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Energy efficiency with the application of Virtual Arrival policy

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ABSTRACT

The shipping sector's emissions and energy efficiency are attracting increasing international scrutiny, with the International Maritime Organization (IMO) actively promoting better energy management by implementing mandatory Ship Energy Efficiency Management Plans (SEEMP). Key potential measures to improve energy efficiency and reduce emissions are speed optimization and improved communication with charterers and ports to work towards 'just in time' operation when there are known delays in port (Virtual Arrival). In this paper we assess empirically, for the first time, the potential reduction in fuel consumption and emissions from the implementation of a Virtual Arrival policy in a global context based on ship position data from the Automated Identification System (AIS). We evaluate 5066 voyages performed by 483 Very Large Crude Carriers (VLCCs) between 44 countries for the period 2013–2015 and estimate the potential for fuel savings if unproductive waiting time at the destination ports can instead be utilized to reduce the average sailing speed. We find that even if only 50% of the estimated waiting time can be avoided, the consequential slow-down in average sailing speeds leads to an average reduction of 422 tonnes of CO_2 and 6.7 tonnes of SO_x emissions per voyage. Our findings are important for policy making and the optimization of voyage management in shipping companies as they illustrate the substantial savings on fuel costs and emissions from the broad implementation of Virtual Arrival compared to the prevailing first-come first-served berthing policy and the standard charterparty term of sailing with 'utmost dispatch'.

1. Introduction

Shipping contributes to a growing share of global Green House Gas (GHG) emissions. Maritime transport emits around 1000 million tonnes of CO_2 annually and is responsible for about 2.5% of global GHG emissions (Smith et al., 2015a). Depending on future economic and energy developments, shipping emissions are projected to increase by 50–150% by 2050 under business-as-usual (BAU) scenarios (Smith et al., 2015a). This is not compatible with the internationally agreed goal of keeping the global temperature increase to below 2 °C compared to pre-industrial levels, which requires worldwide emissions to be at least halved from 1990 levels by 2050. The International Maritime Organization (IMO), as the main regulatory body for shipping, has committed to regulate shipping energy efficiency and thereby control the marine GHG emissions by technological development, operational measures and the use of alternative fuels. Introduced by the IMO in July 2011, the Ship Energy Efficiency Management Plan (SEEMP) entered into force on January 1, 2013. The SEEMP makes it mandatory for

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all ships of 400 gross tonnage and above to monitor, review and consider operational practices and technology upgrades to optimize the energy efficiency performance of a ship (Bazari and Longva, 2011).

Virtual Arrival (VA) is an operational process that involves an agreement to reduce a vessel's speed on a voyage to meet a Required Time of Arrival when there is a known delay at the discharge port (INTERTANKO, 2010). The industry associations which initiated the VA policy – the Oil Companies International Marine Forum (OCIMF) and the International Association of Independent Tanker Owners (INTERANKO), consider that 'it is inherently wasteful for a vessel to steam at full speed to a port where known delays to cargo handling have already been identified (INTERTANKO, 2010). Before a vessel's departure from the load port, or while en route to the discharge port, the port authority communicates to the vessel of delays due to congestion at the berth or lack of cargo handling space. The vessel owner or operator and the vessel charterer may agree to enter into a VA agreement for the voyage to reduce speed in order to make the Required Time of Arrival. A set of calculations and analysis need to be recorded for ship owners or operators and charterers to assess the VA policy implementation and the corresponding fuel savings (and, implicitly, emission reductions). As suggested in a survey by Rehmatulla and Smith (2015), lack of reliable information on potential costs and savings is one of the reasons that the VA policy is seldom implemented, even though a VA policy supports many of the elements detailed in the SEEMP process and should contribute to improving energy efficiency of the industry.

The objective of this paper is to estimate the potential fuel savings and emission reductions that could be achieved from the implementation of the VA policy for large tankers at the global level. For this purpose, we apply a bottom-up approach based on data from the Automated Identification System (AIS). AIS data can be processed to derive detailed information on the routing, speed and port calls for individual vessels, which allows us to assess the potential reductions in sailing speed and fuel consumption if a VA policy is introduced.

The remainder of this paper is structured as follows. Section 2 reviews the literature, Section 3 outlines the data & methodology, Section 4 presents the results and Section 5 contains concluding remarks and suggestions for future research.

2. Literature review

Improving energy efficiency or, equivalently, decreasing energy use, is an effective way to reduce GHG emissions (UNEP, 2011). Historically, shipping emissions were not perceived as a problem since vessels operated at sea far from humans (Lindstad et al., 2015). In 1997, the IMO added the Air Pollution Annex (VI) to the International Convention for the Prevention of Pollution from Ships (MARPOL Convention). Since then, attention has been directed to the damaging effects of shipping emissions in general (Corbett et al., 1999; Capaldo et al., 1999; Endresen et al., 2007; Corbett et al., 2007; Dalsoren et al., 2007) and at port areas in particular (Yang et al., 2007; Dong et al., 2002; Isaksson et al., 2001). The industry has undertaken significant technical development to improve energy efficiency such as hull dimension optimization, lightweight construction, hull coating, and propeller design (see, for instance, Motley et al., 2012; Doulgeris et al., 2012). In this paper, we focus on improving energy efficiency through operational measures.

Speed reduction, initially driven by economical concerns due to high fuel costs, has become one of the main measures regarded as making shipping more environmentally friendly. As an example, the first containerships could sail at up to 33 knots in the late 1960s when fuel was cheap, while Maersk recently ordered new 18,000 TEU 'triple E' (Economy of Scale, Energy efficient and Environmentally improved) containerships with a design speed of 19 knots (Psaraftis and Kontovas, 2013). According to naval architecture theory, there exists a nonlinear relationship between speed and fuel consumption, while CO_2, sulfur and other emissions are proportional to fuel burned, with the emission coefficient depending on the type of fuel (Smith et al., 2015a). Slow steaming has been demonstrated by Corbett et al. (2009) to cut carbon emissions by up to 70% across a range of containership routes. Zis et al. (2014) evaluated the effects of speed reduction and the utilization of alternative marine power on emissions near and at ports. They suggest that major pollutants can be significantly reduced on a full compliance basis. Psarafits and Kontovas (2013) provide a taxonomy of speed and energy efficiency, with the conclusion that, from a theoretical point of view, vessel speed is a key determinant to both shipping economics and the environmental sustainability of maritime transportation. However, empirical studies do not support the notion that ship owners or operators reduce speed according to theory (see, for instance, Adland et al., 2017a; Adland and Jia, 2016a,b; Assman et al., 2015). As noted in Rehmatulla and Smith (2015), there are barriers, such as charter clauses, in implementing operational measures such as speed reduction. Moreover, slow steaming could be an interim reaction to depressed markets but may not be a sustainable solution to an environmentally friendly shipping industry, especially when shipping markets recover.

