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**Modeling the effects of unilateral
and uniform emission regulations
under shipping company and port
competition**

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ABSTRACT: This study develops an integrated model to investigate the economic and environmental effects of a unilateral maritime emission regulation vis-à-vis a uniform maritime emission regulation. The proposed model explicitly incorporates the effects of competition between regional ports and between shipping companies, and captures operational considerations such as the inventory costs of in-transit cargo, and the tradeoff between enlarged fleet size and slow steaming. The behaviors of shipping companies and ports are modeled in a two-stage game so that market equilibria under alternative regulations can be solved and compared. The findings suggest that a unilateral regulation may actually lead to an increase in total emissions, whereas a uniform regulation always reduces total emissions. Under either type of regulation, there can be asymmetric effects on shipping companies and ports. Therefore, regulators and the maritime industry need to strike a balance between emission reduction and fair competition. Our study cautions against unilateral regulations, and emphasizes the importance to take into account the effects of alternative emission policies on the operations of shipping companies and ports.

KEY WORDS: *Unilateral and uniform emission regulations; shipping company and port competition; market equilibrium*

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1. Introduction

With growing trade volumes, marine shipping has become a major source of carbon emissions. According to the International Maritime Organization (IMO), the total greenhouse gas (GHG) emissions from shipping reached 972 million tons in 2012, accounting for about 2.5% of the global emissions volume (Third IMO GHG Study, 2014). Other harmful emissions from international shipping, such as NO₂ and SO₂, have increased to 13% and 12% of global emission levels, respectively. Recently, there is growing interest in mitigating emissions from the maritime sector. Although some progresses have been made on setting international standards for ship's energy efficiency, such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), attempts to implement more emission abatement policies globally have encountered a lot of challenges despite the urgent needs to do so (Lister et al., 2015).

Governments and regulators have resorted, therefore, to regional or unilateral regulations such as emission control areas (ECAs) and regional speed limits (Chang and Wang, 2012; Panagakos et al., 2014; Sys et al., 2016). The Port of Long Beach, for instance, established a reduced speed zone (RSZ) in 2006 that requires vessels to slow down when they are within 20 nautical miles (nm) of the port. This zone was extended to 40 nm in 2010. ECAs were first introduced in the Baltic Sea and North Sea in Europe. In September 2015, China's Ministry of Transport released the *Ship and Port Pollution Prevention Special Action Plan (2015-2020)*, aiming to reduce sulfur and nitrogen oxide emissions by up to 65% in its major port areas. To this end, the central government has designated the Pearl River Delta, Yangtze River Delta, and Bohai-rim Waters as domestic ECAs (see Fig. 1), within which it will be compulsory for ships to burn fuel with a sulfur content of less than 0.5% from January 1, 2019. The local governments in the Yangtze River Delta took action ahead of the schedule. Starting from April 1, 2016, ships are required to switch from regular heavy fuel oil (HFO) to low-sulfur marine gas oil (MGO) with a sulfur content of less than 0.5% when berthing at the four "key ports" identified in the Yangtze River Delta area, i.e., the ports of Shanghai, Ningbo-Zhoushan, Suzhou, and Nantong. This regulation will gradually cover the whole Yangtze River Delta ECAs over the next three years, with tightened caps on sulfur content. Because bunker costs usually account for 50 or even 60% of the total operating cost of a shipping company (Notteboom, 2006; Golias et al., 2009), switching from regular HFO to expensive MGO leads to a significant increase in shipping costs, which could harm both shipping companies and shippers. Therefore, the unilateral sulfur emission regulation imposed by the Chinese government is likely to change the marine transport competition outcome between the Port of Shanghai and the Port of Busan (see Fig. 1). The two ports are major competitors in East Asia especially for intercontinental transshipment cargoes from northern China to Europe and North America (Anderson et al., 2008). Furthermore, as the ECAs for the Pearl River Delta and Bohai-rim Waters have not yet

been implemented, the cargo flow distribution may also be reshaped following the Yangtze River Delta ECA initiative.



Fig. 1. Geographical locations of the newly proposed ECAs in China

In addition to these unilateral administrative measures adopted in different regions, proposals have been made to introduce some market-based measures. Regulators and international organizations have made tremendous efforts to promote plans such as the maritime Emission Trading Scheme (ETS) and carbon tax (Lee et al., 2013; Kim et al., 2013; Franc and Sutto, 2014; Koesler et al., 2015; Wang et al., 2015). These market-based measures have been seriously considered by every Marine Environment Protection Committee (MPEC) since MPEC 56 in July 2006. However, rather limited progress has been made in implementing these schemes on a global scale. Indeed, the European Commission once planned to include the aviation sector in the European Union ETS (EU-ETS) from 2012.¹ The decision, however, encountered strong opposition from other countries and was reduced to covering operations within the European Economic Area only. Nevertheless, the transport industry is concerned that such a regional ETS could induce some “side-effects,” including possible airline network reconfigurations. For example, a direct flight between Singapore and Frankfurt is fully subject to the EU-ETS, whereas with a two-leg flight via Zurich, only the leg between Zurich and Frankfurt is included (Albers et al., 2009). This may induce airlines to switch to inefficient hub routings. Similar concerns may also occur in the maritime sector if a maritime ETS is unilaterally imposed in certain regions (Franc and Sutto, 2014).

Whether a regional administrative measure or a unilateral market-based instrument is imposed, it would

¹ The proposed EU-ETS requires that all flights (regardless of carrier nationality) should acquire allowances to cover their CO₂ emissions before operating from/to an airport within the EU-ETS countries (Malina et al., 2012).

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become a cost component for the carriers equivalent to an increase in effective average fuel prices (Brueckner and Zhang, 2010; Wang et al., 2015). This is due to the fact that emission amount is directly proportional to fuel consumption.² Therefore, if unilateral emission regulations (e.g., RSZs, ECAs, carbon tax, or ETS) are to be implemented in certain regions only, the average effective bunker fuel prices will vary between alternative shipping routes. In such a case, shippers can either stick to the shorter shipping routes with higher effective fuel prices or switch to alternative routes that are exempt from emission regulations such as carbon tax, ETS, or RSZs/ECAs (e.g., recall the situation between the Port of Shanghai and Port of Busan). The majority of studies only investigate the optimal operational strategy of shipping companies on specific routes if a certain emission regulation is introduced, especially on the trade-off between slow steaming and increased fleet size (i.e., the trade-off between fuel cost and capital cost). Although these studies offer rich insights into the effects of emission regulations on shipping companies' operations, they rarely consider the resultant competition between regional ports and between shipping companies, and how shipping companies and port authorities would respond to unilateral regulations implemented in specific regions. As a result, the overall effects of such regulations on the maritime industry remain unclear. There is a need to explicitly consider shipping company and port competition in the evaluation of emission policies.

On the other hand, although the IMO has succeeded in promoting certain uniformly adopted environmental regulations in the maritime sector (such as the EEDI and the SEEMP), some countries and/or regions are not satisfied with the IMO's slow progress and have been introducing unilateral regulations. Koji Sekimizu, the former Secretary General of the IMO, emphasized at the 2015 International Chamber of Shipping conference in London that "Shipping is international and global, not national and not regional... no state should seek, unilaterally, to impose national, or regional, requirements or standards".³ It is obvious that there exists quite a discrepancy between the IMO and some governments with regard to the best approach to introduce emission regulation. Intuitively, a uniform policy adopted globally should be superior to unilateral regulations implemented in different regions. On the other hand, if the differences are marginal, it may be practical to also consider unilateral regulations in certain circumstances. Economic and trade developments promote the growth of the maritime sector, whereas the performance of the maritime sector significantly influences economic and trade patterns, environmental issues and social welfare (Chang et al., 2007, 2010; Lee et al., 2010, 2011, 2012, 2013; Lam, 2015). With such large stakes, it is important to fully compare the economic and environmental effects of these emission regulations before introducing any of them to the maritime sector.

² For a detailed explanation, see Page 963 in Brueckner and Zhang (2010).

³ Lloyd's List, <http://www.lloydlist.com/ll/sector/regulation/article468397.ece>.

This study aims to contribute to this important policy debate by developing an integrated model to compare the overall economic and environmental effects of a unilateral emission regulation vis-à-vis a uniform regulation under shipping company and port competition. Following Brueckner and Zhang (2010) and Wang et al. (2015), the emission regulations considered in this study are not restricted to any particular form (e.g., ECAs, ETS, or carbon tax), but are modeled as an asymmetric increase or a symmetric increase of average effective price of fuel under uniform regulations and unilateral regulations, respectively. Such a treatment allows us to capture the fundamental characteristics of alternative regulations in a general framework. We first model the competition equilibrium in a maritime shipping market with two ports, each served by a shipping company. The behaviors of shipping companies and ports are modeled in a two-stage game, so that market equilibria under alternative regulations can be solved and compared. In the first stage, the two ports set their own service charges. In the second stage, the shipping companies compete with each other by choosing their own freight rates and vessel speeds. Both shipping companies and ports are profit-maximizing decision-makers. Subsequently, the economic (in terms of profit, cargo volumes etc.) and environmental (in terms of total emissions) effects of unilateral and uniform emission regulations are compared. The analytical results are finally illustrated in a numerical study with two hypothetical competing routes.

