. RT-EEOI against deadweight for *LPG Tankers.*

comparison results derive from two different approaches in estimating both the emissions as well as the cargo mass. Nonetheless, the proof of concept study conducted here shows similar trend with the UCL report as well as IMO estimates with respect to vessel size for different vessel types.

5. Discussion

This paper proposes a novel framework with respect to the recent studies on the CO_2 emission and EEOI (refer to [17,18]), focusing on achieving a framework for the real-time monitoring of the RT-EEOI index. To do so, the use of AIS messages is proposed similar to [17,18], with modifications to the way input information are used to determine the CO_2 emission and the cargo mass. More specifically:

- In Refs. [17,18], CO_2 emission is estimated retrospectively based on the load of the vessel as well as the time at sea using the STEAM model. This paper proposes a real-time implementation of the refined fuel consumption and emission model and extends it to arrive at the operational energy efficiency of vessels by estimating the transport work done.
- In Ref. [18], the transport work is estimated using equation (3), assuming linear relationship between the draft and the cargo mass. This paper exploits the nominal cargo mass and the net tonnage to derive the cargo mass instead. Verification results are quite promising. With this, other CO_2 emission models discussed in Ref. [17] could also be incorporated into the RT-EEOI framework as most of their input data are already reported by AIS.

To enable real-time computation, the proposed framework can be fully automated. Although the computation methodologies currently face some problems of missing auxiliary engine data (refer to section 3.3), approximation methods have been proposed to enable the tracking of the real-time index. Nevertheless, as global authorities are pushing for mandatory reporting of fuel consumption and transport work data [22], such estimation error would likely be minimized in the future. The development of Satellite-AIS technology is also quite promising. Commercial companies like ORBCOMM are planning to launch more satellites, mostly micro- or even nano-satellites with AIS payloads soon [28]. This means wider geographical coverage and improved latency for the Satellite AIS tracking. Coupled with data streaming systems like ASSIST and future real-time interface for modeling, energy efficiency of marine vessels in terms of CO_2 emissions could be monitored in real time globally with similar architectures proposed in this paper.

Acting to improve the quality of RT-EEOI evaluation is important for several reasons. For individual vessels, the automatic and real-time tracking enabled by the proposed technology and framework could alleviate on-board data collection and monitoring. Furthermore, shipping companies can use this framework to benchmark the energy consumption and efficiency of their fleet in real time. At the regional level, port authorities can detect in real time inefficient behaviors and react accordingly. An example of this is to set an upper-bound to the CO_2 emission and construct a priority for vessels based on their efficiency. This framework can also be helpful to various regional and international authorities, as part of their regulatory reporting and monitoring schemes. At the global level, the real-time tracking can provide a forecast of efficiency profiles in different areas of interest, highlighting efficient routes in real time. Such a time-dependent consideration cannot be performed if the analysis is retrospective. Hence, this standardized framework of monitoring greenhouse gas emissions and energy efficiency of individual ships can provide better control and focus on reducing greenhouse gas emissions and improving operational efficiency of vessels around the globe.

6. Conclusions

This paper presents the first step towards a practical framework for the real-time monitoring of vessels' operational energy efficiency. The framework consists of a new methodology for the estimation of the transport work and CO_2 emissions, as well as a software architecture to implement this using AIS data. This approach overcomes the unavailability of such information as real-time cargo mass and fuel consumption.

A proof of concept for the framework is provided for the Singapore Strait and the results are compared with the report in Refs. [18,22] which presented retrospective analysis of global efficiency for marine vessels. The results show much agreement with the retrospective average efficiency measure in Refs. [18,22]. Nevertheless, the proof of concept also revealed some discrepancies, which leave room for further investigation of the real-time measurement for controlling and forecasting the efficiency in sea shipping.

The procedures for the estimation of cargo mass and, ultimately energy efficiency are validated with the real-time AIS data of the Singapore Strait. The validation sheds light on several hurdles brought by the lack of publicly available data. Considering this, it is apparent how the mandatory reporting of more information (e.g., ship register information) as well as automatic update of the data (e.g., navigation status, current draft) can largely improve the quality of the obtained results. If information such as the cargo mass were available, approximation errors can be minimized and the proposed framework can provide more accurate index estimation. The geographical reach of the current framework seamlessly extends to a global scale with the Cloud design of ASSIST and opportunities created by Satellite AIS technology.

This work represents a first step towards a framework for real-time performance monitoring. The ongoing discussion within organizations like IMO and EU, regarding mandatory data collection and sharing would provide even greater impetus to the implementation of such a framework.

Acknowledgments

This work was supported in part by the Singapore Maritime Institute [grant numbers R-SMI-2013-MA-11].