On the other hand, Virtual Arrival is a practical process aimed at improving efficiency within the transportation chain, while achieving real benefits with regard to safety, fuel saving and the reduction in vessel emissions (INTERTANKO, 2010). Alvarez et al. (2010) use a simulation model where berth allocation, land-side equipment assignment and speed optimization is implemented in an object-oriented C++ algorithm to minimize costs. One port and four vessels were used in the simulation. Their results suggest that the virtual arrival policy can reduce fuel consumption by about 6% compared to the traditional First-Come-First-Served policy. Johnson and Styhre (2015) note that there exists a large, cost-effective potential to increase energy efficiency in short sea shipping through reduced speed at sea enabled by shorter waiting time in port. By using two vessels that operate in the North Sea and Baltic Sea as a case study, they demonstrate that a conservative 4 h shorter port waiting time (out of total 17 and 30 h unproductive waiting time per port call, respectively, by the two vessels), and a corresponding increase in sailing time, can decrease energy consumption by two to eight percent. Their results are of a similar magnitude as those found in Miola et al. (2010) and Faber et al. (2011). Bazari and Longva (2011) suggest that the implementation of a full range of SEEMP measures can potentially lead to a 30% reduction in an individual ship's fuel use.

The assessment of energy efficiency, particularly in energy consumption and emission accounting, stem from two approaches: top-down or bottom-up. A top-down approach usually refers to estimations based on fuel sales statistics (see, for instance, Endresen et al., 2007; Smith et al., 2015b). The top-down approach does not care which vessel carries out the activity and at what geographic location. Then, at a later stage, assumptions are made in order to assign total emissions to the different ships (Miola et al., 2010). In a bottom-up approach, the pollution that a single ship emits on a voyage is evaluated using vessel activity data (see, for instance, Paxian et al., 2010; Hulskotte and van der Gon, 2010). Since the first launch of satellites dedicated to capturing AIS signals in 2010, the application of AIS data in energy efficiency analysis has seen growing popularity. However, except for the recent IMO study (Smith et al., 2015a), the literature has so far been focusing on the evaluation of emission inventory in regional ports. Jalkanen et al. (2009) pioneered the evaluation of exhaust emissions of marine traffic based on AIS data, which enables the identification and location determination of ships. Miola et al. (2010) highlight the importance of utilizing AIS data in maritime transportation emission accounting. Ng et al. (2013) evaluate vessels emission inventory for Hong Kong port in 2007 using AIS data. Tichavska and Tova (2015a,b) estimate exhaust pollutants related to cruise and ferry operations in Las Palmas Port in 2011.

Perhaps due to the inherent challenges in working with very large AIS datasets, there are no empirical studies on the potential benefits of VA implementation on a global scale. Our research aims to fill this gap. We apply an AIS-based bottom-up approach to evaluate the reduction in fuel consumption and emissions if a Virtual Arrival policy is implemented for a large fleet of oil tankers in global trade.

3. Data and methodology

3.1. Data

The Virtual Arrival policy was initially conceived for the oil tanker markets. Oil tankers, like other tramp services, do not follow a fixed departure or arrival schedule, and therefore have more flexibility in adjusting sailing speed. We here focus on the fleet of Very Large Crude Carriers (VLCCs), typically transporting between 1.9 million and 2.2 million barrels of crude oil from the main exporting regions of the Arabian Gulf and West Africa, and to a lesser extent the North Sea and Venezuela, to the main importing areas of Asia and the United States.

Technical vessel specifications, including DWT, design speed, design draught and pump capacity, are provided by the Clarksons World Fleet Register (WFR). The AIS data, supplied by exactEarth for the years 2013–2015, contains information on vessel identification (MMSI/IMO, vessel name), geographic location (longitude and latitude), speed over ground (SOG), and the corresponding timestamps at a few seconds to minutes' interval depending on vessel sailing speed. Additional information on vessel draught and next port of call is updated less frequently, typically a few times per voyage.

We develop algorithms that identify port calls, and thus the end points of voyages, based on whether the vessel is stationary for a sustained period of time (defined here as SOG < 1 knot for at least 6 h) at a location close to land. We note that the total duration of a port call, according to this definition, may include loading or discharge operations, bunkering or other marine services, and waiting at anchorage. However, for the purpose of calculating savings due to VA implementation we will later exclude the expected time utilized for loading and discharge.

We identify a total of 5066 voyages performed by 483 Very Large Crude Carriers (VLCCs) between 210 ports in 44 countries, out of which 2812 voyages are laden (55.5%). Fig. 1 shows that 80% of the port calls in our sample are completed within 6 days. The descriptive statistics in Table 1 show that the average duration of a port call is 4 days vs. average sailing time of 22.7 days. In Appendix A we include port time statistics for the top 50 most visited ports in our sample. Port Kiire in Japan, Serangoon Harbor in Singapore, and Ain Sukhna Port in Egypt are among the most efficient oil terminals in the sample with less than two days average port time per call. Conversely, Chinese ports (Jintang, Rizhao and Zhen Hai, in particular) have some of the longest waiting times in the sample, averaging from 7 to 8 days. We note that port time per vessel or across time does not vary much, indicating that port identity is the major influencing factor in determining how long vessels need to wait.

Jia et al. (2017) find that the AIS-reported draught provides a good estimation of vessel payload. Thus, the loading condition of a vessel is determined by its draught ratio, defined as the ratio between reported draught and its design draught. Fig. 2 shows the plot of draught ratio in relationship to speed and illustrates the clear separation between ballast and laden condition in the tanker market. For the remainder of the paper, we consider voyages with a draught ratio below 70% as ballast voyages and above as laden voyages. Out of total sample of 5066 voyages, 2812 voyages are laden (55.5%) and 2164 voyages are ballast (43%), with the remaining 90 voyages missing draught information. In case of missing draught information, we refer to the port country to determine whether it's a crude oil importing or exporting country. For instance, vessels arriving at ports in countries such as Angola, Brazil and Qatar are almost certainly in ballast, while vessels arriving at ports in countries such as China, Japan or India are almost certainly laden.