This paper aims to contribute to both academic literature and industrial practices. First, the proposed two-stage game explicitly considers the competition of regional ports and shipping companies in the presence of emission regulations. It also captures operational considerations, such as the inventory costs of in-transit cargo, and the tradeoff between increased fleet size and slow steaming. Compared with the qualitative studies and the general equilibrium models proposed in the literature, such an approach allows us to incorporate important operational details in a general analytical framework that models the effects of alternative policies and market dynamics. Second, the findings indicate that a unilateral regulation may actually lead to an increase in total emissions, whereas a uniform regulation always reduces total emissions. Either type of regulation may result in asymmetric effects on shipping companies and ports. A unilateral emission regulation harms the affected ports and shipping companies in terms of lower cargo volume and profits, and benefits the ports and shipping companies not subject to such regulation. Similarly, a uniform emission regulation favors those ports and shipping companies with a shorter sailing distance at the expense of the ports and shipping companies on longer routes. Therefore, regulators and the maritime industry need to strike a balance between emission reduction and fair competition. Our study cautions against unilateral regulations, and emphasizes the importance to take into account the effects of alternative policies on the operations of shipping companies and ports.

The remainder of the paper is organized as follows. The next section provides a brief summary of the

related literature and highlights the contributions of this study. Section 3 formulates a two-stage game to characterize the decisions of shipping companies and port authorities when transport demand is fixed (inelastic). Market equilibria are analytically solved and benchmarked under a unilateral regulation versus a uniform regulation. Section 4 provides a numerical study of the two-stage game for the case of elastic demand. Section 5 concludes the paper and identifies areas for future studies.

2. Literature review

Various regulations have been proposed in the maritime industry for the control of emissions, ranging from mandatory operational requirements to industry standards and market-based instruments (Miola et al., 2011; Lam and Notteboom, 2012). In the climate policy literature, many technical reports and studies were devoted to addressing the design issues and/or the legal implications (territorial jurisprudence) of various uniform or unilateral emission regulations (see, for example, CE Delft, 2009; IMO, 2010a; Kremlis, 2010; Ringbom, 2011; Koesler et al., 2015; Hermeling et al., 2015). There were also some relevant studies in the transnational environmental regulation literature (see Lister et al., 2015 and the references therein). Quite a few researchers analyzed the economic and environmental effects of unilateral regulations in the aviation transport sector (see, for example, Albers et al., 2009; Scheelhaase et al., 2010; Yuen and Zhang, 2011; Vespermann and Wald, 2011; Malina et al., 2012). For the maritime transport sector, Lee et al. (2013) analyzed the effects of a maritime carbon tax on individual countries' container trade volumes and real GDP levels. Compared with a uniform carbon tax implemented globally, European countries would suffer more economic losses if such a tax was only adopted across the EU. Franc and Sutto (2014) investigated the economic consequences of different maritime ETS schemes (in terms of geographic scope and degree of connection to other carbon trading markets) on the re-organization of shipping network and services to ports. Hermeling et al. (2015) explored the economic and legal implications of an EU maritime ETS imposed over three possible geographical areas, namely the European territorial waters, the European economic zones plus European territorial waters, and the whole route. They concluded that the whole route regulation was economically optimal but would violate world trade laws.

Previous studies have frequently used computable general equilibrium models to identify the overall effects of alternative regulations for different economies. These models, however, often ignored the competition dynamics of shipping companies and ports. In contrast, Wang et al. (2015) examined the effects of two alternative ETS schemes: an open ETS under which the maritime sector could trade emission permits with other sectors; and a closed, maritime-only ETS, under which shipping companies could only trade permits with each other. Their study was based on partial equilibrium analysis. The results suggest that it is very important to consider the competition dynamics in the maritime sector; otherwise, biased conclusions may be obtained. The authors cautioned a simple generalization of their

conclusions to the cases of regional ETS schemes, because their model did not consider operational details such as shipping network reconfiguration and route choices.

In terms of operational-level analyses, quite a few studies have investigated the effects of emission regulations on shipping operations, with a particular focus on the selection of vessel speed and fleet size on a route-specific basis. Cariou and Cheaitou (2012) compared the effects of a regional speed limit zone versus an international fuel tax on shipping operations and the resultant CO₂ emissions. Using two independent transatlantic liner services as examples, their numerical studies suggested that a regional speed limit was inferior to a bunker levy in terms of total CO₂ emissions and abatement cost. Using a case study of the Port of Kaohsiung, Chang and Wang (2012) compared the effectiveness of a reduced speed zone, ECA, and alternative power schemes in reducing fuel consumption and emissions. The calculations were based on simple simulations of the current shipping operations. Doundnikoff and Lacoste (2014) examined whether the sulfur emission control area (SECA) would induce shipping companies to differentiate their vessel speeds inside and outside of the SECA. They applied a cost minimization model to four liner service cases, all of which suggested that total CO₂ emissions would increase because shipping speeds outside the SECA would rise to compensate for the extra time and slow speed inside the SECA. Fagerholt and Psaraftis (2015) proposed two vessel-speed optimization models to address ships sailing in and out of ECAs. In both cases, the objective was to maximize daily profit. Given the importance of ECAs, a special issue in *Transportation Research Part D* (Cullinane and Bergqvist, 2014) has published several relevant papers investigating ECAs and their effects on maritime transport.

These above-mentioned studies are mostly extensions of the basic speed-choice models developed earlier in the operations research and maritime economics literature.⁴ Their goals are to choose the optimal vessel speeds under various emission regulations to maximize (minimize) shipping companies' profits (costs). Vessel speed is a crucial decision in maritime emission studies for both economic and environmental reasons (Psaraftis and Kontovas, 2013). It is well established that shipping emissions are directly proportional to fuel consumption, which is approximately proportional to the third power of the vessel speed (Corbett et al., 2009; Ronen, 2011; Wang and Meng, 2012). When a ship reduces its cruising speed, fuel consumption decreases dramatically and so do the emissions. However, slow steaming comes with side effects: as the voyage time per trip increases, more ships must be deployed to maintain the same throughput or weekly service frequency. Most studies have focused on the operational decisions of shipping companies, taking into account the tradeoffs between lower speed/emissions versus more ships/capital inputs on specific routes. Few have captured the overall

⁴ See Psaraftis and Kontovas (2013) for a comprehensive review of various models.

effects of these emission regulations because a unilateral regulation imposed within a region may lead to asymmetric effects on alternative routes and trigger market competition dynamics. Competing ports and shipping companies may act strategically to maximize their own profits, and such actions could significantly change the overall effects of unilateral regulations.

Homsombat et al. (2013) compared a unilateral and a coordinated pollution tax policy in a region in which competing ports provide differentiated but substitutable services to shipping companies. They found that a port that unilaterally imposes a local pollution tax will not only drive shipping business to its rival port, but will also suffer increased spill-over pollution.⁵ Therefore, it is important for regional ports and governments to coordinate their pollution control efforts. Although their study provided useful managerial and policy insights, it was based on a stylized Hotelling model with strong assumptions, such as uniformly distributed shippers along a linear corridor and a linear relationship between pollution costs and cargo volume. Such a modeling method restricted the study to inland transportation and thus to in-port pollution. In addition, although Homsombat et al. (2013) highlighted the importance of explicitly considering the effects of market competition on pollution control, their study focused on port policies without modeling shipping operation decisions. As the majority of shipping emissions are generated at sea, their model needs to be extended to investigate the broad effects of emission regulations.

In this paper, we aim to fill the gap in the literature by investigating the economic and environmental effects of unilateral and uniform marine emission regulations in the presence of competition between shipping companies and between ports. Unlike most studies that have focused on shipping lines' decisions on specific routes, we explicitly model the demand side: the possible diversion of cargo to alternative shipping routes and inter-port competition. We therefore make several contributions to the literature on maritime emissions control, which are summarized as follows. First, we explicitly consider the strategic behavior of ports and shipping companies, which allows us to control the effects of market dynamics when unilateral/uniform emission regulations are imposed. Second, our model considers important operational decisions, thus ensuring that the effects of cargo in-transit inventory costs, the cubic approximation of the emission-speed relationship, and the tradeoff between slow steaming and the high capital costs of increasing the shipping fleet are properly embedded in the proposed model. Closed-form solutions are obtained for the case of fixed cargo demand, allowing us to obtain rich analytical results from a generalized model. Numerical simulations are carried out for the case of elastic demand to validate the robustness of our conclusions. These methodological improvements allow our model to better reflect the complexity in the maritime industry and thus allow solid conclusions and

⁵ Spill-over effect refers to the outcome that if two ports are located close to each other, the pollutants generated at one port may impose negative effects, or inter-port externalities, to the community or stakeholders in the other port.

practical policy recommendations to be made. The modeling details are introduced in the following section.

