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ORIGINAL ARTICLE

Reducing pollutant emissions from vessel maneuvering in port areas

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Abstract

We propose an activity-based model to calculate ships' exhaust emissions while maneuvering in port. The exhaust emissions from the seven international commercial ports in Taiwan (namely Kaohsiung, Keelung, Taichung, Taipei, Hualien, Anping, and Suao) were calculated using actual data. Then, the regional ship exhaust emissions were estimated based on the number and size of ships and the type of fuel they used. Our method of predicting and evaluating the effectiveness of green port policies is shown to be intuitive and precise. Small vessels, which are the most common vessel type to enter and leave Taiwan ports, were shown to generate most of the emissions, but unit emissions from large vessels were the highest among three types of vessels (i.e., small, medium, and large). Moreover, greenhouse gas (GHG) emissions corresponded to sailing speed. Taiwan International Ports Co., Ltd (TIPC) has slightly reduced carbon dioxide equivalent and sulfur oxide emissions by implementing a green port policy, consisting of multiple ways of building a sustainable port environment (such as vessel speed reduction and use of low-sulfur oil). However, nitrogen oxide emissions have not decreased significantly. Our findings indicate that lower speeds and onshore power supply can reduce local air pollution, and assist transportation authorities, who should consistently monitor GHG emissions in port, to proactively respond to the International Maritime Organization's regulations for ensuring a sustainable future.

Keywords Activity-based model · Maneuvering · Ship exhaust emissions · Green port policies · Greenhouse gas (GHG) · Sustainability

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1 Introduction

Shipping is a major mode of transportation, handling 80% of the world's traded goods by volume [United Nations Conference on Trade and Development (UNCTAD) 2019]. Although ocean transportation is one of the most environmentally efficient modes of transport in terms of emissions per ton of cargo transported (Song 2014), because seaborne trade volume has reached 11.08 billion tons and because container ports handled 811.2 million 20-foot equivalent units in 2019 (UNCTAD 2020), shipping companies and port authorities must implement carbon neutrality strategies to comply with intergovernmental obligations and national policies. According to the Fourth International Maritime Organization (IMO) Greenhouse Gas (GHG) Study, shipping's share of global anthropogenic emissions increased from 2.76% in 2012 to 2.89% in 2018. Although the effect of coronavirus disease 2019 (COVID-19) on emissions projections cannot yet be quantitatively assessed, emissions in 2020 and 2021 will likely be considerably lower (International Maritime Organization 2020a, 2020b).

In 2015, The United Nations released a document entitled "Transforming Our World: the 2030 Agenda for Sustainable Development," which consists of 17 sustainable goals (SDGs; https://sdgs.un.org/goals). In response to that agenda, the IMO began to support Sustainable Development Goal 13, climate action, to address climate change, and adopted a strategy to reduce GHG emissions from ships in accordance with the 72nd and 74th sessions of the Marine Environment Protection Committee.

In July 2021, the IMO announced "World Maritime theme 2022: New technologies for greener shipping." The theme was linked to SDGs 13, climate action; 14, sustainable use of the oceans, seas, and marine resources; 9, industry, innovation, and infrastructure; and 17, the crucial role of partnerships in achieving these goals (International Maritime Organization 2021).

The abatement of maritime air emissions in and around ports heavily affects air quality and the health of those around the ports (Tichavska and Tovar 2015). Air emissions consist mainly of carbon dioxide (CO_2), sulfur oxides (SO_X), nitrogen oxides (NO_X), particulate matter (PM_X), volatile organic compounds, and ozone (O_3) and have become a major concern because of their substantial impact on human health, global warming, and climate change (Christodoulou et al. 2019; Cullinane and Cullinane 2013; Hui-Huang 2015; Tai and Lin 2016).

Ports occupy a vital position between sea and land transportation (Liu et al. 2016). Ports are under increasing pressure from stakeholders, such as port users, regulators, and surrounding communities, to reduce the air emissions generated by their activities. Port operations are associated with large amounts of air emissions and external costs, and air quality is a major concern among the general public (Sornn-Friese et al. 2021).

Efforts to reduce GHG emissions must be analyzed both from the perspective of ports and that of ships. Various policies and incentives have been proposed to reward the reduction of air emissions. Zis et al. (2014) evaluated onshore power (also known as "cold ironing") and speed reduction (also known as "slow steaming") when vessels maneuver in ports, and Winnes et al. (2015) examined the potential of various measures to reduce emissions, such as alternative fuels and ship designs and operations. Zhou et al. (2020) investigated the emissions related to ports and their environmental impact and discovered that the emissions from trucks were much higher than those of cargo-handling equipment in container terminals. Tseng and Ng (2020) analyzed green policies in three container ports, and the results indicated that financial considerations (port pricing, investment in port infrastructure, and port incentives) were the main criteria driving the adoption of such policies. The introduction of slow steaming and the adoption of liquefied natural gas (LNG), as an alternative source of marine fuel, are some of the measures that have been undertaken by the shipping industry to reduce fuel consumption (Maloni et al. 2013).

The main factors that affect a ship's fuel consumption are its design, size, and speed, and slow steaming is the most popular strategy for shipping companies to increase fuel efficiency and lower GHG emissions from ships (Psaraftis and Kontovas 2010, 2014; Woo and Moon 2014). Therefore, an investigation of optimum sailing speeds could yield highly valuable information.

There are many studies discussing green port policies of port cities, but few of them have reviewed the performance of those policies by using existing port data as we do here. We apply an activity-based model to evaluate the performance of ports in Taiwan from 2011 to 2020 and their green harbor policies. In doing so, the study offers general managerial insights to port authorities in other countries.

The rest of this paper is organized as follows: Sect. 2 provides the literature review; Sect. 3 establishes an examination of the empirical studies on emissions from ship maneuvering, and an activity-based model to calculate air emissions; Sect. 4 presents the results; and Sect. 5 consists of the concluding remarks.

2 Literature review

2.1 Policies, incentives, and measures to reduce GHG emissions

Air pollution from ships in port has a substantial negative effect on the health of port city residents (Dragović et al. 2018). The pollution produced by port activities can originate from several complex sources (i.e., air pollution, water pollution, and soil and sediment). According to Chen et al. (2017), ship emissions are a major source of air pollution in port cities and inland river regions, and they negatively affect regional air quality, global climate, and human health. The IMO has instigated a series of regulations and operational practice guidelines to reduce emissions from the shipping industry. CO_2 emissions can be reduced by, for instance, implementing more efficient operational practices, such as slow steaming (Psaraftis and Kontovas 2014). This is because a ship's fuel consumption is a function of the displacement of the ship (to the power of 2/3 ($D^{2/3}$) and to the cube of the ship's speed (V^3) (International Maritime Organization 2016; Psaraftis and Kontovas 2014); reducing the speed of vessels is already underway in reducing emissions (Psaraftis 2019). Reducing waiting times in port can accelerate turnaround and is a cost-effective, energy-efficient measure with limited adverse effects on cargo transit time and vessel productivity.

Port authorities can establish environmental policies to prevent pollution, based on international maritime conventions, such as the International Convention for the Prevention of Pollution from Ships (MARPOL), on central competent authorities, and on local law enforcement agencies (Tseng and Pilcher 2019). Lam and Notteboom (2014) indicated that meeting the minimum environmental standards for port environmental regulations requires incentive mechanisms and technical assistance. Various ports worldwide have adopted new policies, such as emission control areas (ECAs) and the use of alternative power (i.e., LNG, biofuels, or onshore power technologies; Olcer and Ballini 2015; Poulsen et al. 2018).

The optimization of sailing speeds in container ports has also gained considerable attention from scholars (e.g., Psaraftis 2019). Pang et al. (2021) concluded that green shipping practices positively affect corporate reputation and stakeholders in the supply chain. Therefore, shipping companies should investigate and implement green shipping practices. In addition, studies have investigated the so-called scheduling problem by developing models to optimize global liner networks and guide the selection of speed under different commercial constraints (Wang and Meng 2017). Several studies on scheduling problems and speed selection have also explicitly considered environmental externalities associated with shipping-related air emissions (Psaraftis and Kontovas 2014; Tai and Lin 2013). An additional benefit of quicker vessel turnaround is that it reduces local air pollution in ports, many of which are located near densely populated areas.