For the purposes of calculating the equivalent fuel costs per voyage we apply the 380Cst HFO bunker price in Fujairah on the day of departure. Fig. 3 plots the bunker price during the sample period.

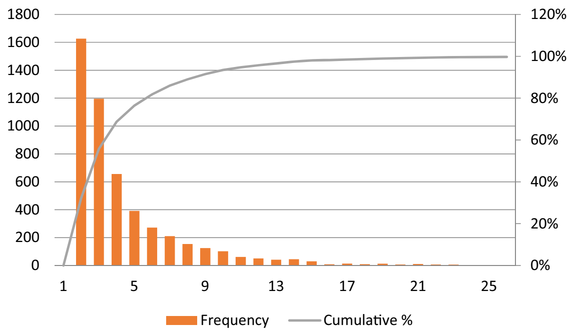

Fig. 1. Port time (days) histogram.

3.2. Bottom-up vessel fuel consumption calculation

A vessel's actual fuel consumption at sea depends on many parameters, such as vessel engine type and size (incl. main and auxiliary engines), hull shape, propeller design, load factor, and weather conditions. The fuel consumption function can be complex and may not even be defined in a closed form (Psaraftis and Kontovas, 2013). In general, the fuel consumption can be expressed as a function of displacement and speed (Adland et al., 2017b; MAN Diesel and Turbo, 2013; Gorski et al., 2013; Molland et al., 2011). With access to high-frequency speed data from AIS we can define the fuel consumption over a voyage as:

$$F_{i,j} = \sum_{t=1}^{T} \left(\frac{v_{i,j,t}}{v_{d,i}} \right)^{n} \cdot \left(\frac{\nabla_{\mathrm{i,j}}}{\nabla_{d,i}} \right)^{2/3} \cdot F_{d,i} \tag{1}$$

where $F_{i,j}$ is the total fuel consumption for vessel i during voyage j; $v_{i,j,t}$ is the sailing speed for vessel i during voyage j at hour t (total voyage time T); $v_{d,i}$ is the design speed for vessel i; n is a vessel-specific parameter; $\nabla_{i,j}$ is vessel i's displacement (tonnes) during voyage j; $\nabla_{d,i}$ is the full load displacement (tonnes) for vessel i; $F_{d,i}$ is the fuel consumption at design speed for vessel i (g fuel/kW h).

Psaraftos and Kontovas (2013) suggest that n = 3 is a good approximation for tankers and bulk carriers. Assuming the displacement can be approximated by the draught ratio (MAN Diesel and Turbo, 2013) we then have:

$$F_{i,j} = \sum_{t=1}^{T} \left(\frac{v_{i,j,t}}{v_{d,i}} \right)^{3} \cdot \left(\frac{\mathrm{D}_{\mathrm{i,j}}}{\mathrm{D}_{d,i}} \right)^{2/3} \cdot F_{d,i} \tag{2}$$

where $D_{i,j}$ is the draught for vessel i during voyage j; $D_{d,i}$ is the designed draught for vessel i.

We apply a bottom-up approach to calculate fuel consumption in tonnes for individual voyages by computing total voyage fuel consumptions based on hourly AIS speed data following the methodology that is also used in the 3rd IMO GHG study (Smith et al., 2015a). We also take into account vessels' engine type (main, auxiliary, auxiliary boilers); engine rating (SSD, MSD, HSD); whether engines are pre-IMO Tier I, or meet IMO Tier I or II requirements; and type of service (duty cycle) in which they operate (propulsion or auxiliary). For detailed bottom-up fuel consumption calculation procedures, please refer to Smith et al. (2015a).

Table 1
Descriptive statistics.

Unit	Port call duration days	Sailing time days	Port days/voyage days %	Sailing speed knots	Draught meters	Draught ratio[a] %	DWT Tonnes	DWT/pump capacity hours
Average	4.01	22.66	20.73%	11.26	16.28	75.60%	305,838	20.19
Median	2.72	20.24	13.56%	11.32	19.20	88.50%	303,994	19.43
Min	1.00	10.00	1.68%	7.01	7.00	33.92%	265,353	9.00
Max	47.33	71.19	357.28%	20.88	25.50	118.48%	323,182	63.69
Std. Dev.	3.71	10.52	22.80%	1.74	4.61	21.33%	10,022	7.26
Obs	5066	5066	5066	5066	4976	4976	5066	5066

[a] Draught ratio = AIS_reported draught/Design draught.

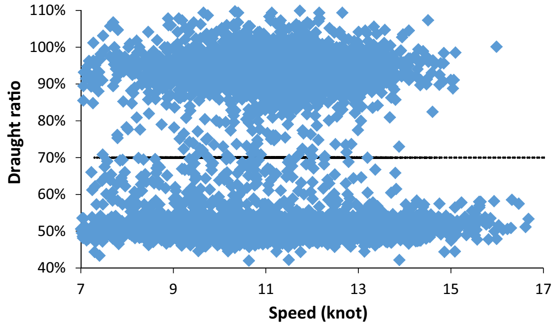

Fig. 2. Scatter plot of draught ratio vs. speed.

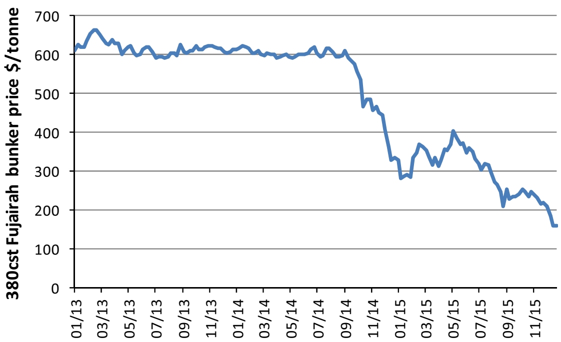

Fig. 3. Bunker price (Fujairah 380cst spot) $/tonne.