3. The model

Competition in the maritime industry is no longer at the level of individual ports or shipping companies, but rather at the level of logistics chains (Suykens and Van de Voorde, 1998; Van de Voorde and Vanelslander, 2009). When choosing between ports, shippers consider sets or combinations of “ports and shipping companies” rather than an individual port or shipping company. Therefore, following an approach similar to that used in Barbot (2009), we consider a market with two ports, each served by a shipping company. Previous studies have used extended model specifications when the research objectives were focused on port competition, terminal concessions and specialization *per se*, or other issues such as capacity investments or revenue sharing (see, for example Zhang et al., 2010; Luo et al., 2012; Xiao et al., 2013; Zhuang et al., 2014; Yip et al., 2014). As depicted in Fig. 2, these two ports compete for a fixed volume of cargo Q designated for the same catchment area / destination port. Port/Route 1 is served by shipping company 1 and Port/Route 2 by shipping company 2. It is assumed that the shipping companies do not change the port they serve during the period under investigation.⁶ In this sense, ports compete for cargo through the shipping companies. For ease of notation, subscript i ($i = 1, 2$) is introduced to refer to port i , shipping company i or route i because there is a one-to-one correspondence between port, shipping company, and route. Their competitors are denoted with a subscript j ($j = 1, 2, j \neq i$).

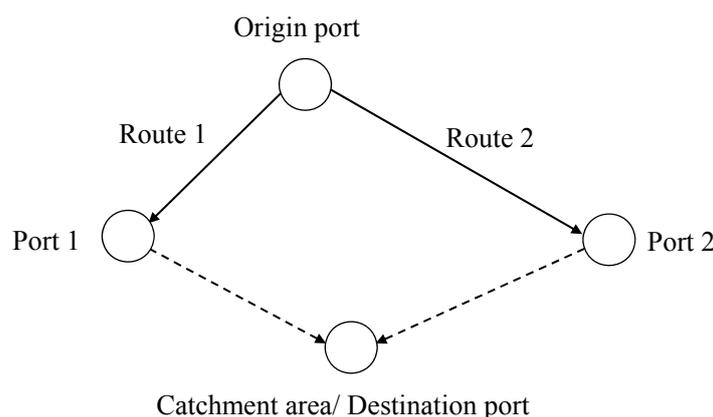


Fig. 2. An illustrative network

⁶ As noted by Álvarez-SanJaime et al. (2013) and Lam et al. (2013), the shipping market is increasingly vertically integrated. Shipping companies often invest heavily in ports to gain control over port capacity and secure preferred services (e.g., dedicated terminals). As a result, there may be significant switching costs for a shipping company to relocate to a different port in a region.

The behaviors of the shipping companies and ports are characterized in a two-stage game. In the first stage, the two ports set their own service charges w_i , respectively. In the second stage, the shipping companies compete with each other by choosing their own freight rates and vessel speeds. Both shipping companies and ports are profit-maximizing decision-makers. Similar multi-stage game modeling frameworks have been widely used in various maritime (aviation) transport economic studies examining the vertical relations between seaports (airports) and carriers (see, for example, Zhang and Zhang, 2006; Basso and Zhang, 2007; De Borger et al., 2008; Saeed and Larsen, 2010; Yuen and Zhang, 2011; Bae et al., 2013; Homsombat et al., 2013; Ishii et al., 2013; Song et al., 2016).⁷

To facilitate the presentation of the essential ideas, without loss of generality the following assumptions are made in this paper.

A1 Two emission regulation scenarios are examined and compared: a unilateral regulation imposed in a region vis-à-vis a uniform regulation imposed on the whole market. Although emission regulations take various forms in practice (e.g., ECAs, ETS or carbon tax), they are modeled as increases in the effective average price of fuel as this is how emission regulations affect carriers' decisions (Brueckner and Zhang, 2010; Wang et al., 2015). This study follows this general approach. Therefore, a unilateral emission regulation implies asymmetric effective fuel prices on different shipping routes, which corresponds to a situation in which the two ports are not regulated by a single government or port authority (e.g., Port of Shanghai and Port of Busan). A uniform emission regulation, in contrast, relates to the situation where a single government or port authority has jurisdiction over the whole market considered (e.g., Port of Shanghai and Port of Ningbo).

A2 The generalized shipping cost per unit of cargo (e.g., per ton or per container) consists of the freight rate, the in-transit inventory cost at sea, and the congestion cost at the port. Latent variables such as reliability, flexibility, safety etc. are not considered (Panagakos et al., 2014).

A3 The congestion cost at port is assumed to be a linear function of the volume-capacity ratio (see, for example, similar specifications in De Borger and Van Dender, 2006; Basso and Zhang, 2007; De Borger

⁷ In addition to service charges, port capacity expansion has been identified as another important strategic decision variable in port competition issue. In this study, however, port capacity expansion decisions are not considered because they are less relevant in the context of emission regulations, which are the focus of this study. Port authorities are unlikely to initiate a lumpy capacity expansion project in response to emission regulations. On the contrary, they tend to use more flexible pricing tools.

et al., 2008; Wan and Zhang, 2013; Álvarez-SanJaime et al., 2015). In addition, the considered ports have the same capacity and marginal cost.

A4 The operating cost per vessel consists of fixed operation costs, variable bunker fuel costs for the main engines and port service charges (see Yin et al., 2014). There are other port-related charges and fees, which include various fees levied on the vessels and/or cargo for use of the facilities and services offered by the port, such as docking, pilotage, towage, and cargo handling (Stopford, 2009). These charges are not considered in our model. If these costs can be regarded as constant, then explicitly considering such costs will not bring any material change to our model.

3.1. Market equilibrium without emission regulation

According to **A2**, if a shipper chooses route i (and hence port i and shipping company i , $i = 1, 2$) to transport its cargo, the generalized shipping cost per unit of cargo (e.g., per ton or per container) C_i consists of the freight rate P_i , the in-transit inventory cost at sea, and the congestion cost at the port. Let L_i be the average sailing distance of route i and v_i be shipping company i 's vessel speed. The transit time t_i at sea is defined as the sailing distance divided by the vessel speed, i.e., $t_i = L_i/v_i$. Following **A3**, the congestion cost at port i depends on the ratio of cargo volume Q_i at port i and the port capacity K_i . It is assumed to be a linear function of the volume-capacity ratio Q_i/K_i , i.e., $\beta' Q_i/K_i$, where β' is a constant. More general congestion cost functions could be adopted (e.g., a quadratic form), but this would strongly complicate the technical analysis without providing significantly different insights for our policy evaluation. In addition, we consider the case in which both ports have the same capacity, i.e., $K_1 = K_2 = K$. The congestion cost at a port is thus simplified as βQ_i , where $\beta = \beta'/K$. Asymmetric port capacities can be easily modeled by changing the specification to $\beta_i Q_i$ instead. Specification βQ_i is kept because our objective is to identify the net effects of competition dynamics caused by emission regulations instead of port capacity *per se*. Shipping cost C_i can, therefore, be specified as

$$C_i = P_i + \alpha \frac{L_i}{v_i} + \beta Q_i, \quad \forall i = 1, 2, \quad (1)$$

where α is the value of transit time (VOT) of shippers, which depends on the commodity to be transported and is higher for more expensive cargo (Psaraftis and Kontovas, 2014). For instance, it has

been estimated that a one-day delay in cargo delivery entails an inventory cost of \$5.75/ton for high-value industrial products with an average price of \$30,000/ton and the cost of capital at 7% (Psaraftis and Kontovas, 2010). For a vessel with a payload of 8,000 tons, this implies a sizeable in-transit inventory cost of \$46,000 per day. Ruling out the unlikely case in which one route (and thus the associated shipping company and port) receives no traffic volume at all, at equilibrium, we have

$$\begin{cases} C_1 = C_2, \\ Q = Q_1 + Q_2. \end{cases} \quad (2)$$

Following De Borger et al. (2008), Wan and Zhang (2013) and Ishii et al. (2013), the above equilibrium conditions imply that the generalized shipping cost is equal across the two alternative routes and the total cargo is distributed between them. Substituting Eq. (1) into Eq. (2) and solving Eq. (2) yields the following demand function for shipping company i :⁸

$$Q_i = \frac{1}{2\beta} \left(\beta Q + \alpha \left(\frac{L_j}{v_j} - \frac{L_i}{v_i} \right) + P_j - P_i \right), \quad \forall i, j = 1, 2, i \neq j. \quad (3)$$

In Eq. (3), note that an increase in the freight rate P_i or a decrease in the vessel speed v_i of shipping company i will reduce its own cargo volume Q_i and increase its competitor j 's cargo volume Q_j .