2.2 Case study of nations with high GHG emissions

Technical, operational, and market-based strategies have been implemented worldwide to reduce air pollution from ships (Lim et al. 2019). However, no single measure is by itself sufficient to substantially reduce GHG emissions. Several studies have investigated the reduction of GHG emissions through technical measures (e.g., energy efficiency design index and ship energy efficiency management plan) and their costs of implementation (Giziakis and Christodoulou 2012). Psaraftis and Kontovas (2010) evaluated operational models and policies to reduce GHG emissions along the maritime intermodal container chain, focusing on reduced port service times and the prompt berthing of vessels upon arrival. In addition, several studies have identified a need for efficient market-based incentives and policy instruments that encourage investment in innovative abatement technologies, and the use of alternative fuels in the shipping industry (Giziakis and Christodoulou 2012). Wan et al. (2018) evaluated the development of technical, operational, and market-based policies to abate GHG emissions from shipping. According to their study, market-based approaches must be adopted to address the environmental impact of shipping.

From a national perspective, according to statistics from the European Union (EU), transportation is the dominant sector in final energy consumption (i.e., 31% of total energy consumption), followed by households and industry uses (Eurostat 2019). Tsita et al. (2019) indicated that biofuels represent a viable option for reducing carbon emissions, and that the EU has established a goal for all member states to replace 10% of road transport fuel with biofuel in pursuit of its "neutral EU" concept by 2050 (https://op.europa.eu/s/uFOT) and in accordance with the climate action guidelines of the Paris Agreement. To achieve these goals, the EU carbon emissions must decrease by 55% by 2030. For maritime stakeholders, the European Commission proposed the goal of renewable and low-carbon fuels constituting approximately 6–9% of the bunker fuel mix by 2030 and 86–88% by 2050. The European Commission proposed three mechanisms for regulating GHG emissions from shipping: a blending mandate requiring a minimum share of certain green fuels in the fuel mix; a goal-based carbon intensity target for vessels independent of fuel choice; and a goal-based intensity target with a reward system to encourage high achievement (European Commission 2021). During the Conference of the Parties 26 (COP26) summit, European Commission President Ursula von der Leyen pledged €1 billion in funding for the Global Forests Finance; €100 million for the Climate Adaptation Fund; a Just Energy Transition Partnership with South Africa; and officially launched the Global Methane Pledge, a joint EU–USA initiative that has mobilized over 100 countries to cut their collective methane emissions by at least 30% by 2030, compared with 2020 (https://ec.europa.eu/commission/presscorner/detail/pt/ip_21_6021).

Some ports in the United States, such as the Port of Los Angeles and Long Beach, the Port of New York and New Jersey, and the Port of San Diego, have designated a reduced speed zone to reduce the emissions from ships, and mandated upgrading propellers and installing hydrogen fuel cells (Chang and Park 2016).

China, as the second-largest economy in the world, has undertaken the task of reducing CO_2 emissions by committing to reducing its CO_2 emission intensity by 60–65% by 2030, compared with 2005 (Li et al. 2019). In 2015, the China Ports and Harbors Association published the "Guideline for Green Port Rating System (Trial Implementation)" as a self-evaluation guidebook for ports (and a guideline for third parties) to assess the green performance of ports. The guidelines list strategies such as using intelligent control technology for outdoor lighting, applying electricity instead of fuel for power supply, switching to vehicles powered by LNG or electricity in ports, protecting the marine ecosystem of terminals and harbor districts, performing risk assessments for local ecosystems in port expansion projects, and developing environmental pollution emergency plans for production security (Chen and Pak 2017; Du et al. 2019).

2.3 Activity-based modeling

Endresen et al. (2007) used a traditional aggregate activity-based model to calculate and show that the fuel consumption of the global fleet of vessels increased from 152 to 201 million tons from 1970 to 2000. The authors also noted that, since 1973, improvements in vessel construction and operations have allowed fuel consumption and emissions not to increase at the same rate as the size of the global fleet. In addition, they concluded that the main factors affecting annual fuel consumption are vessel size, engines, and the degree of utilization of the fleets.

Song and Xu (2012) developed an operational activity-based method suitable for estimating CO_2 emissions from container shipping, and Chang and Chang (2013) investigated reducing vessel speeds to decrease energy consumption for international dry bulk carriers, using the activity-based method and the CATCH model (Eide et al. 2009). The study revealed that reducing speeds could decrease both energy consumption and CO_2 emissions. However, this policy only benefits the environment and does not reduce operating costs.

Although several studies have explored these topics, most of them having investigated a limited range of pollutant reduction methods (Yang 2016), we here use for the first time actual port data in an activity-based model. Taiwan's intentional commercial ports is our testing ground and case study. GHG emissions are calculated without setting facilities to monitor them. Rasouli and Timmermans (2014) identified three activity-based modeling approaches: (1) constraint-based models, (2) utility-maximizing models, and (3) computational process models. Systems of transportation modeling, especially activity-based models, have become more complex because of the availability of computational resources. The main advantage of the activity-based model is its behavioral realism and integrity, which allow for comprehensive prediction of a sequence of activities. Studies have used emerging methods, such as machine learning, to develop different components of activity-based models, especially for pattern recognition in daily activity.

Allahviranloo and Aissaoui (2019) applied a combination of *k*-means clustering and the affinity propagation method to cluster activity patterns. Researchers have also used the fuzzy *C*-means clustering algorithm and the random forest algorithm to model activity patterns (Hafezi et al. 2019). In addition, various simulation systems are being developed to facilitate analysis and decision-making by researchers, practitioners, and policymakers. Calibration and validation are key aspects that must be addressed for these models to be reliable and widely applied, especially for the activity-based models. However, few studies have investigated the development and application of robust techniques for calibrating the demand-side parameters of activity-based models (Chen et al. 2020).

3 Empirical studies on emissions during ship maneuvering in port

3.1 Requirements to reduce shipping emissions

GHG emissions include NO_X, SO_X, CO_2, hydrocarbons, and PM_X. CO_2 emissions account for the highest percentage (UNCTAD 2011), while PM_X and SO_2 are harmful to human health (Corbett et al. 2009). According to the IMO 2020 rules, the limit on the amount of sulfur in the fuel oil used onboard ships operating outside designated emission control areas (ECAs) should be 0.50% m/m (mass by mass). Within ECAs, this amount should be 0.10% m/m, which is considerably lower than the previous limit of 3.5% m/m. This means that the sulfur content of bunkers oil used should be reduced to 0.1% when vessels sail within 200 nautical miles of a coast (Sofiev et al. 2018). This compulsory limit was established by an amendment to MARPOL Annex VI, to reduce ships' CO_X, SO_X, and PM_X emissions.

Limiting the sulfur content of marine fuels and mandating the use of low-pollution fuels are crucial to reducing pollution. Zervas (2006) reported that decreasing CO_2 emissions is the most effective method for minimizing the impact of climate change because the transportation sector accounts for the highest percentage of the world's oil consumption. The transportation sector also accounted for 24% of the world's CO_2 emissions in 2018, second to the electricity and heat production sector (Table 1).

The use of low-sulfur fuel oils, such as marine gas oil, marine diesel oil, very-low-sulfur fuel oil (0.5% m/m sulfur content), and ultra-low-sulfur fuel oil (0.1% m/m sulfur content), is a viable approach to meeting the new sulfur requirements (Zhu et al. 2020). The use of low-pollution fuels meets the requirement to reduce pollutant emissions in the shipping industry but negatively affects fuel costs.