3.3. GHG and pollutant emissions

The production of greenhouse gases (e.g. carbon dioxide CO_2, methane CH_4 and nitrous oxide N_2O) and other pollutants (e.g. sulfur dioxide and particular matter PM) are proportional to the amount of fuel burned, with the proportionality constant being known as the 'emission coefficient'. The values of the coefficients are not absolute and are subject to factors such as fuel quality and engine conditions. For instance, the first IMO GHG study of 2000 used a carbon coefficient of 3.17 (tonne of CO_2 per tonne of fuel) independent of fuel type. The second IMO GHG study (Buhaug et al., 2009) updated the coefficient to 3.021 for HFO and to 3.082 for marine distillate oil such as Marine Gas oil (MGO). We use the latest figures from the third IMO GHG study of 2014, which are shown in Table 2.

3.4. The impact of speed reduction

The savings in fuel consumption and emissions from implementing a virtual arrival policy arise from the reduction in sailing speeds over the voyage. The theoretical reduction in fuel consumption based on comparing average sailing speeds across the voyage can be derived as follows. For a given voyage and a given vessel, the classical non-linear relationship between daily fuel consumption and vessel speed is given in the literature (Manning, 1956; Avi-Itzhak, 1974; Artz Jun, 1975) as:

$$\bar{f}_i = B \cdot \bar{v}_i^3 \tag{3}$$

where $\bar{f}_i$ is the average fuel consumption for vessel i per hour; $\bar{v}_i$ is the average sailing speed; B is a vessel-specific constant.If we ignore fuel consumption in port and at anchorage, total fuel consumption for vessel i during voyage j can be written as:

$$\bar{F}_{i,j} = B \cdot \bar{v}_{ij}^3 \cdot \frac{D_j}{\bar{v}_{ij}} \tag{4}$$

where $\bar{F}_{i,j}$ is the fuel consumption for vessel i during voyage j; $\bar{v}_{ij}$ is the average speed for vessel i during voyage j; D_j is sailing distance for voyage j.

The pseudo speed (v'_{ij}) for the alternative voyage where VA is implemented is computed based on the original voyage distance (D_j) and the original sailing time ($t_{0,i,j}$) plus the time that can be utilized due to shortened port waiting time $\Delta t_{i,j}$:

$$v'_{ij} = D_j/(t_{0,ij} + \Delta t_{ij}) \tag{5}$$

Table 2
emission factors for major GHG and pollutants.

Emissions species	Marine HFO (g/g fuel)	Marine MGO/MDO (g/g fuel)
CO_2	3.114	3.206
CH_4	0.00006	0.00006
N_2O	0.00016	0.00015
SO_X	0.04908	0.00264
PM	0.00699	0.00102

Source: IMO 3rd GHG Study (Smith et al., 2015a).

where $t_{0,ij}$ is the original sailing time at speed v_{ij} for vessel i during voyage j; t_{ij} is the port waiting time that can be reallocated for sailing for vessel i on voyage j;

Obviously, $v'_{ij} \leqslant v_{ij,0}$. According to Eq. (4), the new fuel consumption for the voyage becomes:

$$F'_{i,j} = B \cdot v'^{n}_{ij} \cdot \frac{D_j}{v'_{ij}} \tag{6}$$

Assuming all else remains the same, the approximate[1] percentage fuel consumption saving is then:

$$\Delta F_{i,j} = 1 - F'_{i,j}/\overline{F}_{ij} = 1 - (v'_{ij}/v_{ij})^2 \tag{7}$$

We note that due to less time ($\Delta t_{i,j}$ hours) spent in port, total fuel consumed by auxiliary engines while waiting is also reduced. However, given the marginal savings from reduced waiting at ports, this is omitted in the results.

3.5. Estimating savings in fuel costs and emissions

We recognize that a large portion of the observed duration of a port call might be necessary for maneuvering and cargo handling purposes. It may also be the case that some waiting time at the terminal is unavoidable, for instance due to logistical bottlenecks such as available tank storage capacity or structural congestion in the port that improved scheduling cannot solve. Finally, the flexibility of a vessel to reduce speed is dependent on her loading condition and the commercial terms on which she is hired (charter party clauses). When the vessel is laden, the charter party most likely contains contractual clauses which require the captain to "dispatch at utmost speed". When a vessel is in ballast, the captain has more flexibility to slow down unless he/she is under a contract to pick up a cargo within a laycan, which is the period within which the vessel must be presented at the agreed load port. The relationship between loading condition and speed reduction has also been discussed in Adland and Jia (2016a,b) and Adland et al (2017c).

Unfortunately, we do not have access to the detailed information required for the estimation of unnecessary waiting time during a port call ($\Delta t_{i,j}$) – what we here refer to as *excess port time*. Specifically, even if we could observe highly detailed ship movements within the port area, such as when a vessel arrives in and leaves the anchorage, this does not tell us how much of the waiting time was unavoidable due to e.g. weather and tidal conditions, lack of berthing space, or insufficient tank storage capacity. Consequently, we must make some further simplifying assumptions as outlined below:

- For laden voyages we set the minimum time in the discharge port as the ratio between vessel DWT (tonnes) and its pump capacity (cubic meters per hour), where tonnes are converted to cubic meters by a factor of 0.86. If the real pump capacity is not available for a vessel we use the fleet average.
- For ballast voyages, we set the minimum time in the loading port as 3.25 days (78 h), which is suggested to be the typical laytime for tankers (ICS, 2013).
- We consider four scenarios where the implementation of a Virtual Arrival policy is reducing the excess port time (i.e. the duration of a port call over and above the minimum port time for cargo handling) by 25%, 50%, 75% or 100%, respectively.

For analyzing the impact of a VA policy on fuel consumption reduction, we only include cases with average sailing speeds of 7 knots or above during the voyage. Seven knots is typically taken as the lowest feasible sailing speed for VLCCs (Adland and Jia, 2016b).

[1] We acknowledge that due to the non-linearity in Eq. (3), the average fuel consumption per time unit during a voyage need not be identical to the fuel consumption at the average voyage speed. This is therefore only a first-order approximation.

4. Results

4.1. Bottom-up benchmarking of fuel consumption and emissions

Based on the AIS-reported hourly vessel speeds and the formula in Eq. (2), we can calculate the fuel consumption per voyage as presented in Fig. 4 in relation to sailing time.