3.1.1. Shipping company's profit

According to **A4**, the annual operating cost per vessel of shipping company i can be divided into three parts. First, a fixed operation cost γ_i , which includes the cost for crews, supplies, insurance, periodic maintenance, and fuel consumption for auxiliary engines; γ_i is assumed to be exogenously given. Second, the variable bunker fuel costs for the main engines f_i , which are assumed to follow the cubic rule thus that bunker fuel consumption is proportional to the third power of sailing speed (Corbett et al., 2009; Psaraftis et al., 2010, 2013, 2014; Wang et al., 2015). The fuel cost is specified as $f_i = \rho_i \eta_i \lambda_i v_i^3$, where λ_i is a coefficient representing a vessel's energy efficiency, η_i is the effective bunker fuel price on route i , ρ_i denotes the average working time at sea per year for a vessel. Third, the port service

⁸ Generally there are two approaches to determine the demand function for shipping companies, i.e. a spatial price equilibrium (SPE) model as presented in this paper or a discrete choice model such as multinomial logit (MNL) model. For more discussions on applications of the latter model, please refer to Wang et al. (2014) and the references therein.

charges per unit of cargo, w_i . With the above specifications, shipping company i sets the freight rate P_i and vessel speed v_i to maximize its own profit π_i^s (superscript s denotes a shipping company), written as

$$\max_{P_i, v_i} \pi_i^s = (P_i - w_i)Q_i - (f_i + \gamma_i)N_i, \quad \forall i = 1, 2, \quad (4)$$

where N_i denotes the number of vessels required to transport Q_i units of cargo.

Let u_i represent a vessel's capacity. The annual cargo output per vessel is thus $u_i \rho_i / t_i = u_i \rho_i v_i / L_i$ (Wang et al., 2015). We then have $N_i = Q_i L_i / (u_i \rho_i v_i)$, reflecting an inverse relation between N_i and v_i . The explanation is straightforward: a lower vessel speed implies a longer transit time and thus fewer deliveries each year, calling for more vessels to be deployed. Hence, the second cost component in Eq. (4) (i.e., $(f_i + \gamma_i)N_i$) captures the tradeoff between the fuel cost saving (decrease in f_i) and the capital cost increase (increase in N_i) due to slow steaming. The first-order optimality conditions for the shipping company's profit-maximization problem (4) are

$$\frac{\partial \pi_i^s}{\partial P_i} = Q_i + \left(P_i - w_i - \frac{L_i(\eta_i \rho_i \lambda_i v_i^3 + \gamma_i)}{\rho_i u_i v_i} \right) \frac{\partial Q_i}{\partial P_i} = 0, \quad \forall i = 1, 2, \text{ and} \quad (5)$$

$$\frac{\partial \pi_i^s}{\partial v_i} = \left(P_i - w_i - \frac{L_i(\eta_i \rho_i \lambda_i v_i^3 + \gamma_i)}{\rho_i u_i v_i} \right) \frac{\partial Q_i}{\partial v_i} - \frac{2L_i \eta_i \lambda_i}{u_i} Q_i v_i + \frac{\gamma_i L_i}{\rho_i u_i v_i^2} Q_i = 0, \quad \forall i = 1, 2. \quad (6)$$

It can be shown that the Hessian matrix associated with the profit function π_i^s is negative definite (for a sketched proof, please see Appendix A). The resultant (unique) equilibrium vessel speed and freight rate can thus be solved as follows:

$$v_i = \sqrt[3]{\frac{\alpha \rho_i u_i + \gamma_i}{2 \eta_i \rho_i \lambda_i}}, \quad \forall i = 1, 2, \text{ and} \quad (7)$$

$$P_i = \beta Q + \frac{2w_i + w_j}{3} + \frac{L_j}{2v_j} \left(\alpha + \frac{\gamma_j}{\rho_j u_j} \right) + \frac{L_i}{v_i \rho_i u_i} \gamma_i, \quad \forall i, j = 1, 2, i \neq j. \quad (8)$$

The optimal vessel speed in Eq. (7) implies, other things being equal (the values of ρ_i , u_i , λ_i and γ_i), that shipping companies will choose the same vessel speed as long as the effective fuel price, which is the sum of the bunker fuel price and the fuel tax or cost increase due to regulation, is equal on both routes (i.e., $\eta_1 = \eta_2$). In addition, a higher VOT (α) or fixed cost (γ_i) or a lower effective fuel price (η_i) will induce a higher vessel speed. For example, a higher fixed operation cost or a lower effective fuel price makes slow steaming less desirable because the cost increase associated with a larger N_i will outweigh the fuel cost savings (i.e., smaller f_i). A higher VOT will prompt shipping companies to increase the vessel speed to capture more cargoes from its competitor. Eq. (8) suggests that an increase in the port charge of either port will induce a higher freight rate, although a shipping company's pricing decision is more sensitive to the charge set by the port it serves.

Substituting Eq. (8) into Eq. (3) yields the resultant demand for shipping company i :

$$Q_1 = \left(\beta Q + \frac{w_2 - w_1}{3} + 3\varphi \right) / 2\beta, \quad Q_2 = \left(\beta Q + \frac{w_1 - w_2}{3} - 3\varphi \right) / 2\beta, \quad (9)$$

where $\varphi = \frac{L_2}{v_2} \left(\frac{\alpha}{6} + \frac{\gamma_2}{6\rho_2 u_2} \right) - \frac{L_1}{v_1} \left(\frac{\alpha}{6} + \frac{\gamma_1}{6\rho_1 u_1} \right)$. The demand along a route depends on the difference in port charges ($w_1 - w_2$). This further confirms the effects of inter-port competition.

3.1.2. Port's profit

Following De Borger et al. (2008), Homsombat et al. (2013), Wan and Zhang (2013), Song et al. (2016), although port-handling operations are usually privately controlled by a few terminal operating companies, these companies are aggregated into one monopoly operator per port. Each port sets its service charge w_i to maximize its own profit. Without loss of generality, it is assumed that the two ports have the same constant marginal cost c . Its objective function π_i^p (superscript p denotes a port) can be specified as

$$\max_{w_i} \pi_i^p = (w_i - c)Q_i, \quad \forall i = 1, 2. \quad (10)$$

Substituting Eq. (9) into Eq. (10) and solving for the corresponding first-order optimality conditions, we have the following optimal port service charges:

$$\begin{cases} w_1 = 3\beta Q + c + 3\phi, \\ w_2 = 3\beta Q + c - 3\phi. \end{cases} \quad (11)$$

For ease of understanding, the interrelationships among the three stakeholders (ports, shipping companies, and shippers) are summarized in Fig. 3. It can be seen in Fig. 3 that the input of a stakeholder is the outputs of the other stakeholders, and vice versa. Note that so far we have derived the solutions without assuming ρ_i , u_i , λ_i , and γ_i to be the same across the two shipping companies. In the following section, however, we let these parameters be the same. Such an approach is used to isolate the combined effects of these parameters so that the net effects of competition in the presence of imposed emission regulations can be clearly identified. For the convenience of readers, Table 1 summarizes the equilibrium solutions associated with ports and shipping companies (for tables please refer to Appendix).