Hui-Huang (2015) formulated a *clean-liner strategy*, whereby carriers replace heavy oil with LNG, as ship fuel, to save energy and reduce emissions. At similar prices to heavy oil, LNG that meets the MARPOL Annex VI regulations can reduce SO_2 emissions by more than 90% and CO_2 emissions by more than 20%. However, specific operational conditions apply to each country's shipping and port industries. For example, more than 3% of ship space must be reserved for LNG storage tanks, the temperature of storage tanks and pipelines must be kept below −163 °C, and the safety training procedures for ship crews must be modified accordingly. Because of these measures, ship operating costs increase by 10%, and LNG supply stations must be established in ports *en route* (Hui-Huang 2015). The energy-saving and emission-reducing potential of this strategy can only be fulfilled by satisfying these conditions (Fossey 2012).

In addition to the IMO regulations on ship navigation, *slow steaming* can effectively reduce emissions produced by commercial shipping. In the wake of the global financial crisis, ships reduced their speed because of the decrease in trade. As ships burned less fuel, GHG emissions decreased too. After the crisis, many companies

Table 1 Oil consumption and emissions by sector

World oil consumption

Year	Transport (%)	Industry (%)	Non-energy use (%)	Other (%)
1973	45	20	12	23
2010	62	9	17	12
2012	64	9	16	11
2018	65	7	17	11

World CO_2 emissions from fuel combustion by sector

Year	Transport (%)	Electricity and heat production (%)	Other energy industry use (%)	Manufacturing industries and construction (%)	Other sectors (%)
2009	23	41	5	20	11
2018	24	41	3	24	8

Source: IEA Key World Energy Statistics (2020), UNCTAD (2011) continued to slow steam to mitigate the negative effects of shipping on the environment and climate (Woo and Moon 2014) as well as support rates from a freefall, as a result of the excessive capacity they had created in the years prior to the crisis.

Chang and Wang (2012) discovered that adopting slow steaming in the reduced speed zones of ports substantially reduced fuel consumption, costs, and pollutant emissions. Winnes et al. (2010) identified a considerable impact on air quality in port cities during the short periods in which ships maneuvered at decreased speeds. However, slow steaming entails considerable and potentially negative operational and economic consequences for shippers because of the increase in sailing time (Maloni et al. 2013).

3.2 Estimating unit emissions: activity-based modeling

Yin et al. (2021) introduced the top-down and bottom-up methods, two commonly used approaches to create ship exhaust emission inventories. In the top-down method, total fuel consumption and emissions are estimated by using historical fleet data. The bottom-up method is used to gather information regarding individual ship activity, and the energy consumption and emissions of each ship are summed to obtain the total emissions. The main difference between methods is that the top-down method estimates emissions using large-scale statistical data by making reasonable assumptions without consideration for the characteristics of individual ships. In the bottom-up method instead, each ship within a specific boundary is investigated; however, the resulting large-scale emission calculations can be tedious.

The fuel-based approach is a top-down approach for creating ship exhaust emission inventories in which ship exhaust emissions are calculated using the total fuel consumption and fuel emission factors (Peng et al. 2020). Winnes et al. (2010) categorized ship operations into three activities, namely being at berth, maneuvering, and being at sea on a voyage. Chang and Wang (2012) and Tai and Lin (2013) used the three activities to evaluate the pollutant emissions of ships. Hui-Huang (2015) used a refined model to estimate unit emissions and plan fuel-efficient intercontinental transshipment strategies that can substantially reduce emissions in the Caribbean Basin by ships traveling Asia–East Coast North American routes.

We apply a top-down method to estimate GHG emissions, using Taiwan International Ports Corporation (TIPC) data. Table 2 presents the equations used in this study.

To identify the reason ships wait in port, port calls are divided into different phases from approach to departure (Poulsen and Sampson 2020). Accordingly, activity-based methods could be effective for estimating pollutant emissions (Liao et al. 2009; Song and Xu 2012; Hui-Huang 2015; Tai and Lin 2013; Winnes and Fridell 2010). By using de facto activity-based data (e.g., port operations, service operation activities, and ship static data) for various sizes and types of ships, for the entire process, we are able to calculate emission levels. With regard to ship sizes, according to "Propulsion Trends in Container Vessels" and "Propulsion Trends in Bulk Carriers," published by MAN Energy Solutions (https://www.mandieselturbo.com/), container vessels are divided into six tonnage groups: Small, Feeder, Panamax, Post-Panamax,

Table 2 Notations for emissions reduction estimations

Notations	Contents
P^{e}	• Total pollutant emissions (unit: tons) a ship emits while maneuvering and in port • *e* represents emissions [i.e., nitrogen oxides (NO_X), sulfur oxides (SO_X), carbon dioxide (CO_2), hydrocarbons (HC), and particulate matter (PM_X)]
$P^{\mathrm{e}}_{\mathrm{maneuvering}}$	• Pollutant emissions (unit: tons) a ship emits while maneuvering • *e* represents emissions (i.e., NO_X, SO_X, CO_2, HC, and PM_X)
$P^{\mathrm{e}}_{\mathrm{port}}$	• Pollutant emissions (unit: tons) a ship emits while in port • *e* represents emissions (i.e., NO_X, SO_X, CO_2, HC, and PM_X)
$\mathrm{Time}_{\mathrm{maneuvering}}$	• Ship maneuvering time (unit: h), including time waiting in terminals with an estimated 6–12 h at hub ports for liner-owned private terminal operators • Derived from the number of vessels in and out of ports in Taiwan
$\mathrm{Time}_{\mathrm{port}}$	Terminal handling time at port (unit: h) for each ship based on variable handling and operational situation of terminals
Q_i	• Quantity of cargo handled at port *i*, including loaded and unloaded cargo for all ships • Derived from the cargo handling data of TIPC
EF_i	• Gross terminal handling efficiency *EF* at port *i*. Because different types of ships with different types of cargo dock at different ports, *EF* was averaged to calculate the berthing time (*Q*/*EF*) of ships in ports • Derived from the cargo handling data of TIPC
F^{o}_t	• Main engine fuel economic efficiency (unit: tons/h) • *o* represents different types of fuel [i.e., diesel oil (DO) and heavy oil (HO)] • *t* represents ship type [gross tonnage (GT)] • Derived from the data of TIPC; vessel size categorized as large, medium, or small (LV, MV, or SV)
$K^{o}_{m,e}$	• Emission factor (tons/ton of fuel type) of pollutants • *o* represents different types of fuel (i.e., DO and HO) • *m* represents maneuvering time (unit: h) • *e* represents emissions (i.e., NO_X, SO_X, CO_2, HC, and PM_X)
$K^{o}_{p,e}$	• Emission factor (tons/ton of fuel type) of pollutants • *o* represents different types of fuel (i.e., DO and HO) • *p* represents port time (unit: h) • *e* represents emissions (i.e., NO_X, SO_X, CO_2, HC, and PM_X)
UELVs	Unit emissions from LVs
UEMVs	Unit emissions from MVs
UESVs	Unit emissions from SVs

Source: Author

New Panamax, and Ultra Large Container Vessel. Bulk carriers are divided into five tonnage groups: Handysize, Handymax, Panamax, Capesize, and Very Large Bulk Carriers (Chang and Chang 2016).

We categorize vessel sizes into three tonnage groups (i.e., small, medium, and large) and two types of fuel (i.e., heavy oil and diesel oil). Speed is assumed directly proportional to the cube of a vessel's fuel consumption in the main engine. The fuel-based approach is a top-down approach to create ship exhaust emission inventories in which the amount of ship exhaust emissions is calculated using the total fuel consumption and fuel emission factors. This calculation method was applied to estimate global seagoing ships' emission inventories on the basis of the total fuel used by the ships, obtained

Table 3 Fuel economy of vessel engines by oil type (unit: tons/h)

F (fuel economy)	V (knot; nm/h)	Heavy oil (ho/h)	Diesel oil (do/h)
Large-vessels above 60,000 GT	5–10	0.833–1.667	0.063
	11–15	1.701–2.708	0.063
	16–20	2.710–3.750	0.063
Medium-sized vessels 10,000–59,999	5–10	0.667–1.292	0.052
	11–15	1.293–2.083	0.052
	16–20	2.084–3.125	0.052
Small-vessels less than 9999 GT	5–10	0.500–1.250	0.042
	11–15	1.251–1.667	0.042
	16–20	1.668–2.500	0.042

Source: Corbett and Koehler (2003), Liao et al. (2009), Tai and Lin (2016)

Table 4 Emission factors of pollutants (unit: tons/ton of fuel type)

K (emission factor)	NO_X	SO_X	CO_2	HC	PM_X
Maneuvering period: ho[a]	0.0640	0.0540	2.6829	0.0076	0.0106
Maneuvering period: do[a]	0.0509	0.0538	2.6743	0.0076	0.0106
Berthing at terminal[b]: do (ho = 0)	0.0615	0.0693	2.6743	0.0017	0.0035

[a] *Source*: Chang and Wang (2010), International Maritime Organization (2008, 2009), Liao et al. (2009), Hui-Huang (2015), Tai and Lin (2016)

[b] The emission factors (k) for terminal time in port are the same as those for maneuvering and ship operations

from the Energy Information Administration of the United States (Endresen et al. 2007).