Appendix A. Comparison of various operational energy efficiency indicators

In line with the three-step approach outlined in MEPC 69, several relevant indicators are selected for comparison, based on the recent MEPC 71 paper submitted by Norway [34]. It is possible to compare the selected indicators based on the following performance measures: (C1) ease of adoption, (C2) feasibility of real-time monitoring, (C3) sensitivity to factors not considered in the index formulation, (C4) comparability across different modes of transport, (C5) completeness as energy efficiency indicator. In particular, (C3) refers to the sensitivity of the indicator to the variation of external factors which are not explicitly considered in the formulation of the index itself. An example is the weather condition. The criterion (C4) favors indicators that can be easily adopted and compared in contexts different from sea-transportation (e.g., air, rail transportation). Finally, (C5) refers to the ability of the indicator to capture CO_2 emissions with respect to transport work as indicated by the IMO guidelines [33] and in the UCL report [18]. The results of the comparison are organized and reported in Table 14.

Appendix B. Additional validation results

B.1. Carbon dioxide emission model validation

To validate the approach of estimating CO_2 emission rate, the specific category of Crude Oil Tanker in the proof of concept is used to compare against the hourly fuel consumption and CO_2 emission rate calculated in the Third IMO GHG Study [22]. Table 15 below shows the average fuel consumption per Oil Tanker in units of 1000 ton/year in the IMO study, for the year 2011 (page 181 [22]). Based on the average days at sea reported in the IMO study [10] and assumptions in 3.3.1 in this paper, the mean hourly CO_2 emission rate is computed for the different deadweight categories of Oil Tankers. In addition, a 95% prediction interval is derived for the estimated emissions for each deadweight category based on the uncertainties in the bottom-up approach of the IMO study (see Ref. [22] page 245).

With this, the estimated emissions of observed vessels from the test period is compared against the prediction interval estimated obtained from Ref. [22] for their respective size category. The comparison result for Crude Oil Tankers is shown in Table 16 below.

From Table 16, it is shown that for majority of the size categories observed, the average estimated hourly CO_2 emission rate falls within the 95% prediction interval based on [22]. The only difference lies in the size category of 120,000–199,999 (deadweight), which only has one sample point over the test period. Taking a closer look at this data point, (which corresponds to the vessel name: Cap Lara, MMSI: 240592000), it shows the vessel has the navigational status of 1 (At Anchor) and a very low speed (0.1 knots). This indicates that the vessel is not sailing at sea (likely at anchor waiting to enter port) and thus not consuming much fuel apart from using auxiliary engine. Hence, this data point can be classified as an outlier, which is not comparable with the aggregated global data from Ref. [22].

Overall, this section demonstrates that the proposed CO_2 emission model is reliable and the estimation procedure is accurate compared to retrospective analysis by the IMO 3rd GHG Study [22]. The detailed proof of concept data used can be found in Table 12.

B.2. Cargo mass estimation validation

To validate the proposed cargo mass estimation method, a retrospective approach is proposed and the aggregate estimates from the proposed method with publicly available cargo mass data from the Maritime Port Authority of Singapore (MPA) are compared. To estimate the cargo mass carried by tanker vessels in real time, Table 17 for the assumed density of cargo carried for different types of tankers is constructed.

This section will attempt to verify the output of the proposed approach for cargo mass estimation. As explained in the paper, AIS data does not contain the cargo mass due to industry confidentiality reasons. In order to perform the validation, the estimated cargo mass using the proposed framework is compared against the data for the category of Oil Tankers for the year 2014 published by MPA. The data is obtained from www.mpa.gov.sg [32].

It is noteworthy that the proposed framework is general. For validation purposes, a specific category of tankers is considered, i.e., the “Oil Tankers” according to the classification provided by MPA. The data from MPA, together with estimated cargo mass per vessel for each month of 2014 is outlined in Table 18 below. As the data reported by MPA is aggregated over all tanker vessels carrying oil cargo, the range of cargo types is broad, with cargo densities between [0.58, 0.81] g/cm^3, where the lower bound corresponds to liquefied petroleum gas and the upper bound

Table 18
Comparison between MPA Data [32] against estimated average cargo mass per Oil Tanker throughout 2014.