Table 3 summarizes the descriptive statistics for the fuel consumption and bunker cost per voyage. For the 5066 voyages in the sample, the average fuel consumption is 1248 tonnes at an average cost of 630,000 USD per voyage.

Once fuel consumption is calculated, emissions of GHG and pollutants are computed based on the emission factors in Table 2. Table 4 presents the descriptive statistics for the 5066 voyages in our sample. We note that the average CO_2 emission per voyage is 3886 tonnes with the maximum estimated at 25,130 tonnes (a 63-day voyage from Singapore to the US).

4.2. The impact of Virtual Arrival policy implementation

Table 5 summarizes the potential fuel consumption savings in percentage terms for the four scenarios. For scenario (1) where excess port time is reduced by 25%, the average fuel consumption saving is 7.26%, and the average port time reduction is 10.9 h. In scenario (2) where excess port time is reduced by 50% and the excess port time is reduced by 37 h, the VA policy leads to an average 12.5% savings in fuel consumption. In scenario (3), the average fuel consumption saving across the sample of voyages is 16%. In the final scenario (4) where all excess port time can be utilized for sailing, a 19% savings in fuel consumption can be achieved with 64 h average reduction in port time.

Tables 6 and 7 illustrates the corresponding savings in fuel costs and emissions based on the estimated savings in fuel consumption for the four scenarios defined above. For scenario (1), the average fuel consumption per voyage is 77 tonnes, corresponding to a cost saving of about 39,000 USD. Across the more than 5000 voyages performed by our sample fleet of

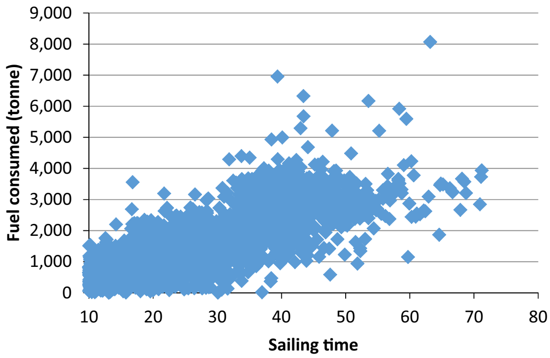

Fig. 4. Fuel consumption (tonne) and sailing time.

Table 3
Descriptive statistics for estimated fuel consumption and cost per voyage.

	Fuel consumption (tonnes)	Bunker cost (USD)
Mean	1248	630,342
Median	1011	497,114
Min	4.25	1594
Max	8070	4,858,106
Std. Dev.	828	463,030
Obs	5066	4786

Table 4
Descriptive statistics for GHG and pollutant emissions per voyage.

	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	SO_X (kg)	PM (kg)
Mean	3,886	75	200	61	8722
Median	3148	61	162	50	7067
Min	13	0	1	0	30
Max	25,130	484	1291	396	56,409
Std. Dev.	2578	50	132	41	5788
Obs	5066	5066	5066	5066	5066

Table 5
Descriptive statistics for fuel savings per voyage based on VA policy (%).

Scenarios	I. 25% excess port Time reduction		II. 50% excess port Time reduction		III. 75% excess port Time reduction		IV. 100% excess port Time reduction	
	Fuel saving	Port time (hr) saved	Fuel saving	Port time (hr) saved	Fuel saving	Port time (hr) saved	Fuel saving	Port time (hr) saved
Mean	7.26%	19.4	12.46%	36.8	16.34%	51.8	19.13%	63.8
Median	4.55%	11.7	8.56%	23.0	12.19%	33.7	15.37%	43.0
Min	0.00%	0.0	0.00%	0.0	0.00%	0.0	0.00%	0.0
Max	60.41%	192.3	70.27%	384.5	77.41%	540.1	75.54%	644.1
Std. Dev.	7.76%	21.6	11.67%	39.6	13.80%	54.2	14.66%	63.0
Obs	5013	5013	4917	4917	4798	4798	4650	4650

Table 6
Descriptive statistics for fuel savings per voyage from VA policy (tonnes and US$).

	I. 25% excess port Time reduction		II. 50% excess port Time reduction		III. 75% excess port Time reduction		IV. 100% excess port Time reduction	
	Fuel saving (tonne)	Bunker cost saving (USD)	Fuel saving (tonne)	Bunker cost saving (USD)	Fuel saving (tonne)	Bunker cost saving (USD)	Fuel saving (tonne)	Bunker cost saving (USD)
Sum	386,374	194.6 m	678,860	341.6 m	896,304	450.2 m	1,050,545	526.2 m
Mean	77.1	38,821	138.1	68,142	186.8	89,809	225.9	104,976
Median	47.3	22,854	89.4	42,231	126.8	58,216	158.8	69,596
Min	0.0	6	0.0	–	0.0	–	0.0	–
Max	914.4	566,957	1519.6	942,148	1940.7	1,203,231	1879.4	1,042,463
Std. Dev	86.6	46,579	146.1	78,723	189.6	101,585	221.4	117,572
Obs	5013	5013	4917	5013	4798	5013	4650	5013

483 vessels this amounts to total fuel cost savings of 195 million USD. This increases to as much as 105,000 USD or 226 tonnes of fuel oil per voyage in scenario (4), where all excess port time can be utilized for sailing. The CO_2 emission reduction ranges from 240 tonnes (scenario 1) to 653 tonnes (scenario 4) on average per voyage. Similarly, sulfur dioxide emissions can be reduced by 3.8 tonnes (scenario 1) to 10 tonnes (scenario 4).

5. Conclusion and discussion

The shipping industry is facing a growing pressure on reducing carbon emissions, especially after the 2015 United Nations Climate Change Conference. IMO has committed to reduce carbon emissions from shipping by 50% by year 2050. The implementation of a Virtual Arrival policy is one of the measures that the industry can adopt to achieve this goal. Other measures, such as the inclusion of the shipping industry in the EU Emission Trading System (ETS) or a similar IMO initiative such as a CO_2 fund would explicitly price emissions and make the monetary savings of a VA implementation even higher. Until then, shipowners' interests are aligned with those of the environment only through the fuel cost savings that a VA policy would entail.