The model for ship fuel consumption is as follows: in (1)–(3), GHG emissions are obtained by multiplying activity duration (h) by the engine fuel economy (tons/h) for maneuvering time (i.e., ships arrive to and depart from port). Total emissions (tons) of pollutants shown in (2)–(3) are estimated by multiplying fuel economy (see *F* value in Table 3—*F* value differs among different types of vessel, speed, and oil) by the emission factor of pollutants (see *K* value in Table 4—*K* value differs between different periods of ship in port and pollutant types). To obtain *F* and *K*, we refer to Hui-Huang (2015), United States Environmental Protection Agency (2018), and POLA (2019). The formula to calculate carbon emissions is identical with this paper. The sum (P^e) of the ships' emissions while maneuvering can then be estimated for each fuel type. Pollutant emissions are divided into several classes for each stage of ship operations, and the equation provides information regarding the relative weights of the individual classes in pollutant emissions.

$$P^e = P^{\mathrm{e}}_{\mathrm{Manoevring}} + P^{\mathrm{e}}_{\mathrm{Port}} \tag{1}$$

$$P^{\mathrm{e}}_{\mathrm{Manoevring}} = \mathrm{Time}_{\mathrm{Manoevring}} \cdot F^{o}_{t} \cdot K^{o}_{m,e} = \mathrm{Time}_{\mathrm{Manoevring}} \cdot \left(F^{\mathrm{ho}}_{t} \cdot K^{\mathrm{ho}}_{m,e} + F^{\mathrm{do}}_{t} \cdot K^{\mathrm{do}}_{m,e} \right) \tag{2}$$

$$P^{\mathrm{e}}_{\mathrm{Port}} = \mathrm{Time}_{\mathrm{Port}} \cdot F^{o}_{t} \cdot K^{o}_{p,e} = \frac{Q_i}{EF_i} \cdot F^{\mathrm{do}}_{t} \cdot K^{\mathrm{do}}_{p,e} \tag{3}$$

Table 3 presents the main engine fuel economy for different types of oil. Several ships at three levels of speed were analyzed to obtain the engine power factor and fuel consumption data. The parameters in Table 3 represent the real-world data. Table 4 presents the emission factors of the various pollutants according to the data reported by the International Maritime Organization (2008, 2009) and Tai and Lin (2016).

With the increasing recognition of ports as crucial nodes in the wider supply chain, ports should facilitate the reduction of GHG emissions from shipping, and reducing waiting time presents itself as a feasible approach (Johnson and Styhre 2015; UNCTAD 2019). Qi and Song (2012) explored the design of a vessel schedule, optimized to minimize fuel consumption and carbon emissions by considering variations in port time and call frequency requirements through simulation-based stochastic approximation methods. Their study revealed that the fuel consumption and emissions of a ship per nautical mile are a quadratic convex function with respect to speed. Norlund and Gribkovskaia (2013) examined various speed optimization strategies with periodic vessel schedules. Modeling results indicated that a 25% reduction in emissions and fuel costs can be achieved without any increase in fleet size.

The port call process is generally suboptimal because ships may spend 5–10% of their time either in anchorage or maneuvering around the port while waiting for available berths, fairways, and nautical services (Veenstra and Harmelink 2021).To minimize waiting time, the IMO published the “Just in Time” (JIT) arrival guide in 2020, which introduced the concept of JIT arrival, guiding ships to optimize their speeds during their voyage, so as to arrive at the Pilot Boarding Place when berths, fairways, and nautical services are available. JIT arrival allows ships to optimize speeds during their voyages, which helps reduce GHG emissions in two ways: The first is that the optimization of sailing speeds during the voyage increases engine efficiency, resulting in lower fuel consumption. The second is that the time ships spend maneuvering as they approach ports or waiting at anchorage is reduced (International Maritime Organization 2020a, b).

Although JIT arrival is simple, its feasibility is questionable because it requires collaboration among many stakeholders, such as port authorities, terminals, shipping companies, and service providers (Gonzalez-Aregall et al. 2018). Broadly speaking, the barriers to JIT arrival can be categorized as operational and contractual. Operational barriers comprise the exchange of high-quality and reliable data among stakeholders in the port and the ship. Contractual barriers are related to the ability of the recipient to use the data (e.g., to optimize ship speeds en route).

Therefore, the maneuvering speed of ships decreases from 18 to 0 knots when berthing (Fig. 1). According to the Vessel Traffic Service (VTS) regulations in Taiwan commercial ports, ships are monitored within 20 nautical miles, and are requested to reduce

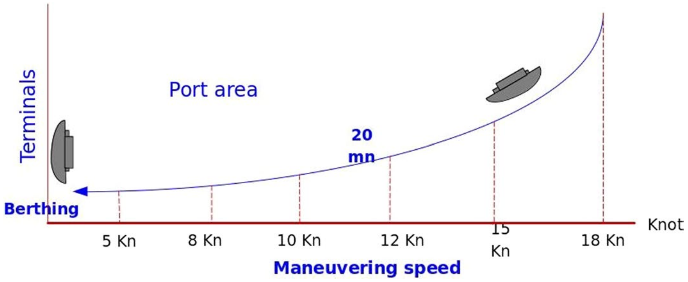

Fig. 1 Maneuvering to berth

speed within 12 nautical miles. Regardless of ship type, ships may reach speeds higher than 18 knots or lower than 12 knots in high seas. However, every ship has to reduce speed when entering the port, and we assume these ships adjust their speeds depending on the distance from the berth as shown in Table 5.

4 Results

Three methods can be used to calculate carbon footprint: input–output analysis (top-down approach), process analysis (bottom-up approach), and a combination of the two. Input–output analysis is the most widely adopted method in the literature (Liu et al. 2016) and is widely used for a macro-estimation of carbon footprint at a national or international level (Wiedmann 2009).

We applied the activity-based model to calculate the total emissions of a ship while maneuvering within 20 nautical miles of a port, using the exact number of ships (37,891 vessels) entering and leaving ports in Taiwan in 2020 (Taiwan International Port Co., Ltd. 2020a). The results were compared with statistics published by the Harbor and Marine Technology Center (2012), aiming to evaluate the performance of the Taiwan Greening the Ports Action Plan.

Ship size was divided into three categories, with percentages allocated on the basis of empirical insight: large vessels [above 60,000 gross tonnage (GT)] accounted for 10% of total vessels; medium vessels (from 10,001 to 59,999 GT) accounted for 25% of the total; and small vessels (below 10,000 GT) accounted for 65% of total vessels. As our study investigated all types of ships, the results may not have been as accurate as those yielded through a bottom-up approach; we averaged the parameters to generalize our findings.