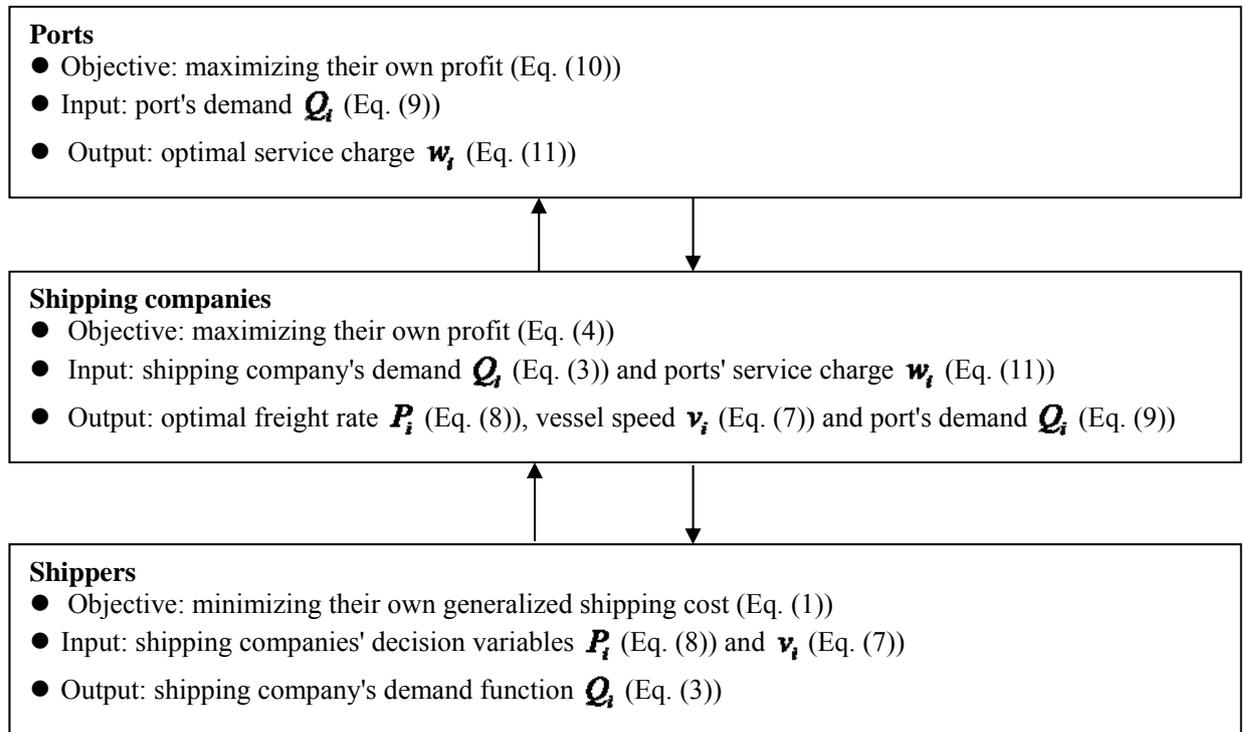


Fig. 3. A diagrammatical representation of the model

3.2. Effects of emission regulations on shipping company and port competition

When the EU proposed to include the aviation industry in the EU-ETS, a major concern was whether airline competition would be significantly affected (Albers et al., 2009; Scheelhaase et al., 2010). In the following analysis, we check whether a similar problem arises in the maritime industry. First, we consider Scenario 1, in which a unilateral regulation on marine emissions is implemented in a region.

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Without loss of generality, we assume that part of route 1 is subject to emission regulations whereas route 2 is not. The effective fuel prices along the two routes are thus asymmetric/differentiated, i.e., $\eta_1 \neq \eta_2$. From Table 1, the following comparative statics results can be derived (the detailed proof is omitted to save space, but is available from the authors on request):

$$\frac{\partial v_1}{\partial \eta_1} < 0, \quad \frac{\partial v_2}{\partial \eta_1} = 0, \quad (12)$$

$$\frac{\partial P_1}{\partial \eta_1} < 0 \text{ if } \alpha > \frac{5\gamma}{\rho u}; \text{ Otherwise, } \frac{\partial P_1}{\partial \eta_1} > 0, \quad \frac{\partial P_2}{\partial \eta_1} > 0, \quad (13)$$

$$\frac{\partial w_1}{\partial \eta_1} < 0, \quad \frac{\partial w_2}{\partial \eta_1} > 0, \quad \frac{\partial Q_1}{\partial \eta_1} < 0, \quad \frac{\partial Q_2}{\partial \eta_1} > 0, \text{ and} \quad (14)$$

$$\frac{\partial \pi_1^s}{\partial \eta_1} < 0, \quad \frac{\partial \pi_2^s}{\partial \eta_1} > 0, \quad \frac{\partial \pi_1^p}{\partial \eta_1} < 0, \quad \frac{\partial \pi_2^p}{\partial \eta_1} > 0. \quad (15)$$

When the effective fuel price η_1 on route 1 increases due to the emission regulation, shipping company 1 will lower its optimal vessel speed (i.e., $\partial v_1/\partial \eta_1 < 0$), leading to increased transit time. It thus has an incentive to lower its freight rate to compensate for the increased transit time. However, it will also want to increase its freight rate to offset the increased fuel cost. Therefore, shipping company 1 can either increase or decrease its freight rate P_1 . If the value of transit time is large ($\alpha > 5\gamma/\rho u$ in this study), the former incentive dominates the latter, leading to a decrease in the freight rate P_1 (when $\partial P_1/\partial \eta_1 < 0$), and thus the reverse conclusion holds. As port 1 serves the same amount of cargo that shipping company 1 captures, port 1 will decrease its service charge ($\partial w_1/\partial \eta_1 < 0$) to subsidize shipping company 1 in competition with port 2. Shipping company 2's optimal vessel speed ($\partial v_2/\partial \eta_1 = 0$) will not change, so it will increase its freight rate P_2 ($\partial P_2/\partial \eta_1 > 0$) to take advantage of the increased shipping cost on route 1. For the same reason, port 2 increases its service charge ($\partial w_2/\partial \eta_1 > 0$). Finally, a higher effective fuel price on route 1 will divert some cargoes from route/port 1 to route/port 2 ($\partial Q_1/\partial \eta_1 < 0$, $\partial Q_2/\partial \eta_1 > 0$). The profit of shipping companies on route 1 will decrease whereas the profit of shipping companies on route 2 will increase. Clearly, a unilateral emission regulation will put the affected shipping companies and ports at a disadvantage.

We now look at Scenario 2, in which a uniform emission regulation is implemented over the whole

market. This leads to an identical increase in the effective fuel price on both routes, i.e., $\eta_1 = \eta_2 = \eta$. The following results (i.e., Eqs. (16)-(19)) can be derived when route 2 is a longer route, i.e., $L_1 < L_2$. For the case of route 1 being a longer route, i.e., $L_1 > L_2$, the results can be easily obtained by interchanging the route indicators in these expressions (i.e., the subscripts). The detailed proof of Eqs. (16)-(19) is omitted here, but is available from the authors on request.

$$\frac{\partial P_1}{\partial \eta} > 0, \quad (16)$$

$$\frac{\partial P_2}{\partial \eta} < 0 \text{ if } \alpha > \frac{5\gamma}{\rho u} \text{ and } \frac{L_2}{L_1} > \frac{4\alpha\rho u + 4\gamma}{\alpha\rho u - 5\gamma}; \text{ Otherwise, } \frac{\partial P_2}{\partial \eta} > 0, \quad (17)$$

$$\frac{\partial w_1}{\partial \eta} > 0, \quad \frac{\partial w_2}{\partial \eta} < 0, \quad \frac{\partial Q_1}{\partial \eta} > 0, \quad \frac{\partial Q_2}{\partial \eta} < 0, \text{ and} \quad (18)$$

$$\frac{\partial \pi_1^s}{\partial \eta} > 0, \quad \frac{\partial \pi_2^s}{\partial \eta} < 0, \quad \frac{\partial \pi_1^p}{\partial \eta} > 0, \quad \frac{\partial \pi_2^p}{\partial \eta} < 0. \quad (19)$$

Inequality $\partial P_1 / \partial \eta > 0$ implies that an identical increase in the effective fuel price always raises the freight rate on the shorter route (i.e., route 1). Although $\partial P_2 / \partial \eta < 0$ is possible in theory, it seems unlikely in reality because it requires L_2 to be at least four times longer than L_1 . Therefore, it is plausible that a uniform emission regulation could lead to an increase in the freight rates on both routes. Other comparative statics results show that a uniform emission regulation discourages shipping companies and ports from serving the longer routes. Some cargoes will be diverted to the shorter route 1, and both shipping company 2 and port 2 will suffer a profit loss. This is consistent with the simulation results in Lee et al. (2013), which showed that the effects on the cargo volume are likely to be asymmetric even under a uniform carbon tax implemented globally. The routes with longer distances would lose some cargo volume to the routes with shorter distances. These results are summarized in the following proposition:

Proposition 1. *A unilateral emission regulation harms the affected ports and shipping companies in terms of lower cargo volume and profits, and benefits the ports and shipping companies not subject to such regulation. Similarly, a uniform emission regulation favors those ports and shipping companies with a shorter sailing distance at the expense of the ports and shipping companies on longer routes.*

3.3. Effects of emission regulations on total emissions

It is important to fully assess and compare the effectiveness of different emission regulations before implementation (CE Delft, 2009; Kim et al., 2013). This section devotes to comparing the effectiveness of unilateral and uniform regulations in reducing the total fuel consumption/emissions. It should be mentioned that emission amount is directly proportional to fuel consumption. The total fuel consumption is the sum of the fuel consumption of all shipping companies, given by $F^s = \frac{\lambda}{u} (L_1 Q_1 v_1^2 + L_2 Q_2 v_2^2)$. In Scenario 1, in which the effective fuel price η_1 goes up, both Q_1 and v_1 go down and thus the fuel consumption of shipping company 1 decreases. Meanwhile, Q_2 increases but v_2 remains unchanged, leading to an increase in the fuel consumption of shipping company 2. To identify the net effect of fuel price on the total fuel consumption, we can calculate

$$\frac{\partial F^s}{\partial \eta_1} = \frac{\partial F^s}{\partial v_1} \frac{\partial v_1}{\partial \eta_1} = \frac{\lambda}{2\beta u v_1^2} \frac{\partial v_1}{\partial \eta_1} (A v_1^3 - B v_1^2 - C), \quad (20)$$

where $A = 2L_1\beta Q + \frac{2L_1L_2}{v_2} \left(\frac{\gamma}{6\rho u} + \frac{\alpha}{6} \right) > 0$, $B = L_1^2 \left(\frac{\gamma}{6\rho u} + \frac{\alpha}{6} \right) > 0$, and $C = L_1L_2v_2^2 \left(\frac{\gamma}{6\rho u} + \frac{\alpha}{6} \right) > 0$. It can be proved that $\partial F^s / \partial \eta_1 > 0$ if $\eta_1 > (\alpha\rho u + \gamma) / 2\rho\lambda\tilde{v}^3$ and $\partial F^s / \partial \eta_1 < 0$ if $\underline{\eta} < \eta_1 < (\alpha\rho u + \gamma) / 2\rho\lambda\tilde{v}^3$ (the detailed proof is given in Appendix B), where $\underline{\eta}$ denotes the lower bound of the bunker fuel price (i.e., the lowest possible bunker fuel price) and \tilde{v} is the sole positive real root of the equation $f(v_1) = A v_1^3 - B v_1^2 - C = 0$. Therefore, there exists a threshold of effective fuel price, beyond which unilateral regulation can actually increase the total emissions. Hence, unilateral regulation will produce a counterproductive outcome.