Month	Average cargo per Oil Tanker reported by MPA [tons/vessel]	Average cargo per Oil Tanker estimated from our framework (using cargo density of 0.58 ton/m^3) [ton/vessel]	Average cargo per Oil Tanker estimated from our framework (using cargo density of 0.81 ton/m^3) [ton/vessel]
Jan	11250.95	10569.03	29340.55
Feb	12389.01	4769.268	23826.95
Mar	12859.48	10243.81	26939.12
Apr	12351.12	12030.28	33688.92
May	12088.72	5996.83	24139.9
Jun	12265.98	9029.938	24301.59
Jul	9965.808	8093.661	26300.65
Aug	12460.12	8679.413	27936.84
Sep	12420.9	6950.95	25088.85
Oct	11331.27	8295.532	25232.45
Nov	9999.674	8312.015	28604.53
Dec	12702.26	7973.533	24523.65

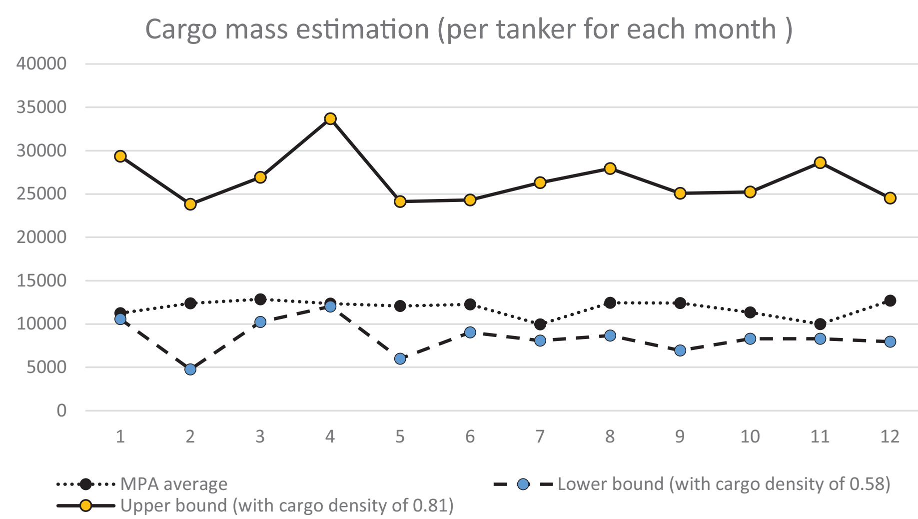

Fig. 12. Comparison of estimated cargo mass with the reported average from MPA.

corresponds to crude oil. Here, the cargo estimation procedure outlined in section 3.3.2 on monthly AIS data collected in 2014 is applied. First, the lower bound cargo density [0.58 g/cm^3] is applied to obtain a lower bound estimate on the average cargo per Oil Tanker, assuming all vessels carry liquefied petroleum gas. Next, the upper bound cargo density [0.81 g/cm^3] is applied to obtain an upper bound average cargo per Oil Tanker, assuming all vessels carry heavy crude oil. The monthly estimated bounds from the proposed approach are shown in the last two columns of Table 18.

In the construction of the lower and upper bound, outliers are removed in our cargo mass estimation due to potential presence of super-tankers which can significantly skew the results. As shown in Fig. 12, the reported statistics on the average cargo mass of Oil Tankers calling at Singapore falls well within the estimated upper and lower bounds of the average cargo mass per Oil Tanker throughout 2014. This shows that our cargo estimation procedure is reasonable as a wide range of tankers carrying different types of oil cargos call at Singapore; and our approach is able to correctly estimate the bounds of the cargo mass. Although the validation here is conducted with respect to the aggregated data over tankers carrying all types of oil cargo, more detailed validation of the cargo mass estimation can be carried out if more detailed data, broken down to the different types of oil cargoes is available to validate with.

References

[1] Jafarzadeh S, Utne IB. A framework to bridge the energy efficiency gap in shipping. Energy 2014, May 1;69:603–12.
[2] Andreoni V, Galmarini S. European CO_2 emission trends: a decomposition analysis for water and aviation transport sectors. Energy 2012;45(1).
[3] The International Council of Clean Transportation. The energy efficiency design index (EEDI) for new ships. ICCT; 2011. Policy Updates.
[4] Faber J, Wang H, Nelissen D, Russell B, Amand D. Marginal abatement costs and cost effectiveness of energy-efficiency measures. London, UK: International Maritime Organization; 2011.
[5] Attah EE, Bucknall R. An analysis of the energy efficiency of LNG ships powering options using the EEDI. Ocean Eng 2015;110:62–74.
[6] Bockmann E, Steen S. Calculation of EEDIweather for a general cargo vessel. Ocean Eng 2016;122:68–73.
[7] Sasa K, Terada D, Shiotani S, Wakabayashi N, Ikebuchi T, Chen C, et al. Evaluation of ship performance in international maritime transportation using an onboard measurement system-in case of a bulk carrier in international voyages. Ocean Eng 2015;104:294–309.
[8] Xing S, Xinping Y, Bing W, Xing S. Analysis of the operational energy efficiency for inland river ships. Transport Res Part D 2013;22:34–9.
[9] Larsen U, Pierobon L, Baldi F, Haglind F, Ivarsson A. Development of a model for the prediction of the fuel consumption and nitrogen oxides emission trade-off for large ships. Energy 2015;80:545–55.
[10] Chatzinikolaou SD, Ventikos NP. Holistic framework for studying ship air emissions in a life cycle perspective. Ocean Eng 2015;110:113–22.
[11] Lindstad H, Eskeland GS. Low carbon maritime transport: how speed, size and slenderness amounts to substantial capital energy substitution. Transport Res Part D Transport Environ 2015;41:244–56.
[12] Bouman EA, Lindstad E, Rialland AI, Strømman AH. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—A review. Transport Res Part D Transport Environ 2017;52:408–21.