Table 6 presents unit emissions of different types of vessels. Total annual NO_X emissions were 18,870.7 tons, mainly produced by the smaller vessels, as these outnumber the others. In terms of unit size, larger vessels produced the most emissions because

Table 5 Speed allocation

Knot	5	8	10	12	15	18
Maneuvering distance (nautical mile)	3	3	3	3	4	4

Source: Author

Table 6 Pollutant emissions by maneuvering speeds in port areas (unit: tons)

Maneuvering speed	5 kt	8 kt	10 kt	12 kt	15 kt	18 kt	Total emission
Emission: NO_X	2858.9	2714.1	2790.1	2840.8	3551.1	4115.7	18,870.7
Large vessels	351.6	331.1	344.4	353.3	451.4	504.2	2336.0
Medium vessels	773.0	731.4	742.8	750.4	944.9	1111.1	5053.7
Small vessels	1734.2	1651.6	1702.9	1737.1	2154.8	2500.4	11,481.0
UELV	0.093	0.087	0.091	0.093	0.119	0.133	0.616
UEMV	0.082	0.077	0.078	0.079	0.100	0.117	0.534
UESV	0.070	0.067	0.069	0.071	0.087	0.102	0.466
Emission: SO_X	2740.0	2609.2	2670.5	2711.3	3311.3	3786.0	17,828.2
Large vessels	326.5	308.0	318.9	326.1	409.0	453.3	2141.9
Medium vessels	731.6	694.1	702.9	708.8	873.1	1012.8	4723.2
Small vessels	1681.8	1607.1	1648.7	1676.4	2029.2	2319.9	10,963.1
UELV	0.086	0.081	0.084	0.086	0.108	0.120	0.565
UEMV	0.077	0.073	0.074	0.075	0.092	0.107	0.499
UESV	0.068	0.065	0.067	0.068	0.082	0.094	0.445
Emission: CO_2	122,672.3	116,174.6	119,218.7	121,248.1	151,054.8	174,639.8	805,008.3
Large vessels	15,042.3	14,122.0	14,662.3	15,022.6	19,138.2	21,341.0	99,328.4
Medium vessels	33,129.9	31,265.4	31,702.8	31,994.5	40,157.0	47,099.2	215,348.8
Small vessels	74,500.1	70,787.3	72,853.5	74,231.0	91,759.6	106,199.6	490,331.1
UELV	3.970	3.727	3.870	3.965	5.051	5.632	26.214
UEMV	3.497	3.301	3.347	3.378	4.239	4.972	22.734
UESV	3.025	2.874	2.958	3.014	3.726	4.312	19.909
Emission: CH	244.4	226.0	234.6	240.3	324.8	391.6	1661.7
Large vessels	33.6	31.0	32.5	33.5	45.2	51.4	227.1
Medium vessels	69.2	63.9	65.1	66.0	89.1	108.8	462.1
Small vessels	141.6	131.1	137.0	140.9	190.5	231.4	972.6
UELV	0.009	0.008	0.009	0.009	0.012	0.014	0.060
UEMV	0.007	0.007	0.007	0.007	0.009	0.011	0.049
UESV	0.006	0.005	0.006	0.006	0.008	0.009	0.039
Emission: PM_X	360.6	334.9	346.9	355.0	472.7	565.9	2436.0
Large vessels	48.5	44.9	47.0	48.5	64.7	73.4	327.1
Medium vessels	101.2	93.8	95.6	96.7	129.0	156.4	672.8
Small vessels	210.8	196.2	204.3	209.8	279.0	336.1	1436.1
UELV	0.013	0.012	0.012	0.013	0.017	0.019	0.086
UEMV	0.011	0.010	0.010	0.010	0.014	0.017	0.071
UESV	0.009	0.008	0.008	0.009	0.011	0.014	0.058

they consume more energy than the others. The results indicate that, for SO_X, CO_2, and CH_X, the higher the speed, the more the emissions that are generated; for speeds over 12 knots, the slope for emissions steepens (Fig. 2). Table 7 was generated from Table 6, presenting the emissions of the five pollutants. The results indicate that unit emissions from large vessels (UELVs) are the highest among the three size groups (Table 8).

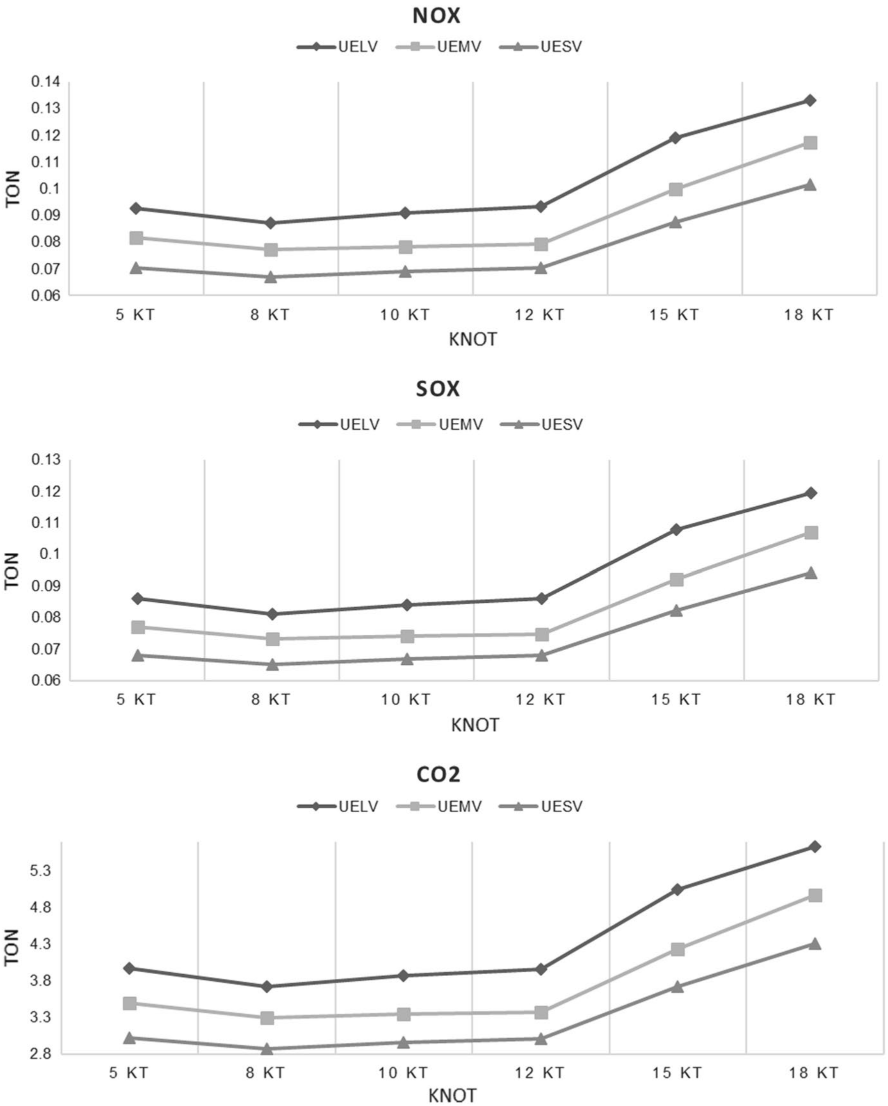

Fig. 2 Pollutant emissions per vessel in port areas (unit: tons)

The emissions of certain compounds [i.e., NO_X, SO_X, and CO_2 equivalent (CO_{2e})] were obtained from a publication of the Harbor and Marine Technology Center (2012). We collected data on the total emissions produced by vessels while maneuvering in Taiwan's seven international commercial ports. Pollutant emissions were relatively low from 2009 to 2011 but soared in 2012. In addition, only NO_X decreased in 2013; the other two pollutants (i.e., SO_X and CO_{2e}) increased.