In Scenario 2, with a uniform emission regulation, $\eta_1 = \eta_2 = \eta$ holds; we thus have $v_1 = v_2 = v$ according to Table 1. The total fuel consumption can be simplified as

$$F^s = \frac{\lambda}{2\beta u} \left((L_1 + L_2)\beta Q v^2 - (L_2 - L_1)^2 \left(\frac{\gamma}{6\rho u} + \frac{\alpha}{6} \right) v \right). \quad (21)$$

Eq. (21) shows that F^s is a quadratic function of v , whose graph is a parabola opening-upwards with

$\underline{v} = \frac{(L_2 - L_1)^2 (\gamma + \alpha \rho u)}{12(L_1 + L_2) \rho u \beta Q}$ as the axis of symmetry. As Q_1 and Q_2 (shown in Table 1) are positive, we

must have $v > \frac{(L_2 - L_1)(\gamma + \alpha \rho u)}{6 \rho u \beta Q} > \underline{v}$. It can be shown that $\frac{\partial F^s}{\partial v} > 0$ holds. Given $\frac{\partial v}{\partial \eta} < 0$ (see

Table 1), we have $\frac{\partial F^s}{\partial \eta} = \frac{\partial F^s}{\partial v} \frac{\partial v}{\partial \eta} < 0$, so that total fuel consumption always decreases in the effective

fuel price. Combining the findings in both scenarios, we have the following proposition:

Proposition 2. *A uniform regulation imposed over the whole market always reduces total emissions. In contrast, a unilateral regulation reduces total emissions when the effective fuel price is not too large, and increases total emissions if the effective fuel price is larger than a threshold.*

In the past decades, little progress has been made in devising a uniform maritime emission regulation that can be accepted on a global/multi-lateral basis. Some regulators have decided to move forward with unilateral regulations. Our analytical results caution policy-makers against such practices. On the one hand, the international society has to start from somewhere to attack the global warming problem and control maritime emissions. On the other hand, unilateral regulation carries a risk of backfiring as it may increase rather than reduce global emissions. Therefore, it is important to consider market dynamics and to evaluate the effects of unilateral/regional regulation on a case-by-case basis.

It should be mentioned that Proposition 2 is derived when shipping companies and ports make decisions separately. As noted by Álvarez-SanJaime et al. (2013) and Lam et al. (2013), vertical integration is an increasingly prominent feature in the shipping market. It can be shown that the result in Proposition 2 still holds if shipping companies and ports are vertically integrated. The proof is provided in Appendix C.

4. Numerical study

In the previous sections, the closed-form solutions and solution properties of the proposed model have been obtained under the assumption that demand is fixed, i.e., $Q = Q_1 + Q_2$. To validate the robustness of these conclusions, in this section we consider a (linear) elastic demand function case. As not all of the analytical solutions can be derived under the elastic demand case, a numerical simulation is carried out instead. In the following, we first set the parameter values for a base case, then carry out extensive sensitive tests to validate the robustness of the simulation results.

Following Wang et al. (2015), we consider the most widely used containership type, the Post Panamax,

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with an approximated capacity u of 6,000 TEUs. For containerships with a capacity of 6000-7000 TEUs, the bunker fuel consumption is estimated to be 203.4 tons per day when sailing at a design speed of 25 knots (Notteboom and Cariou, 2009). The corresponding calculated hourly engine efficiency is $\lambda = 203.4 \times 25^{-3} / 24 = 5.42 \times 10^{-4}$. The average voyage distance is 9,036 nm according to the international seaborne traffic data published in 2007 in the Review of Maritime Transport (UNCTAD, 2008). Without loss of generality, L_1 and L_2 are assumed to be 9,000 nm and 9,500 nm, respectively. According to the Second IMO GHG Study (2009), the average working time at sea for a ship is 270 days per year, equivalent to $\rho = 6480$ hours. The daily fixed operating cost varies from \$8,150 for a Panamax vessel of 4,000 TEUs to \$11,575 for a Mega-Post-Panamax vessel of 10,000 TEUs (Notteboom, 2006). In this study, the daily fixed operating cost for the 6,000 TEU Post Panamax is assumed to be \$10,000, which amounts to an annual fixed operating cost of $\gamma = \$2.7$ million. Using the performance statistics from the Port of Prince Rupert in 2011, the average cargo value is set as \$10,957/TEU.⁹ This implies an in-transit inventory cost of $\alpha = \$0.87/\text{h}/\text{TEU}$ for a capital cost of 7%. Cariou and Cheaitou (2012) used a weekly cargo demand of about 7200 TEUs, resulting in an annual demand of 0.375 million TEUs. Assuming a 20% potential demand growth rate, the potential annual demand is $Q = 0.45$ million TEUs. The bunker fuel price η_2 on route 2 for the base case is set as \$300/ton, a representative average price in 2007 (Notteboom and Vernimmen, 2009). Table 2 summarizes the parameter values used in the numerical simulation.

For the fixed demand case (i.e., $Q = Q_1 + Q_2$), we have proved that there exists a threshold of the effective fuel price, beyond which total emissions will increase in the effective fuel price. To verify the robustness of this result under variable demand, a linear elastic demand function is specified as $Q_1 + Q_2 = Q - b \text{Cost}$, in which the coefficient b is assumed to vary from 0 to 50. It is noteworthy that when $b = 0$, the linear demand function reduces to the fixed demand case investigated earlier. The effects of a unilateral regulation and the coefficient b on the total emissions are depicted in Fig. 4, in which the unilateral emission regulation is modeled by changing the effective bunker fuel price η_1 on route 1 from \$300/ton to \$1200/ton. A higher effective fuel price corresponds to a stricter emission regulation, and vice versa. The price range reflects the fluctuation of the bunker price (Notteboom and Vernimmen, 2009; Wang and Meng, 2012). Fig. 4 follows a U-shaped surface. For all values of b considered, there always exists a threshold beyond which a stricter unilateral regulation (i.e., a higher effective fuel price on route 1) leads to more total emissions. For the fixed demand case with $b = 0$, the simulated threshold fuel price is about \$694/ton, which can be analytically verified using Eq. (20).

⁹ <http://www.rupertport.com/documents/value-of-trade-2012/pdf>.

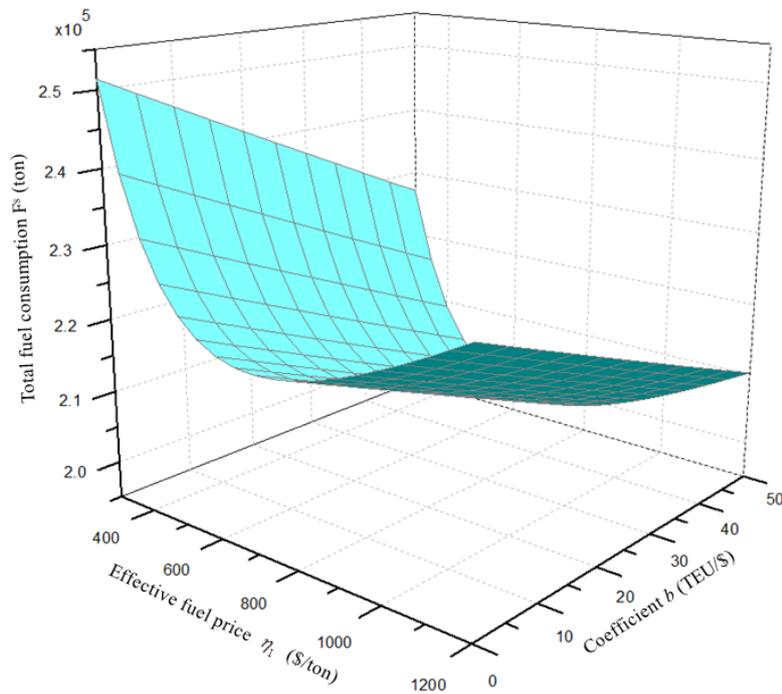


Fig. 4. Effects of unilateral regulation on total fuel consumption with different values of b

For further clarification, Fig. 5 depicts the contour in the space of the effective fuel price η_1 and the coefficient b . The dashed blue curve in Fig. 5 represents the best response of the threshold fuel price η_1 to the coefficient b . To prevent a counterproductive outcome, the effective fuel price with regulation effects considered should be kept below the dashed curve. In contrast to unilateral regulations, a uniform regulation is modeled by equating η_1 and η_2 , which vary simultaneously from \$300/ton to \$1200/ton in the numerical simulation. Different from Fig. 4, the total emissions always decrease in the effective fuel price for any value of b , as shown in Fig. 6.