[13] Rehmatulla N, Calleya J, Smith T. The implementation of technical energy efficiency and CO 2 emission reduction measures in shipping. Ocean Eng 2017;139:184–97.

[14] Liao CH, Tseng PH, Cullinane K, Lu CS. The impact of an emerging port on the carbon dioxide emissions of inland container transport: an empirical study of Taipei port. Energy Pol 2010;38(9):5251–7.

[15] Burel F, Taccani R, Zuliani N. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy 2013;57:412–20.

[16] Wang K, Yan X, Yuan Y, Li F. Real-time optimization of ship energy efficiency based on the prediction technology of working condition. Transport Res Part D Transport Environ 2016;46:81–93.

[17] Moreno-Gutierrez J, Calderay F, Saborido N, Boile M, Valero RR, Duran-Grados V. Methodologies for estimating shipping emissions and energy consumption: a comparative analysis of current methods. Energy 2015, June 15;86:603–16.

[18] Smith TWP, O'Keeffe E, Aldous L, Agnolucci P. Assessment of Shipping's efficiency using satellite AIS data. 2013.

[19] Yao Z, Ng SH, Lee LH. A study on bunker fuel management for the shipping liner services. Comput Oper Res 2012;39(5):1160–72.

[20] Climate Action, European Commission. Reducing emissions from the shipping sector. 2016. http://ec.europa.eu/clima/policies/transport/shipping/index_en.htm. [Accessed 26 November 2016].

[21] Media Center, International Maritime Organization. IMO takes further action on climate change. 2016. http://www.imo.org/en/MediaCentre/PressBriefings/Pages/11-data-collection-.aspx. [Accessed 26 November 2016].

[22] International Maritime Organization. Reduction of GHG emissions from ships. Third IMO GHG Study 2014-Final Report. In: Marine environment protection committee 67th session; 2014.

[23] Japan. Further technical and operational measures for enhancing energy efficiency of international shipping. In: Marine protection committee 67st session, agenda item 5 (MEPC 67/5/4). International Maritime Organization; 2014.

[24] Faber J, Dagmar N, Stefan S. Further technical and operational measures for enhancing the energy efficiency of international shipping environmental aspects. 2014. https://www.oeko.de/oekodoc/2107/2014-664-en.pdf. [Accessed 3 November 2016].

[25] Energy Efficiency Indicators. Fundamentals on statistics (publication). 2014. https://www.iea.org/publications/freepublications/publication/IEA_EnergyEfficiencyIndicatorsFundamentalsonStatistics.pdf. [Accessed 6 November 2016].

[26] Jalkanen J-PB. A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. Atmos Chem Phys 2009, 9: 9209–23.

[27] De Meyer Pieter, Maes Frank, Volckaert Annemie. Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports. Atmos Environ 2008;42:196–206 (2008).

[28] Ball H. Satellite AIS for dummies. John Wiley & Sons Canada, Ltd; 2013.

[29] Class a AIS position report (messages 1, 2, and 3). 2016. https://www.navcen.uscg.gov/?pageName=AISMessagesA, . [Accessed 30 March 2017].

[30] Haifeng Wang NL. Long-term potential for increased shipping efficiency through the adoption of industry-leading practices. The International Council on Clean Transportation; 2013.

[31] Thomas Kister JC-J. ASSIST: access controlled ship identification streams. In: GIS: proceedings of the ACM international symposium on advances in geographic information systems; 2011.

[32] The maritime port authority of Singapore. 2015. http://www.mpa.gov.sg/sites/pdf/infokit2.pdf. [Accessed 8 November 2015].

[33] International Maritime Organization. Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI). 2009. MEPC.1/Circ.684.

[34] Norway. Reductions of GHG emissions from ships, consideration of a timeline for the three-step approach. In: Marine protection committee 71st session, agenda item 7 (MEPC 71/7/1). International Maritime Organization; 2017.