However, according to the activity-based model and the vessel data from 2020, NO_X emissions rapidly increased to 18,871 tons, SO_X emissions slightly decreased,

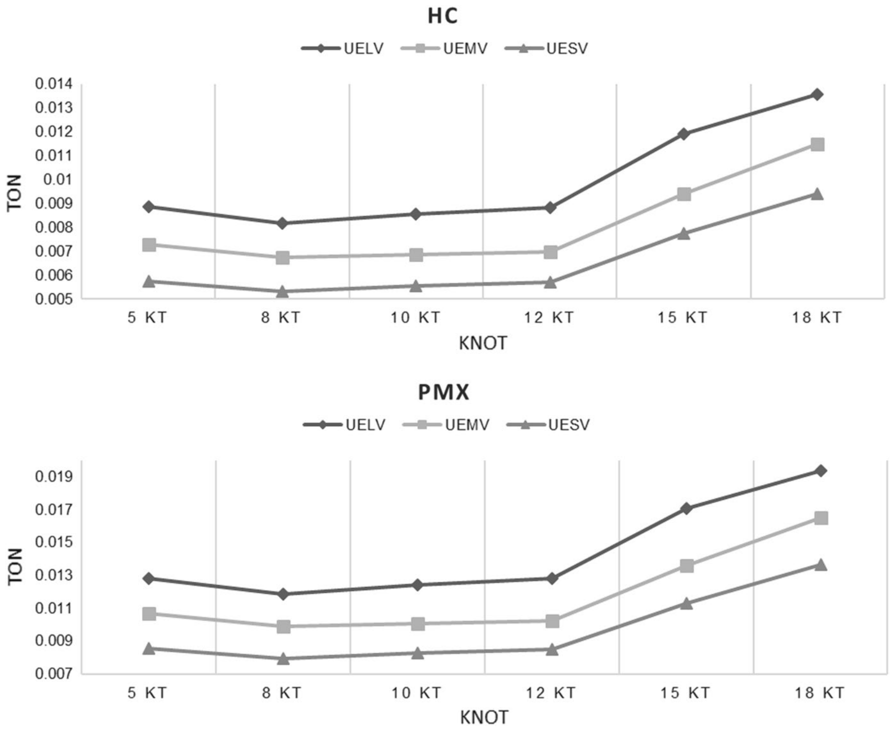

Fig. 2 (continued)

Table 7 Total emissions of vessels maneuvering in port (unit: tons)

Pollution	NO_X	SO_X	CO_2	CH	PM_X	Total emission
Pollutant emission	18,870.7	17,828.2	805,008.3	1661.7	2436.0	845,804.9
Large vessels	2336.0	2141.9	99,328.4	227.1	327.1	104,360.5
Medium vessels	5053.7	4723.2	215,348.8	462.1	672.8	226,260.5
Small vessels	11,481.0	10,963.1	490,331.1	972.6	1436.1	515,183.9
UELV	0.616	0.565	26.214	0.060	0.086	27.5
UEMV	0.534	0.499	22.734	0.049	0.071	23.9
UESV	0.466	0.445	19.909	0.039	0.058	20.9

and CO_{2e} emissions decreased substantially. The increase in NO_X emissions indicates the urgency of using low-sulfur oil. Because GHG emissions produced by vessels while maneuvering were not recorded, the long-term trend could not be identified.

As a locus for pollution from various anthropogenic inputs produced by extensive consumption of fossil fuels, ports have received considerable attention from authorities. In response to the international trend of green ports and the transition

Table 8 Total emissions of vessels maneuvering around Taiwanese ports (unit: tons per year)

Year	NO_X	SO_X	CO_{2e}
2009	557	133	10,505
2010	570	137	10,811
2011	497	120	9,390
2012	8588	18,090	1,071,721
2013	8048	20,555	1,233,710
–	–	–	–
2020	18,871	17,828	805,008

Source: Harbor and Marine Technology Center (2011): 2–27

2009–2013: Harbor & Marine Technology Center, 2014, Promoting the benefit of energy conservation and carbon reduction in Taiwan harbor area (Report NO. 103-H1DB005. https://www.iot.gov.tw/dl-8720-24902b8465bd486fb61ac01840b883c9.html. Page 6–63

2020: The data was provided by TIPC faculty, which is not publicly reviewd

to eco ports, TIPC launched the "Taiwan Greening the Ports Action Plan" (https://www.twport.com.tw/en/cp.aspx?n=3C08FE6E60F9553F), which consists of four components: cargo operations, cruise terminals, community outreach, and port environments (Table 9). According to the "Taiwan Green Ports Environmental Report" (Taiwan International Port Co., Ltd. 2020b), three methods can be used to reduce GHG emissions at the port level. The first is to decrease vessel speeds when entering or leaving ports because this decreases fuel consumption and NO_X emissions. TIPC requires vessels traveling within 20 nautical miles of port areas to decrease their speeds to below 12 knots. The second method is to use low-sulfur fuel to reduce air pollution in port areas. TIPC began to use low-sulfur fuel in their tug boats and harbor crafts, and half of these vessels have switched to super diesel. However, because Taiwanese ports are not ECAs, shipping companies are encouraged to use low-sulfur fuels. The last method is to use alternative maritime power (AMP) at berth for services such as supplying cargo lighting, pumping, and providing ventilation in port.

Table 9 Taiwan Greening the Ports Action Plan

Aspect	Goals
Cruise terminals	Mitigate environmental impacts caused by cruises; establish tourist centers in compliance with green building standards
Cargo operations	Reduce environmental pollution related to cargo operations on both land and water; encourage upgrading equipment to more efficient or electric models
Community outreach	Develop a recreational waterfront area; integrate port development with community development policies
Port environment	Enhance aspects of port environments by increasing air and water quality and creating more green space; establish a positive reputation of environmental sustainability and social and corporate responsibility

Source: TIPC website

This solution can effectively reduce GHG emissions at berth. TIPC provides berths for port service vessels and smaller ships with low-voltage shore power facilities (110–440 V), and the tug boats owned by TIPC use AMP while berthing in port.

TIPC has gradually implemented a port environment monitoring system to control environmental quality in and around port areas, track possible pollution sources, determine long-term environmental quality, and evaluate the effectiveness of environmental management. This information can be used to perform background analysis of the environmental impact of emissions reduction, which may contribute to the development of new projects and demonstrate the TIPC's commitment to corporate social responsibility.

5 Concluding remarks

The IMO (2018) has introduced strict guidelines that require shipping companies to comply with sulfur regulations, by using abatement technologies, compliant fuels, and LNG. These guidelines urge shipping companies to emphasize reductions in GHG emissions and harmful gases, produced by their ships, and to implement environmental regulations and policies. In addition, port sustainability has received considerable attention, and numerous measures to reduce GHG emissions have been proposed for ports, such as providing onshore power for ships at berth, encouraging voluntary speed reduction, assessing green port dues for ships, and offering various other incentives. Shipping companies must explore new options to reduce fuel consumption, which can benefit the economy and the environment. Onboard crew must implement their companies' environmental regulations and policies to ensure ships comply with international regulations.

We discovered that, first, small vessels generate the most emissions because they represent the vessel group most frequently entering and leaving ports in Taiwan. We suggest port authorities in general should implement a carbon reduction policy, specifically for the numerous small vessels, which produce the most GHG emissions in the port area. Second, we find that UELVs produce the highest emissions among the three types of vessels. Last, we show that the higher the sailing speed, the more GHG emissions are produced. This leads us to purport that lower speeds and onshore power supply would reduce local air pollution.

As a port authority, TIPC has succeeded in slightly reducing CO_2 and SO_X emissions. However, NO_X emissions have not decreased considerably, and the long-term trend could not be identified because of lack of data. As a result, we advise policymakers, especially port officials, to continuously monitor GHG emissions to ensure the carbon reduction policies are well executed for a sustainable future. Although the objectives of the study have, in our view, been accomplished, several limitations should be noted. First, data collection was restricted to ports in Taiwan; a sample of other countries can be used to verify the results. Second, although the activity-based approach can be used to calculate ship exhaust emission inventories on a global scale, it underestimates ship exhaust emissions on a regional scale, which causes the results to fluctuate.

Additional studies could explore whether container, tanker, and certain dry bulk shipping segments differ, and investigate other variables affecting environmental performance, such as economic performance, social performance, or health performance.

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References

Allahviranloo, Mahdieh, and Leila Aissaoui. 2019. A comparison of time-use behavior in metropolitan areas using pattern recognition techniques. *Transportation Research Part A: Policy Practice* 129: 271–287.

Aregall, Gonzalez, Marta Gonzalez, Rickard Bergqvist, and Jason Monios. 2018. A global review of the hinterland dimension of green port strategies. *Transportation Research Part D: Transport and Environment* 59: 23–34.