In this paper we have expanded the literature on bottom-up emission accounting in shipping to consider the effects of implementing a Virtual Arrival policy for VLCC tankers at the global level. Based on AIS-derived vessel activity data, we consider a large dataset of 5066 ballast and laden voyages for a fleet of 483 VLCCs visiting over 200 oil terminals between 2013 and 2015. This is a substantial and important step up from the minor regional trades and/or small fleets considered in the literature until now. Depending on how much of the 'excess' port time can instead be utilized for sailing, we show that fuel savings can range from 7.26% with only a 25% reduction in 'excess' port time, to 19% if all apparent inefficiencies can be removed. This corresponds to savings of 77 tonnes to 226 tonnes of HFO per voyage, and bunker cost savings ranging from 39,000 USD to 105,000 USD per voyage. Similarly, CO_2 emission reductions range from 240 tonnes for the 25% scenario to 539 tonnes per voyage for the 100% scenario. While 100% reduction in excess port time may not be achievable in practice as a logistics chain will never be perfect, these numbers suggest that there is a substantial untapped environmental benefit from forcing the implementation of a VA policy at the global level in place of the current First-come-first-served port policies. This suggests that current policy discussions at the EU and IMO level should incorporate Virtual Arrival as a key measure to reduce the environmental footprint of the industry.

The implementation of Virtual Arrival policies also has other potential benefits beyond fuel savings and emission reductions. Its successful implementation requires information sharing among market players, such as ship the owner or operator, the charterer and port authorities. Increased transparency and better cooperation and communication can lead to "smarter shipping," as suggested by Stopford (2016). This would echo the trend in aviation transportation where new Air Traffic Man-

Table 7
Descriptive statistics for emissions reduction from VA policy (tonnes).

	I. 25% excess port time reduction				
	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	SO_X (kg)	PM (kg)
Sum	1,203,169.81	23,182.46	61,819.90	18,963,253.70	2,700,756.88
Mean	240.01	4.62	12.33	3,782.82	538.75
Median	147.15	2.84	7.56	2,319.17	330.30
Min	0.03	0.00	0.00	0.52	0.07
Max	2,847.59	54.87	146.31	44,881.02	6,391.98
Std.Dev.	269.52	5.19	13.85	4,247.92	604.99
Obs	5,013.00	5,013,000.00	5,013,000.00	5,013,000.00	5,013,000.00
	II. 50% excess port time reduction				
	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	SO_X (kg)	PM (kg)
Sum	2,113,970.80	40,731.61	108,617.63	33,318.46	4,745,233.08
Mean	421.70	8.13	21.67	6.65	946.59
Median	271.82	5.24	13.97	4.28	610.15
Min	0.00	0.00	0.00	0.00	0.00
Max	4,732.02	91.18	243.14	74.58	10,621.96
Std.Dev.	454.50	8.76	23.35	7.16	1,020.21
Obs	5,013	5,013	5,013	5,013	5,013
	III. 75% excess port time reduction				
	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	SO_X (kg)	PM (kg)
Sum	2,791,091.05	53,778.24	143,408.65	43,990,604.70	6,265,165.80
Mean	556.77	10.73	28.61	8,775.31	1,249.78
Median	374.20	7.21	19.23	5,897.84	839.97
Min	0.00	0.00	0.00	0.00	0.00
Max	6,043.32	116.44	310.51	95,249.31	13,565.46
Std.Dev.	589.55	11.36	30.29	9,291.89	1,323.36
Obs	5,013	5,013,000	5,013,000	5,013,000	5,013,000
	IV. 100% excess port time reduction				
	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	SO_X (kg)	PM (kg)
Sum	3,271,397.94	63,032.71	168,087.23	51,560,759.33	7,343,311.33
Mean	652.58	12.57	33.53	10,285.41	1,464.85
Median	453.78	8.74	23.32	7,152.13	1,018.61
Min	0.00	0.00	0.00	0.00	0.00
Max	5,852.45	112.76	300.70	92,240.91	13,137.00
Std.Dev.	688.59	13.27	35.38	10,852.96	1,545.68
Obs	5013	5,013,000	5,013,000	5,013,000	5,013,000

agement principles have been introduced to redesign routes around the performance of the flight, managing the optimized use of airspace, and allowing flight computers to plot their own, most efficient route (Sarkar, 2012). Also in shipping, there is the potential to deploy AIS data in real time to predict congestion and, hence, aid ship owners and operators in optimizing arrival times, bearing in mind that such optimization need not lead to a reduction in speed in all cases. Furthermore, the ability to adjust speed will also depend on other external factors like weather and contractual clauses.

We acknowledge that further research is necessary to verify the robustness of our results. In particular, while our current sample is large, it does not cover all voyages performed by all VLCCs in the fleet during the period. AIS data are notoriously difficult to handle, with gaps in the data feeds typically occurring in high-density activity areas such as the South China Sea – an important area for oil discharge. Therefore, we cannot be assured that the voyages we have been able to extract are representative and unbiased. Furthermore, smaller vessel sizes should also be considered, as they will have a higher ratio of port time to sailing time. They may therefore show even greater emission reduction potential from the implementation of a VA policy.

We also acknowledge that a more detailed geospatial analysis of each port call based on AIS data would be beneficial. Ideally, we would specify the coordinates of each anchorage area and jetty/terminal for loading/discharge in every port and track movements of the vessel within the greater port area to better assess the time actually spent in anchorage. However, given the substantial work involved and the highly uncertain payoff in terms of improved accuracy, we leave such improvement in our algorithms for future research. In this context, it is worth noting that some cargo handling operations may take place while the vessel is at anchorage by way of ship-to-ship transfers (e.g. US East Coast lightering operations).

An important future line of research would also be how to implement a VA policy in a manner that aligns the interests of both shipowners, charterers and port authorities. Specifically, researchers should explore new contractual arrangements to share the fuel savings from a Virtual Arrival implementation between stakeholders across all charterparty types to encourage its adoption.

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Appendix A

See Table 8.

Table 8
Top 50 most visited ports port time profile (source: own calculation based on sample).