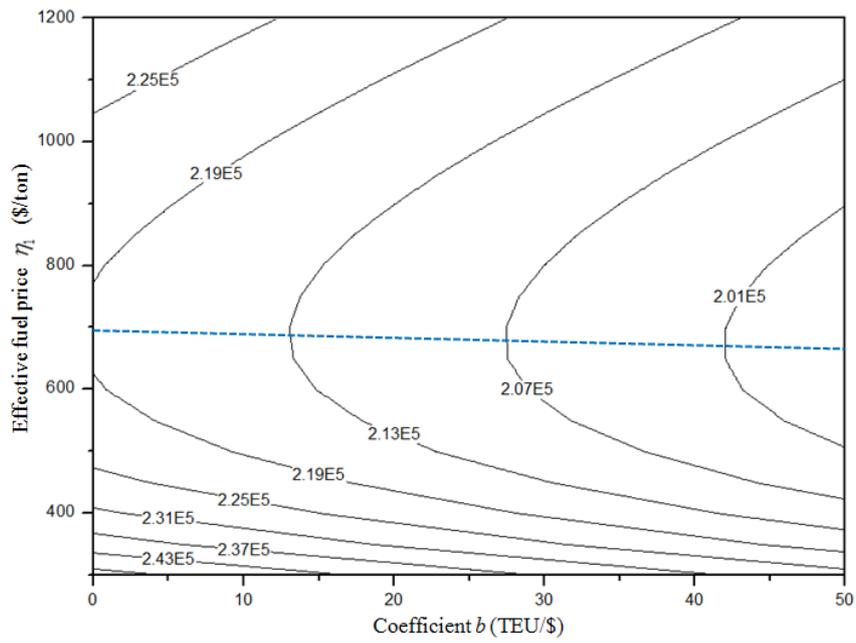


Fig. 5. Change in the threshold fuel price with b

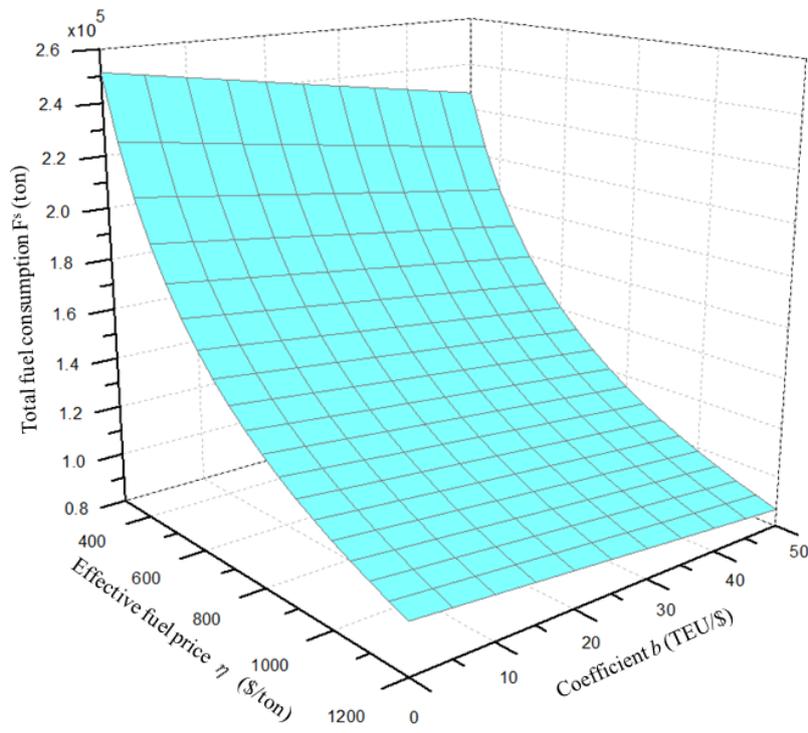


Fig. 6. Effects of uniform regulation on total fuel consumption with different values of b

5. Conclusion and further studies

With growing trade volumes, marine shipping has become a major source of carbon emissions. Various regulations have been proposed in the maritime industry for the control of emissions, ranging from mandatory operational requirements to industry standards and market-based instruments. Against this background, many technical reports and studies were devoted to discussing the design issues or the legal implications of various uniform or unilateral emission regulations (see CE Delft, 2009; IMO, 2010a; Kremlis, 2010; Ringbom, 2011; Koesler et al., 2015), with a few addressing their associated macroeconomic effects (Lee et al., 2013; Hermeling et al., 2015). There is another stream of studies in the literature investigating how the introduction of certain emission regulations on specific routes affects the operational strategies of shipping companies, especially the trade-off between slow steaming and increased fleet size (see, among others, Corbett et al., 2009; Cariou and Cheaitou, 2012; Chang and Wang, 2012; Doundnikoff and Lacoste, 2014; Fagerholt and Psaraftis, 2015). Although the previous related studies have offered rich insights into the effects of emission regulation on shipping companies' operations, they have rarely considered the competition between regional ports and shipping companies, and the responses of the shipping companies and port authorities to unilateral/uniform regulations (Homsombat et al., 2013; Sys et al., 2016). The overall effects of such regulations on the maritime industry therefore remain unclear.

In this study, a two-stage game model is proposed to investigate the effects of alternative emission regulation regimes taking into account market dynamics. The main contributions of this paper are summarized as follows.

1. This paper supplements extant maritime emission studies by explicitly modeling ports' strategic behaviors when evaluating the emission regulations. Although the previous related studies have offered rich insights into the effects of emission regulations on shipping company's operations, they rarely considered the competition of regional ports and shipping companies due to the implementation of unilateral or uniform emission regulations. The comparative statics results derived in Section 3.2 indicate that port charges would be affected (e.g., port may subsidize towards its shipping company) under either unilateral or uniform emission regulations. This finding confirms the importance to explicitly consider ports' behavior in relevant studies. Therefore, governments have to take ports' response into consideration when evaluating the effects of any proposed emission regulation; otherwise, biased results would be obtained.
2. The proposed model incorporates demand-side responses as well as shipping companies' operational decisions, thus that the effects of cargo in-transit inventory cost, the cubic

approximation of the emission-speed relationship, and the tradeoff between slow steaming and high capital costs of ship fleet are properly embedded into the proposed model. Closed-form solutions have been obtained for the case of fixed cargo demand, allowing us to obtain rich analytical results from a generalized model. Therefore, this paper manages to strike a balance between relevant theoretical economic analysis and operational studies.

3. This paper finds that there exists a threshold of effective fuel price, beyond which the unilateral regulation can actually increase the total emission. In order to prevent a counterproductive outcome, the effective fuel price with regulation effects considered should be kept below the threshold, e.g., the dashed curve of the contour figure as depicted in the numerical study. When relevant data are readily available, the proposed model and analytical techniques can be applied to a real case, such as the case between Port of Shanghai and Port of Busan, where the former is recently subject to ECAs while the latter not yet.
4. Under either type of regulation there can be asymmetric effects on shipping companies and ports. A unilateral emission regulation harms the affected ports and shipping companies in terms of lower cargo volume and profits, and benefits the ports and shipping companies not subject to such regulation. A uniform emission regulation favors those ports and shipping companies with shorter sailing distance at the expenses of the ports and shipping companies on the longer routes. Therefore, regulators and the maritime industry need to strike a balance between emission reduction and fair competition.