Chang, Ching-Chin., and Chia-Hong. Chang. 2013. Energy conservation for international dry bulk carriers via vessel speed reduction. *Energy Policy* 59: 710–715.

Chang, Ching-Chin., and Chia-Hong. Chang. 2016. Reducing speed and fuel transfer of the Green Flag Incentive Program in Kaohsiung Port Taiwan. *Transportation Research Part D: Transport and Environment* 46: 1–10.

Chang, Ching-Chin., and Chih-Ming. Wang. 2010. Assessment of the impact of a carbon tax on speed reduction and operating costs in shipping. *Transportation Planning Journal* 39: 441–460.

Chang, Ching-Chin., and Chih-Ming. Wang. 2012. Evaluating the effects of green port policy: case study of Kaohsiung harbor in Taiwan. *Transportation Research Part D: Transport and Environment* 17: 185–189.

Chang, Young-Tae., and Hyosoo Park. 2016. Measuring foregone output under industry emission reduction target in the transportation sector. *Transportation Research Part D: Transport and Environment* 49: 138–153.

Chen, Zhuo, and Myongsop Pak. 2017. A Delphi analysis on green performance evaluation indices for ports in China Maritime. *Policy & Management* 44: 537–550.

Chen, Dongsheng, Xiaotong Wang, Peter Nelson, Yue Li, Na. Zhao, Yuehua Zhao, Jianlei Lang, Ying Zhou, and Xiurui Guo. 2017. Ship emission inventory and its impact on the PM2.5 air pollution in Qingdao Port, North China. *Atmospheric Environment* 166: 351–361.

Chen, Siyu, A. Arun Prakash, Carlos Lima De. Azevedo, and Moshe Ben-Akiva. 2020. Formulation and solution approach for calibrating activity-based travel demand model-system via microsimulation. *Transportation Research Part C: Emerging Technologies* 119: 102650.

Christodoulou, Anastasia, Marta Gonzalez-Aregall, Tobias Linde, Inge Vierth, and Kevin Cullinane. 2019. Targeting the reduction of shipping emission to air. *Maritime Business Review* 4: 16–30.

Corbett, James J., and Horst W. Koehler. 2003. Updated emissions from ocean shipping. *Journal of Geophysical Research* 108: 4650–4665.

Corbett, James J., Haifeng Wang, and James J. Winebrake. 2009. The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment* 14: 593–598.

Cullinane, Kevin, and Sharon Cullinane. 2013. Atmospheric emissions from shipping: the need for regulation and approaches to compliance. *Transport Reviews* 33: 377–401.

Dragović, Branislav, Ernestos Tzannatos, Vassilis Tselentis, Romeo Meštrović, and Maja Škurić. 2018. Ship emissions and their externalities in cruise ports. *Transportation Research Part D: Transport and Environment* 61: 289–300.

Du, Ke., Jason Monios, and Yuhong Wang. 2019. Chapter 11—Green port strategies in China. In *Green ports*, ed. Rickard Bergqvist and Jason Monios, 211–229. New York: Elsevier.

Eide, Magnus S., Øyvind. Endresen, Rolf Skjong, Tore Longva, and Sverre Alvik. 2009. Cost-effectiveness assessment of CO_2 reducing measures in shipping. *Maritime Policy & Management* 36 (4): 367–384.

Endresen, Øyvind., Eirik Sørgård, Hanna Lee Behrens, Per Olaf Brett, and Ivar SA. Isaksen. 2007. A historical reconstruction of ships' fuel consumption and emissions. *Journal of Geophysical Research: Atmospheres*. https://doi.org/10.1029/2006JD007630.

European Commission. 2021. *Delivering the European green deal*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en. Accessed 15 July 2021.

Fossey, J. 2012. Containership: Alternative fuels "Clean Lines". *Containerization International*: 76–77.

Giziakis, Costas, and Anastasia Christodoulou. 2012. Environmental awareness and practice concerning maritime air emissions: the case of the Greek shipping industry. *Maritime Policy and Management* 39: 353–368.

Hafezi, Mohammad Hesam, Lei Liu, and Hugh Millward. 2019. A time-use activity-pattern recognition model for activity-based travel demand modeling. *Transportation* 46: 1369–1394.

Harbor & Marine Technology Center. 2011. *The study to promote the benefit of energy conservation and carbon reduction in Taiwan's harbor areas* (Report No. 100-H1DB005). https://www.iot.gov.tw/cp-78-10105-9749d-1.html.

Harbor & Marine Technology Center. 2012. *Research of Taiwan green port establishment* (Report No. 100-H1DB002). https://www.ihmt.gov.tw/periodical/pdf/B1015520.pdf

Hui-Huang, Tai. 2015. A comparative study on pollutant emissions and hub-port selection in Panama Canal expansion. *Maritime Economics and Logistics* 17 (2): 163–178.

International Energy Agency. 2020. *Key world energy statistics 2020*. https://iea.blob.core.windows.net/assets/1b7781df-5c93-492a-acd6-01fc90388b0f/Key_World_Energy_Statistics_2020.pdf. Accessed July 2021.

International Maritime Organization. 2008. MEPC.58WP.9. *Report of drafting group on amendments to MARPOL Annex VI and the $NO_{X,}$ Technical code*. New York: IMO.

International Maritime Organization. 2009. Second IMO GHG study. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/SecondIMOGHGStudy2009.pdf. Accessed 15 July 2021.

International Maritime Organization. 2016. *IMO Train the Trainer (TTT) course on energy efficient ship operations: Module 3 from management to operation*. London: IMO.

International Maritime Organization. 2018. *Initial IMO strategy on reduction of GHG emissions from ships, resolution MEPC.304(72), adopted on April, 13*. London: IMO.

International Maritime Organization. 2020a. Fourth IMO GHG study. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf. Accessed 15 July 2021.

International Maritime Organization. 2020b. Just in time arrival guide. https://wwwcdn.imo.org/localresources/en/OurWork/PartnershipsProjects/Documents/GIA-just-in-time-hires.pdf. Accessed 15 July 2021.

International Maritime Organization. 2021. *World maritime theme 2022: New technologies for greener shipping*. https://www.imo.org/en/MediaCentre/PressBriefings/pages/WMT2022.aspx. Accessed 15 July 2021.

Johnson, Hannes, and Linda Styhre. 2015. Increased energy efficiency in short sea shipping through decreased time in port. *Transportation Research Part A: Policy Practice* 71: 167–178.

Lam, Jasmine Siu Lee, and Theo Notteboom. 2014. The greening of ports: A comparison of port management tools used by leading ports in Asia and Europe. *Transport Reviews* 34: 169–189.

Li, Yi., Du. Qiang, Lu. Xinran, Wu. Jiao, and Xiao Han. 2019. Relationship between the development and CO_2 emissions of transport sector in China. *Transportation Research Part D: Transport and Environment* 74: 1–14.

Liao, Chun-Hsiung., Po-Hsing. Tseng, and Lu. Chin-Shan. 2009. Comparing carbon dioxide emissions of trucking and intermodal container transportation in Taiwan. *Transportation Part D: Transport and Environment* 14: 493–496.

Liu, Tiantian, Qunwei Wang, and Su. Bin. 2016. A review of carbon labeling: standards, implementation, and impact. *Renewable and Sustainable Energy Reviews* 53: 68–79.

Lim, Sehwa, Stephen Pettit, Wessam Abouarghoub, and Anthony Beresford. 2019. Port sustainability and performance: a systematic literature review. *Transportation Research Part D: Transport and Environment* 72: 47–64.

Maloni, Michael, Jomon Aliyas Paul, and David M. Gligor. 2013. Slow steaming impacts on ocean carriers and shippers. *Maritime Economics & Logistics* 15: 151–171.

Norlund, Ellen Karoline, and I. Irina Gribkovskaia. 2013. Reducing emissions through speed optimization in supply vessel operations. *Transportation Research Part D: Transport and Environment* 23: 105–113.

Olcer, A., and Fabio Ballini. 2015. The development of a decision-making framework for evaluating the trade-off solutions of cleaner seaborne transportation. *Transportation Research Part D: Transport and Environment* 37: 150–170.