Ranking by visits	port name	port country	avg Port days	Min Port days	Max Port days	# visits
1	KHAWR FAKKAN	United Arab Emirates	4.59	1.00	47.33	783
2	FUJAYRAH HARBOR	United Arab Emirates	3.61	1.00	18.08	220
3	ZHOUSHAN	China	5.22	1.12	20.92	178
4	JU AYMAH OIL TERMINAL	Saudi Arabia	2.41	1.00	8.84	170
5	AIN SUKHNA TERMINAL	Egypt	2.00	1.00	8.75	160
6	JURONG ISLAND	Singapore	6.04	1.05	30.66	160
7	YOKKAICHI	Japan	2.60	1.04	8.79	126
8	CHIBA KO	Japan	2.43	1.01	6.08	125
9	KEPPEL - (EAST SINGAPORE)	Singapore	2.86	1.00	17.92	123
10	VADINAR TERMINAL	India	3.44	1.05	21.71	121
11	BEDI	India	3.96	1.20	14.26	109
12	GALVESTON	United States	4.31	1.06	13.22	100
13	MINA AL FAHL	Oman	3.93	1.05	14.18	98
14	KAWASAKI KO	Japan	2.42	1.09	8.08	95
15	DALIAN	China	4.87	1.08	15.71	83
16	RIZHAO	China	6.62	1.34	30.80	75
17	RAS TANNURAH	Saudi Arabia	2.38	1.03	8.92	68
18	GWANGYANG HANG	South Korea	2.98	1.16	10.71	68
19	QINGDAO GANG	China	5.19	1.37	16.08	67
20	ULSAN	South Korea	2.41	1.04	5.69	66
21	MALONGO OIL TERMINAL	Angola	3.22	1.05	9.87	65
22	ZHEN HAI	China	7.47	1.59	19.67	65
23	AL-BASRA OIL TERMINAL	Iraq	10.21	1.23	23.59	65
24	KIIRE	Japan	1.73	1.01	8.54	62
25	XIUYU	China	3.05	1.67	11.33	60
26	KO SI CHANG TERMINAL	Thailand	2.93	1.36	10.23	57
27	SERANGOON HARBOR	Singapore	1.95	1.00	9.60	50
28	TANGSHAN (JINGTANG)	China	6.80	1.14	24.16	50
29	ZIRKUH PETROLEUM PORT	United Arab Emirates	2.56	1.00	8.62	48
30	LOOP TERMINAL	United States	2.68	1.00	6.17	45
31	DAESAN HANG	South Korea	2.71	1.13	8.94	45
32	KAO-HSIUNG	Taiwan	3.92	1.08	14.79	45
33	JABAL AZ ZANNAH/RUWAYS	United Arab Emirates	2.33	1.06	7.24	44
34	MAILIAO	Taiwan	2.52	1.37	14.17	43
35	ZHANJIANG	China	2.73	1.00	9.27	39
36	TOMAKOMAI KO	Japan	5.04	1.66	13.92	39
37	TIANJIN XIN GANG	China	5.13	1.79	14.28	39
38	PARADIP	India	3.09	1.06	9.17	33
39	BAYUQUAN	China	4.22	1.20	8.83	33
40	POINTE NOIRE	Congo (Brazzaville)	4.00	1.11	9.70	32
41	YANGPU	China	5.53	1.52	18.39	32
42	PELABUHAN SUNGAI UDANG	Malaysia	7.12	1.09	22.29	32
43	DURBAN	South Africa	5.15	1.11	21.46	30
44	PULAU SEBAROK	Singapore	3.06	1.00	7.87	29
45	RAYONG TPI TERMINAL	Thailand	2.25	1.05	3.29	28
46	JOSE TERMINAL	Venezuela	7.15	2.29	17.24	28
47	QUA IBOE OIL TERMINAL	Nigeria	5.31	1.02	12.69	27
48	TANJUNG BALAI KARIMUN	Indonesia	6.66	1.21	17.99	27
49	HUIZHOU	China	2.71	1.09	7.07	25
50	MINA AL AHMADI	Kuwait	2.26	1.01	9.46	23

References

Adland, R., Jia, H., 2016a. Dynamic speed choice in bulk shipping. Marit. Econ. Logist. http://dx.doi.org/10.1057/s41278-016-0002-3. forthcoming.

Adland, R., Jia, H., 2016b. Vessel speed analytics using satellite-based ship position data. In: Proceedings of the 2016 IEEE IEEM conference, Bali, pp. 1299–1303, http://dx.doi.org/10.1109/IEEM.2016.7798088.

Adland, R., Alger, H., Banyte, J., Jia, H., 2017a. Does fuel efficiency pay? Empirical evidence from the drybulk timecharter market revisited. Transport. Res. Part A 95, 1–12.

Adland, R., Jia, H., Strandenes, S.P., 2017b. The determinants of vessel capacity utilization: the case of Brazilian iron ore exports. Transport. Res. Part A. http://dx.doi.org/10.1016/j.tra.2016.11.023.

Adland, R., Fonnes, G., Jia, H., Lampe, O.D., Strandenes, S.P., 2017c. The impact of regional environmental regulations on empirical vessel speeds. Transport. Res. Part D 53, 37–49.

Assman, L., Andersson, J., Eskeland, G.S., 2015. Missing in action? Speed optimization and slow-steaming in maritime shipping, discussion paper 13/2015. Norwegian School of Economics.

Alvarez, J.F., Longva, T., Engebrethsen, E.S., 2010. A methodology to assess vessel berthing and speed optimization policies. Marit. Econ. Logist. 12 (4), 327–346.

Artz Jun, J.C., 1975. The economics of tanker slowdown: an observation. Marit. Pol. Manage. 2 (4), 244–249.

Avi-Itzhak, J., 1974. Speed, fuel consumption and output of ships: some quantitative economical and national implications of the oil crisis. Transp. Res. 10 (3), 221.

Bazari, Z., Longva, T., 2011. Assessment of IMO mandated energy efficiency measures for international shipping. Report commissioned by the International Maritime Organization and under Lloy's Register in partnership with Det Norske Veritas, MEPC 63/INF.2. London UK: IMO.

Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K., 2009. Second IMO GHG Study, International Maritime Organization (IMO) London, UK.

Capaldo, K., Corbett, J.J., Kasibhatla, P., Fischbeck, P., Pandis, S.N., 1999. Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean. Nature 400, 743–746.

Corbett, J.J., Fishbeck, P.S., Pandis, S.N., 1999. Global nitrogen and sulphur inventories for oceangoing ships. J. Geophys. Res. 104, 3457–3470.

Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V., Lauer, A., 2007. Mortality from ship emissions: a global assessment. Environ. Sci. Technol. 41, 8512–8518.

Corbett, J.J., Wang, H., Winebrake, J.J., 2009. The effectiveness and costs of speed reductions on emissions from international shipping. Transp. Res. Part D 14 (8), 593–598.

Dalsoren, S.B., Endresen, O., Isaksen, I.S., Gravir, G., Sorgard, E., 2007. Environmental impacts of the expected increase in sea transportation, with a particular focus on oil and gas scenarios for Norway and northwest Russia. J. Geophys. Res. 112, D02310.

Dong, C., Huan, K.L., Chen, C.W., Lee, C.W., Lin, H.Y., Chen, C.F., 2002. Estimation of air pollutants emission from shipping in the Kaohsiung harbor area. Aerosol Air Qual. Res. 2 (1), 31–40.

Doulgeris, G., Korakianitis, T., Pilidis, P., Tsoudis, E., 2012. Techno-economic and environmental risk analysis for advanced marine propulsion systems. Appl. Energy 99, 1–12.

Endresen, O., Sorgard, E., Behrens, H.L., Brett, P.O., Isaksen, I.S., 2007. A historical reconstruction of ships' fuel consumption and emissions. J. Geophys. Res.: Atmos. 112 (D12), 112.

Faber, J., Wang, H., Nelissen, D., Russell, B., Amand, D., 2011. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures. International Maritime Organization, London, UK.

Gorski, W., Abramowics-Gerigk, T., Burciu, Z., 2013. The influence of ship operational parameters on fuel consumption. Sci. J. 36 (108), 49–54.

Hulskotte, J.H.J., van der Gon, H.A.C.D., 2010. Fuel consumption and associated emissions from seagoing ships at berth derived from an on-board survey. Atmos. Environ. 44, 1229–1236.

ICS, 2013. Tanker Chartering. Institute of Chartered Shipbrokers, United Kingdom.

INTERTANKO, 2010. Virtual arrival, optimizing voyage management and reducing vessel emission – an emissions management framework Available from: www.intertanko.com.

Isaksson, J., Persson, T.A., Lindgren, E.S., 2001. Identification and assessment of ship emissions and their effects in the harbor of Goteborg, Sweden. Atmos. Environ. 35, 3659–3666.

Jalkanen, J.P., Brink, A., Kalli, J., Petterson, H., Kubbonen, J., Stipa, T., 2009. A modelling system for the exhaust emission of marine traffic and its application in the Baltic Sea area. Atmos. Chem. Phys. 9, 9209–9223.

Jia, H., Prakash, V., Smith, T., 2017. Estimating vessel payloads using AIS data in bulk shipping. Working paper in review process.

Johnson, H., Styhre, L., 2015. Increased energy efficiency in short sea shipping through decreased time in port. Transp. Res. Part A 71, 167–178.

Lindstad, H., Sandaas, I., Stromman, A.H., 2015. Assessment of cost as a function of abatement options in maritime emission control areas. Transp. Res. Part D 38, 41–48.

MAN Diesel & Turbo, 2013. Basic Principles of Ship Propulsion.

Manning, G., 1956. The Theory and Technique of Ship Design; a Study of the Basic Principles and the Processes Employed in the Design of Ships of All Classes. The MIT Press, Cambridge.

Miola, A., Ciuffo, B., Giovine, E., Marra, M., 2010. Regulating Air Emissions From Ships: The State of the Art on Methodologies, Technologies and Policy Options. European Commission Joint Research Centre, Luxembourg.

Molland, A.F., Turnock, S.R., Hudson, D.A., 2011. Ship Resistance and Propulsion Practical Estimation of Ship Propulsive Power. Cambridge University Press.

Motley, M.R., Nelson, M., Young, Y.L., 2012. Integrated probabilistic design of marine propulsors to minimize lifetime fuel consumption. Ocean Eng. 45, 1–8.

Ng, S.K.W., Loh, C., Lin, C., Booth, V., Chan, J.W.M., Yip, A.C.K., Li, Y., Lau, A.K.H., 2013. Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearly River Delta. Atmos. Environ. 76, 102–112.

Paxian, A., Eyring, V., Beer, W., Sausen, R., Wright, C., 2010. Present-day and future global bottom-up ship emission inventories including polar routes. Environ. Sci. Technol. 44 (4), 1333–1339. http://dx.doi.org/10.1021/es9022859.

Psaraftis, H.N., Kontovas, C.A., 2013. Speed models for energy-efficient maritime transportation: a taxonomy and survey. Transp. Res. Part C 26, 331–351.

Rehmatulla, N., Smith, T., 2015. Barriers to energy efficiency in shipping: a triangulated approach to investigate the principle agent problem. Energy Policy 84, 44–57.

Sarkar, A.N., 2012. Evolving green aviation transport system: a holistic approach to sustainable green market development. Am. J. Clim. Change 1, 164–180.

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., Hoen, M., Chesworth, S., Pandey, 2015a. Third IMO GHG Study 2014. International Maritime Organization (IMO) London, UK.

Smith, T.W.P., Prakash, V.; Aldous, L., Krammer, P., 2015b. The Existing Shipping Fleet's CO_2 Efficiency; International Maritime Organization (IMO) London, UK.

Stopford, M., 2016. Smart shipping: the global vision. Speech at CMA Conference March 22, 2016, Stamford, the United States.

Tichavska, M., Tovar, B., 2015a. Port-city exhaust emission model: an application to cruise and ferry operations in Las Palmas Port. Transp. Res. Part A 78, 347–360.

Tichavska, M., Tovar, B., 2015b. Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. Transp. Res. Part E 83, 126–140.

UNEP, 2011. Bridging the emissions gap. United Nations Environment Programme (UNEP) <http://www.unep.org/pdf/UNEP_bridging_gap.pdf>.

Yang, D., Kwan, S.H., Lu, T., Fu, Q., Cheng, J., Streets, D.G., Wu, Y., Li, J., 2007. An emission inventory of marine vessels in Shanghai in 2003. Environ. Sci. Technol. 41 (15), 5183–5190.

Zis, T., North, R.J., Angeloudis, P., Ochieng, W.Y., Bell, M.G.H. 2014. The effects of speed reduction policies near ports. Transport Research Board 2014 Annual Meeting proceeding.