Although our study extends previous operational models by capturing market dynamics, it can be further extended in several directions. First, although the numerical study uses realistic parameter values wherever possible, it illustrates the model application with two hypothetical competing routes. It would be useful to investigate specific markets, such as the shipping routes to the Port of Shanghai and Port of Busan. Because the Port of Shanghai was included in the newly proposed ECA, it would be meaningful to analyze how market outcomes would evolve in response to the imposed policy. When industry data can be collected in the future, such an empirical study will provide useful managerial insights and policy recommendations complementary to our study. Second, in the medium to long term, shipping companies can improve their vessels' energy efficiency by upgrading their fleets (either by purchasing new ships or adopting innovative technologies) in response to increasingly strict maritime emission regulations. In contrast to the static model proposed in this study, a dynamic multi-period model incorporating such a decision variable is worth exploring (Balland et al., 2012, 2015). Third, this study considers emission regulations in a general way by increasing the average effective price of fuel. In practice, however, there may exist other forms of maritime regulation such as restricting per-trip

emissions (similar to EEDI standards) or simply setting a total emission allowance. It would be interesting to investigate the differential effects of these specific measures. Finally, this study only considers cargo diversion between different shipping routes under unilateral emission regulation. However, there may be a shift to land-based transport modes such as railway or trucks (Holmgren et al., 2014). For instance, cargo moving between the Far East and Europe can be transported either via ocean route or the trans-Siberian railway (Psaraftis and Kontovas, 2010). Therefore, it would be meaningful to extend the proposed model to consider the competition among different transport modes in a further study.

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Appendix A. Definiteness of the associated Hessian Matrix

The Hessian matrix H associated with the shipping company's profit is as follow.

$$H = \begin{pmatrix} \frac{\partial \pi_i^s}{\partial P_i^2} & \frac{\partial \pi_i^s}{\partial P_i \partial v_i} \\ \frac{\partial \pi_i^s}{\partial v_i \partial P_i} & \frac{\partial \pi_i^s}{\partial v_i^2} \end{pmatrix} = \begin{pmatrix} -\frac{1}{2\beta} & \frac{\alpha L_i}{2\beta v_i^2} \\ \frac{\alpha L_i}{2\beta v_i^2} & \frac{-\alpha^2 L_i^2 \rho_i u_i - 12 L_i \rho_i \eta_i \lambda_i Q_i \beta v_i^4}{2\beta \rho_i u_i v_i^4} \end{pmatrix}$$

The order principal minor determinants of matrix H are

$$\left| -\frac{1}{2\beta} \right| = -\frac{1}{2\beta} < 0, \text{ and } |H| = \frac{3L_i \eta_i \lambda_i Q_i}{\beta u_i} > 0.$$

Consequently, the Hessian matrix H is negative definite, and thus the shipping company's profit function is concave and the profit maximization problem has a unique optimal solution.

Appendix B. Proof of sign of $\partial F^s / \partial \eta_i$ in Eq. (20)

To determine the sign of the function $f(v_1) = Av_1^3 - Bv_1^2 - C$, we first investigate its monotonicity. From the first-order optimality condition, we have $f'(v_1) = 3Av_1^2 - 2Bv_1 = 0$, thus leading to two positive solutions, i.e., $v_1 = 0$ and $v_1 = 2B/3A$. It is easy to show that $f'(v_1) < 0$ if $0 < v_1 < 2B/3A$ and $f'(v_1) > 0$ if $v_1 < 0$ or $v_1 > 2B/3A$. Fig. 7 depicts the rough shape of function f .

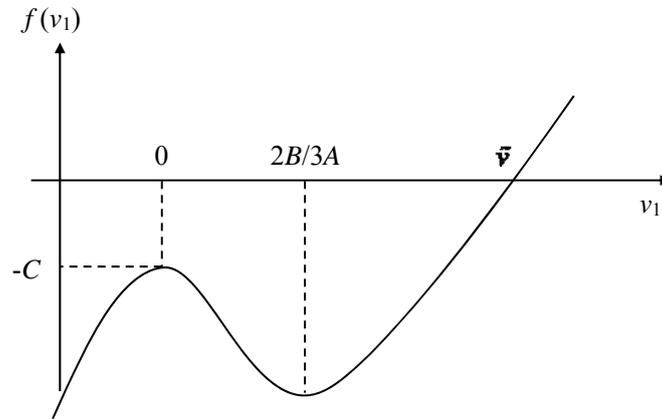


Fig. 7. The rough shape of function $f(v_1)$

As $f(0) = -C < 0$ and $f(v_1) \rightarrow +\infty$ when $v_1 \rightarrow +\infty$, the continuous function f must cross the horizontal axis only once (e.g., at \tilde{v}). Therefore, $f(v_1) < 0$ if $0 < v_1 < \tilde{v}$ and $f(v_1) > 0$ if $v_1 > \tilde{v}$. With the relation between η_i and v_1 expressed in Eq. (7), the threshold effective fuel price can be calculated as $\eta_i^* = (\alpha\rho u + \gamma) / 2\rho\lambda\tilde{v}^3$. Hence, $\partial F^s / \partial \eta_i > 0$ if $\eta_i > \eta_i^*$, and $\partial F^s / \partial \eta_i < 0$ if $\underline{\eta} < \eta_i < \eta_i^*$.

Appendix C. Solutions for vertical integration

When ports and shipping companies are vertically integrated, the objective function is to maximize their joint profit $\pi_i = \pi_i^p + \pi_i^s$, formulated as

$$\max_{P_i, v_i} \pi_i = (P_i - c)Q_i - (f_i + \gamma_i)N_i, \quad \forall i = 1, 2.$$

The port service charges (w_i) disappear since they are internalized from the from the supply chain profit's perspective, i.e., the upstream port's revenue and its downstream shipping company's cost are offset (Song et al., 2016). The optimal solutions of the joint profit maximization problem are shown in Table 3. Similar to the procedure described in Appendix B, it can be shown that Proposition 2 also holds for the vertical integration scenario.

Table 1 Solutions for the two-stage game.

Stage one: Ports

Modeling the effects of unilateral and uniform emission regulations under shipping company and port competition

Sheng, Li, Fu and Gillen

Decision variables	$w_1 = 3\beta Q + c + 3\phi, w_2 = 3\beta Q + c - 3\phi$
Cargo volume	$Q_1 = \frac{1}{2\beta}(\beta Q + \phi), Q_2 = \frac{1}{2\beta}(\beta Q - \phi)$
Profit	$\pi_1^p = \frac{3}{2\beta}(\beta Q + \phi)^2, \pi_2^p = \frac{3}{2\beta}(\beta Q - \phi)^2$

Stage two: Shipping companies

Decision variables	$v_i = \sqrt[3]{\frac{\alpha\rho u + \gamma}{2\eta_i\rho\lambda}}, \forall i = 1, 2$
	$P_i = 4\beta Q + c + \frac{\gamma}{6\rho u} \left(\frac{4L_j}{v_j} + \frac{5L_i}{v_i} \right) + \frac{\alpha}{6} \left(\frac{4L_j}{v_j} - \frac{L_i}{v_i} \right), \forall i, j = 1, 2, i \neq j$
Cargo volume	$Q_1 = \frac{1}{2\beta}(\beta Q + \phi), Q_2 = \frac{1}{2\beta}(\beta Q - \phi)$
Profit	$\pi_1^s = \frac{1}{2\beta}(\beta Q + \phi)^2, \pi_2^s = \frac{1}{2\beta}(\beta Q - \phi)^2$

where $\phi = \left(\frac{\gamma}{6\rho u} + \frac{\alpha}{6} \right) \left(\frac{L_2}{v_2} - \frac{L_1}{v_1} \right)$.

Table 2 Input data for numerical illustration.

Parameter	Description	Value
ρ	Annual working time at sea	6,480 hours
u	Vessel capacity	6,000 TEUs
γ	Annual fixed operating cost	\$2.7 million
λ	Hourly engine efficiency	5.42×10^{-4}
α	Value of time	\$0.87/h/TEU
β	Port congestion cost	$\$10^{-4}/\text{TEU}$
L_1, L_2	Sailing distance	9,000 nm and 9,500 nm
η_2	Fuel price on route 2	\$300/ton
c	Marginal cost at port	\$180/TEU
Q	Potential annual demand	0.45 million TEUs

Table 3 Solutions under the vertical integration between port and shipping companies.

Decision variables	$v_i = \sqrt[3]{\frac{\alpha\rho u + \gamma}{2\eta_i\rho\lambda}}, \forall i = 1, 2$
	$P_i = \beta Q + c + \frac{\gamma}{2\rho u} \left(\frac{2L_i}{v_i} + \frac{L_j}{v_j} \right) + \frac{\alpha}{2} \frac{L_j}{v_j}, \forall i, j = 1, 2, i \neq j$
Cargo volume	$Q_1 = \frac{1}{2\beta} (\beta Q + \xi), Q_2 = \frac{1}{2\beta} (\beta Q - \xi)$
Joint profit	$\pi_1^s = \frac{1}{2\beta} (\beta Q + \xi)^2, \pi_2^s = \frac{1}{2\beta} (\beta Q - \xi)^2$

where $\xi = 3\phi = \left(\frac{\gamma}{2\rho u} + \frac{\alpha}{2} \right) \left(\frac{L_2}{v_2} - \frac{L_1}{v_1} \right)$.