Pang, Kelvin, Lu. Chin-Shan, Kuo-Chung. Shang, and Hsiang-Kai. Weng. 2021. An empirical investigation of green shipping practices, corporate reputation and organisational performance in container shipping. *International Journal of Shipping and Transport Logistics* 13: 422–444.

Peng, Xin, Yuanqiao Wen, Wu. Lichuan, Changshi Xiao, Chunhui Zhou, and Dong Han. 2020. A sampling method for calculating regional ship emission inventories. *Transportation Research Part D: Transport and Environment* 89: 102617.

Port of Los Angeles (POLA).2019. *Port of Los Angeles inventory of air emissions-2018*. https://kentico.portoflosangeles.org/getmedia/ffc72e12-cc1c-4d4d-8dc8-c5a59d28685b/2018_Air_Emissions_Inventory_Presentation.

Poulsen, René Taudal., and Helen Sampson. 2020. A swift turnaround? Abating shipping greenhouse gas emissions via port call optimization. *Transportation Research Part D: Transport and Environment* 86: 102460.

Poulsen, René Taudal., Roberto Rivas Hermann, and Carla K. Smink. 2018. Do eco-rating schemes improve the environmental performance of ships. *Marine Policy* 87: 94–103.

Psaraftis, Harilaos N. 2019. Speed optimization vs speed reduction: the choice between speed limits and a bunker levy. *Sustainability* 11: 2249.

Psaraftis, Harilaos N., and Christos A. Kontovas. 2010. Balancing the economic and environmental performance of maritime transportation. *Transportation Research Part D: Transport and Environment* 15: 458–462.

Psaraftis, Harilaos N., and Christos A. Kontovas. 2014. Ship speed optimization: concepts, models and combined speed-routing scenarios. *Transportation Research Part C: Emerging Technologies* 44: 52–69.

Qi, Xiangtong, and Dong-Ping. Song. 2012. Minimizing fuel emissions by optimizing vessel schedules in liner shipping with uncertain port times. *Transportation Research Part E: Logistics and Transportation Review* 48: 863–880.

Rasouli, Soora, and Harry Timmermans. 2014. Activity-based models of travel demand: promises, progress and prospects. *International Journal of Urban Science* 18: 31–60.

Song, Dong-Ping., and Jingjing Xu. 2012. An operational activity-based method to estimate CO_2 emissions from container shipping considering empty container repositioning. *Transportation Research Part D: Transport and Environment* 17: 91–96.

Song, Su. 2014. Ship emission inventory, social cost and eco-efficiency in Shanghai Yanshan port. *Atmospheric Environment* 82: 288–297.

Sofiev, Mikhail, James J. Winebrake, Lasse Johansson, Edward W. Carr, Marje Prank, Joana Soares, Julius Vira, Rostislav Kouznetsov, Jukka-Pekka. Jalkanen, and James J. Corbett. 2018. Cleaner fuels for ships provide public health benefits with climate tradeoffs. *Nature Communications* 9: 1–12.

Sornn-Friese, Henrik, René Taudal. Poulsen, Agnieszka Urszula Nowinska, and Peter de Langen. 2021. What drives ports around the world to adopt air emissions abatement measures. *Transportation Research Part D: Transport and Environment* 90: 102644.

Tai, Hui-Huang., and Dung-Ying. Lin. 2013. Comparing the unit emissions of daily frequency and slow steaming strategies on trunk route deployment in international container shipping. *Transport Research Part D: Transport and Environment* 21: 26–31.

Tai, Hui-Huang., and Dung-Ying. Lin. 2016. The impact of trunk route deployment changes on pollutant emissions in international container shipping after Panama Canal expansion. *International Journal of Logistics Management* 27: 335–352.

Taiwan International Port Corporation. 2020a. *Annual statistical report*. https://www.twport.com.tw/en/cp.aspx?n=8E9F2CDAA08A72A7. Accessed 15 July 2021.

Taiwan International Port Corporation. 2020b. *Port of Kaohsiung environmental report 2020*. https://kh.twport.com.tw/chinese/cp.aspx?n=813786D87E1C27B6. Accessed 15 July 2021.

Tichavska, Miluše, and Beatriz Tovar. 2015. Port-city exhaust emission model: an application to cruise and ferry operations in Las Palmas Port. *Transportation Research Part A: Policy and Practice* 78: 347–360.

Tseng, Po-Hsing., and Manwo Ng. 2020. Assessment of port environmental protection in Taiwan. *Maritime Business Review* 6: 188–203.

Tseng, Po-Hsing., and Nick Pilcher. 2019. Evaluating the key factors of green port policies in Taiwan through quantitative and qualitative approaches. *Transport Policy* 82: 127–137.

Tsita, Katerina G., Spyros J. Kiartzis, Nikolaos K. Ntavos, and Petros A. Pilavachi. 2019. Next generation biofuels derived from thermal and chemical conversion of the Greek transport sector. *Thermal Science and Engineering Progress* 17: 100387.

UNCTAD. 2011. *Review of maritime transport 2011*. https://unctad.org/system/files/official-document/rmt2011_en.pdf. Accessed 15 July 2021.

UNCTAD. 2019. *Review of maritime transport 2019*. https://unctad.org/system/files/official-document/rmt2019_en.pdf. Accessed 15 July 2021.

UNCTAD. 2020. *Review of maritime transport 2020*. https://unctad.org/system/files/official-document/rmt2020_en.pdf. Accessed 15 July 2021.

United States Environmental Protection Agency. 2018. *Emission Factors for Greenhouse Gas Inventories*. https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf.

Veenstra, Albert, and Rogier Harmelink. 2021. On the quality of ship arrival predictions. *Maritime Economics & Logistics*. https://doi.org/10.1057/s41278-021-00187-6.

Wan, Zheng, Abdel El Makhloufi, Yang Chen, and Jiayuan Tang. 2018. Decarbonizing the international shipping industry: solutions and policy recommendations. *Marine Pollution Bulletin* 126: 428–435.

Wang, Shuaian, and Qiang Meng. 2017. Container liner fleet deployment: a systematic overview. *Transportation Research Part C: Emerging Technologies* 77: 389–404.

Wiedmann, Thomas. 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics* 69: 211–222.

Winnes, Hulda, and Erik Fridell. 2010. Emissions of NO_X and particles from maneuvering ships. *Transportation Research Part D: Transport and Environment* 15: 204–211.

Winnes, Hulda, Linda Styhre, and Erik Fridell. 2015. Reducing GHG emissions from ships in port areas. *Research in Transportation Business & Management* 17: 73–82.

Woo, Jong-Kyun., and Daniel Seong-Hyeok. Moon. 2014. The effects of slow steaming on the environmental performance in liner shipping. *Maritime Policy Management* 41: 176–191.

Yang, Chung-Shan. 2016. Evaluating the use of alternative maritime power in Taiwan. *Maritime Business Review* 1: 208–224.

Yin, Yuwei, Jasmine Siu Lee. Lam, and Nguyen Khoi Tran. 2021. Emission accounting of shipping activities in the era of big data. *International Journal of Shipping and Transport Logistics* 13: 156–184.

Zervas, Efthimios. 2006. CO_2 benefit from the increasing percentage of diesel passenger cars. Case of Ireland. *Energy Policy* 34: 2848–2857.

Zhou, Yuyan, Yan Zhang, Dong Ma, Lu. Jun, YuFu. Wenbin Luo, J. Shanshan Li, C. Feng, W.. Ge. Huang, and H. Zhu. 2020. Port-related emissions, environmental impact and their implication on green traffic policy in Shanghai. *Sustainability* 12: 1–17.

Zhu, Mo., Kevin X. Li, Kun-Chin. Lin, Wenming Shi, and Jialin Yang. 2020. How can shipowners comply with the 2020 global sulphur limit economically? *Transportation Research Part D: Transport and Environment* 79: 102234.

Zis, Thalis, Robin Jacob North, Panagiotis Angeloudis, Washington Yotto Ochieng, and Michael Geoffrey Harrison. Bell. 2014. Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. *Maritime Economics and Logistics* 166: 371–398.